



An Integrated BIM-Based Risk Management Framework for Sustainable and Innovative Bridge Construction

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ABSTRACT:

Bridge construction projects are characterised by high levels of technical, financial, and environmental uncertainty, which frequently lead to delays, cost overruns, and sustainability challenges. At the same time, the digital transformation of the construction sector is creating opportunities for more innovative and value-driven project delivery. This study proposes an integrated framework that combines Building Information Modelling (BIM) with structured risk management to enhance sustainable bridge construction and support improved decision-making. The framework incorporates a Risk Breakdown Structure with Failure Mode and Effects Analysis (FMEA) and the Analytic Hierarchy Process (AHP) to prioritise project risks and embed the weighted risk data into a BIM environment. Risk information is transferred from an external database to 3 Revit using Dynamo, enabling element-level visualisation and integration with the construction schedule in Navisworks for 4D risk analysis. The framework is validated throughout a case study of the Jofra Bridge project in southern Libya, where 35 critical risks were identified through project decomposition, and experts involved assessed using a combined FMEA and AHP techniques and mapped into a 3D/4D model. The results demonstrate that BIM-based risk visualisation improves interdisciplinary communication, supports proactive risk mitigation, and reduces the probability of rework and schedule disruption, contributing to resource efficiency and sustainability. The study concludes that integrating quantitative risk assessment with BIM provides a practical and replicable solution for managing uncertainty in bridge projects. While the framework is validated using a single case study, the approach offers significant practical and social benefits by promoting safer construction practices, improved infrastructure reliability, and innovation-driven engineering workflows.

Keywords: Bridges, Entrepreneurship & Innovation, Building Information Modelling (BIM), Risk Management, Sustainable Construction.

1. Introduction:

Bridges are a long-lasting infrastructure asset that play an essential role in regional connectivity, economic development, and social integration. Their planning and construction involve a complex engineering system, multiple stakeholders, and significant investment in capital, which together create a challenging project environment. In recent

decades, increasing demands for cost efficiency, schedule reliability, and environmental responsibility intensified the need for more innovative and resilient methods to bridge delivery. Consequently, innovation and entrepreneurship are gradually recognised as essential capabilities for enhancing infrastructure performance and achieving sustainable

development objectives (Ali *et al.*, 2018; Ligonenko *et al.*, 2024).

Building Information Modelling has emerged as a key digital technology for enhancing information management, communications, and decision-making across the infrastructure lifecycle. BIM technology enables the development of data-rich 3D models that integrate geometric, temporal, and cost information, supporting improved planning accuracy and collaboration among project stakeholders (Tah and Carr, 2001; A. N. Hasan and Rasheed, 2019a; Jian, 2020). In the construction of bridges, BIM has been applied to design, clash detection, construction sequencing, and cost estimation. However, despite these advances, risk management practices in bridge projects often remain document-based and detached from BIM workflows, limiting their ability to dynamically identify, evaluate, and mitigate project risks (Zayed *et al.*, 2008; Yang Zou *et al.*, 2015; Ongkowijoyo *et al.*, 2021).

Risk management is a fundamental requirement for a successful bridge delivery due to the high levels of uncertainty associated with ground conditions, construction approach, safety, environmental impacts, and stakeholder coordination. Established tools such as FMEA and AHP, and recognised international risk management standards, provide a structured mechanism for identifying, evaluating, and prioritising risk (Chapman and Ward, 2003; Patrick XW Zou *et al.*, 2007; Sharma and Srivastava, 2018). However, these methods are commonly applied as standalone analytical tools, lacking direct integration with design and construction models. As a result, risk management is often static, difficult to communicate, and poorly aligned with evolving project conditions.

While the prior research (Hartmann *et al.*, 2012; Shim *et al.*, 2012; Ding *et al.*, 2016; Y. Zou *et al.*, 2019). demonstrates BIM's potential for risk visualisation, significant issues remain. Most studies emphasise qualitative representations of risks rather than quantitative representations; few integrate risk management tools directly into the BIM environment, and even fewer address the IFC limitations that restrict risk embedding in bridge models. Essentially, recent studies on BIM-based risk identification for bridges, for instance Y. Zou *et al.* (2019), don't fully examine how quantitative risk scores can be operationalised with 3D/4D BIM or how such integration improves decision-making compared with conventional spreadsheet-based tools. These gaps highlight the requirement for a more systematic, data-driven, and BIM-integrated methodology to risk management in infrastructure projects.

To address these gaps, this study proposes an integrated BIM-based risk management framework tailored to bridge construction projects. The framework combines a risk breakdown structure (RBS) with FMEA and AHP to prioritise project risks and embeds the weighted risk data directly into BIM components using a database-driven workflow and Dynamo-based integration with Revit and Navisworks. The

framework is validated through a real-world case study of the Jofra Bridge project in Libya. By enabling element-level and time-based 3D/4D risk visualisation, the proposed approach enhances decision-making, supporting proactive risk mitigation, and contributes to sustainability through reduced rework and improved resource efficiency. In addition, the study highlights how the BIM-based risk information approach can enable innovative and entrepreneurial engineering practices, support the transition of civil engineering towards value-creating, data-driven infrastructure delivery models.

The remainder of this paper is organised as follows: Section 2 reviews the relevant literature; Section 3 describes the research methodology; Section 4 presents validation through a case study; Section 5 reports the results; Section 6 offers a discussion; and Section 7 provides the conclusion.

Literature review

Entrepreneurship and Innovation in Infrastructure Projects
Entrepreneurship and innovation are widely recognised as critical drivers of economic growth and competitiveness, specifically in infrastructure development. Innovation extends beyond technological to include new organisational structures, management practices, delivery models, and creation strategies that enhance the efficiency and adaptability (Cooper, 1998; Talegeta, 2012; Drucker and Maciariello, 2014). Entrepreneurial thinking in infrastructure projects supports engineers and organisations in managing uncertainty, using resources more efficiently, and creating long-term value. The quality and performance of the infrastructure system are closely linked to entrepreneurial activity. High-quality transport infrastructure, including bridges, enhances regional connectivity, reduces transportation costs, and facilitates market access, thereby promoting business development (Kodongo and Ojah, 2016). Empirical studies have further shown that strategic investment in physical and digital infrastructure stimulates innovation by enhancing information flows and reducing operational barriers (Czernich *et al.*, 2011; Audretsch *et al.*, 2015). Public-private partnerships support innovation by combining public sector governance with private sector expertise and risk sharing. However, significant capital requirements, regulatory barriers, and a high-risk level continue to limit the adoption of entrepreneurial approaches in bridge projects, particularly in developing and transitional economies (DALUMPINES *et al.*, 2024). Although growing interest in engineering entrepreneurship, limited studies have examined how digital construction technologies, particularly BIM integrated with risk management, can enable entrepreneurial value creation in infrastructure delivery. This gap is especially evident in bridge projects, which involve

high complexity and uncertainty, and therefore require risk-informed innovation.

Building Information Modelling (BIM) in Bridge Infrastructure

Building information modelling has evolved from early computer-aided design systems into an advanced digital platform that combines geometric 3D, temporal 4D, and financial information across the infrastructure lifecycle. BIM supports collaboration among participants, improves design cooperation, and facilitates simulation-based decision-making during planning, construction, and operation stages (Jian, 2020). In bridge projects, BIM facilitates the modelling of complex geometries, early clash detection, and improved constructability analysis, contributing to enhanced project performance. The extension of BIM into four five-dimensional applications has further expanded its potential. 4D links models to construction schedules, enabling visualisation of construction and optimisation of timelines, while 5D BIM integrates cost data for dynamic budget control (Amjed N Hasan and Rasheed, 2019b). Current studies have also explored the integration of BIM with other technologies for real-time lifecycle monitoring, enhancing safety, extending asset longevity, and reducing long-term costs. Nevertheless, BIM adoption in bridge projects remains inconsistent. Barriers include fragmented stakeholders' understanding, the lack of standardisation, insufficient training, and the limitation of existing industry foundations classes, IFC, which are primarily designed for building rather than bridge-specific elements (Selçuk Çıdık *et al.*, 2017; Floros *et al.*, 2019). As a result, BIM is often underutilised as strategic decision support, particularly in relation to risk management and sustainability.

Risk Management in Bridge Construction Projects

Bridge construction projects involve multiple interrelated risks, including technical, financial, environmental, safety, and organisational uncertainties. Effective risk management is therefore essential to prevent delays, cost overruns, and safety incidents (Chapman and Ward, 2003). The standard risk management process typically involves risk identification, assessment, response planning, and monitoring throughout the project lifecycle (Patrick XW Zou *et al.*, 2007). Established techniques, including Failure Mode and Effects Analysis (FMEA), the Analytic Hierarchy Process (AHP), and recognised international risk management standards, offer structured approaches to risk identification and prioritisation (Sharma and Srivastava, 2018). FMEA is widely used to assess failure probability and severity, while AHP supports multiple criteria decision-making by incorporating expert judgment (Çeliker *et al.*, 2021). However, when applied in isolation, these tools often produce static outputs that are difficult to communicate and insufficiently responsive to evolving project conditions Ganbat *et al.* (2018). This disconnect highlights a critical research gap: although quantitative techniques such as FMEA and AHP are widely used, only a limited number of studies

have explored how each method can be embedded directly within integrated project information environments such as BIM, where risks can be visualised and managed spatially and temporally. Moreover, no studies have combined FMEA and AHP to address their respective limitations and integrate the resulting quantitative risk measures within a BIM environment.

Integration of BIM and Risk Management

To address the limitations of traditional risk management methods, recent studies have explored the integration of BIM with risk assessment and visualisation techniques. BIM-based risk identification methods enable the mapping of risks directly onto model components, improving spatial understanding and stakeholder communication. For instance, Shim *et al.* (2012) developed a BIM-based visual risk management system for bridge projects, indicating that collaborative visual tools improved engineering efficiency and mitigated project risks. Similarly, Hartmann *et al.* (2012) investigated BIM-based 4D models for large infrastructure projects and proposed aligning BIM tools with existing workflow to enhance risk management while reducing implementation disruptions. While Ding *et al.* (2016) utilised ontology and semantic web technologies within BIM to support construction risk assessment by identifying risk causes and proposing mitigation strategies. Y. Zou *et al.* (2017) discovered a knowledge-based system using the Case-Based Reasoning (CBR) cycle, emphasising the value of added project knowledge for future risk management. Building on this, Y. Zou *et al.* (2019) developed a BIM-based identification tool by integrating the work breakdown structure (WBS) and risk breakdown structure (RBS), enabling systematic risk classification. Furthermore, Darko *et al.* (2020) established a comprehensive BIM-based database for risk management in Modular Integrated Construction (MiC), providing a foundation for future BIM-based MiC risk management practices.

Despite these advances, most existing studies treat BIM and risk management as complementary rather than fully integrated systems. Furthermore, many approaches remain qualitative, rely heavily on expert judgment, or lack robust prioritisation mechanisms. In addition, limited attention has been given to the bridge project's specific requirements, interoperability challenges, and the integration of quantitative risk assessment approaches within BIM workflows.

The reviewed literature reveals the absence of a unified BIM-based risk management framework that integrates quantitative approaches such as FMEA and AHP within a 3D/4D BIM environment for bridge projects. Existing BIM risk studies largely rely on qualitative visualisation and offer limited time-based risk monitoring, providing insufficient empirical evidence of improved decision-making, particularly in infrastructure contexts beyond buildings. In addition, Limited research has examined how BIM-enabled risk management can support innovation, sustainability, and entrepreneurial practices in civil engineering. To address these gaps, this

study proposes and validates an integrated BIM-enabled risk management framework that supports systematic risk identification, quantitative prioritization, and enhanced decision-making for bridge construction. The research demonstrates how digital risk integration can enhance decision-making, improve sustainability outcomes, and enable value-creating, innovation-driven practices in bridge infrastructure delivery.

2.1 Research Design:

This study employs a structured methodology to demonstrate how new and digital technologies can be integrated with the Building Information Modelling (BIM) environment to enhance risk information for bridge construction projects. The proposed methodology focused on systematically identifying, assessing, and visualising project risks to support proactive decision-making and sustainable infrastructure delivery. A case study strategy is employed to validate the framework, as it allows in-depth investigations of complex real-world engineering processes within their practical context.

Research Design and Approach

A qualitative-quantitative hybrid method is adopted, combining expert-based risk assessment methods with BIM-based implementation. The methodology combines established risk management tools, Failure Mode and Effects Analysis (FMEA), and the Analytic Hierarchy Process (AHP) with BIM components to achieve both analytical rigor and practical applicability. This integration enables structured risk prioritisation while allowing risks to be dynamically visualised during design and construction stages. A case study methodology is selected due to the complexity and context-specific nature of Foot bridge project, where risks evolve across design and construction stages and are influenced by stakeholder coordination, site conditions, and construction sequencing.

Risk Identification, Classification, and Assessment

The first step involves systematically identifying risks based on a comprehensive review of the literature on bridge construction risks, project decomposition, and expert knowledge. Identified risks are organized and categorized by Risk Breakdown Structure (RBS), which consists of 16 main risk categories to ensure comprehensive coverage and logical classification. Each identified risk is assessed using Failure Mode and Effects Analysis (FMEA), which evaluates risks based on three criteria: severity, occurrence, and detection. Risks Priority Number (RBN) is calculated to provide an initial ranking of risks. Subsequently, the Analytic Hierarchy Process (AHP) is applied. AHP enables pairwise comparison of risk factors and incorporates expert judgment to assign

weighting coefficients, resulting in weighted RPN values that reflect relative risk importance more reliably,

BIM-Based Risk Integration and Task Structuring

To enhance comprehension and control of these risks, the study classifies them into sixteen primary risk factors (referred to as risk dimensions) denoted as D1, D2,..., D16. These risk dimensions include design(D1), structural(D2), personal safety(D3), personal health(D4), construction(D5), equipment and material(D6), organisational(D7), social culture(D8), political(D9), quality(D10), contractual & legal(D11), financial(D12), natural(D13), physical(D14), economic(D15), and time(D16). Each of these risk dimensions is further subdivided into its respective sub-factors (referred to as risk ID), denoted as D11, D1n, D161, and D16n. These groupings are thereafter connected to four specific activities, namely the Project Task, Environment Task, Site Task, and Bridge Task. Additionally, they are tied to the three primary components of a bridge, which are the foundation, substructure, and superstructure.

D11...D1n	D11...D1n	D131..D13n	D71..D07n
D61...D6n	D141..D14n	D141..D14n	D161..D16n
Risk Sub-Factors (RISK ID)			13,15,16
D11...D1n	D11...D1n	D131..D13n	D71..D07n
D61...D6n	D141..D14n	D141..D14n	D161..D16n

The Fundamental Connection between BIM Elements and Risk Information

Risk Data Integration Using Dynamo and BIM Modelling

Risk data, including task identifiers, risk categories, and results from FMEA and AHP, were aggregated by combining these two subjective methodologies to generate a new and more objective RPN are stored in an external database using Microsoft Excel. Dynamo visual programming is used to establish a dynamic link between the external risk database and the 3D Revit BIM model Figure 3. This process enables automatic transfer of risk information into the BIM environment. Within Revit, risk values are assigned to corresponding model elements using instance parameters. Risk severity levels are visualised at the element level through colour coding, allowing users to identify critical components quickly. This visual integration embeds risk intelligence directly into the BIM model, supporting improved understanding and communication among project stakeholders.



Risk Data Integration Using Dynamo and BIM Modelling

3D Modelling and 4D BIM Risk Simulation

A detailed three-dimensional bridge model is developed in Autodesk Revit based on two-dimensional design drawings created in AutoCAD. Native Revit elements are made to ensure accurate geometric representation and effective data control. The enriched BIM model is then imported into Autodesk Navisworks for construction sequencing and time-based analysis. Construction activities are linked to BIM elements using the Navisworks Timeline tool to generate a four-dimensional (4D) model. This integration enables visualisation of how risks evolve over the construction schedule, highlighting when and where high-risk activities occur. The 4D simulation supports proactive planning, verification of task element relationships, and real-time monitoring of risk exposure throughout the construction process.

Case Study and Framework Validation

The proposed methodology is validated through its application to a real footbridge project, namely the Jofra bridge, located in southern Libya. The project was selected as a representative bridge construction case due to its structural complexity, exposure to environmental and logistical uncertainties, and the availability of design documentation and expert input. These characters make the project suitable for evaluating the effectiveness of integrated BIM-based risk visualisation in a real-world construction context. Project documentation, including design drawings, construction plans, and risk-related records, was reviewed to support systematic risk identification and assessment. Furthermore, structured interviews were conducted with experienced engineers and project managers involved in bridge construction to ensure that the identified risks reflected practical site conditions and industry experience.

Based on document review and expert consultations, as a result, 35 critical risks were identified and categorised into main groups and subcategories for both the design and construction stages using Risk Breakdown Structure (RBS), which organises risks into 16 main dimensions covering design, structural, personal safety, personal health, construction, equipment & material, organisational, social culture, political, quality, contractual & legal, financial, natural, physical, economic, and time. Each of these risk dimensions is further divided into subfactors as described in section 3.3. Failure Mode and Effects Analysis (FMEA) was initially applied to evaluate each identified risk, where

severity, occurrence, and detectability scores were assigned based on expert judgment. Risk Priority Numbers (RPNs) were calculated to provide an initial ranking of risk significance. To improve prioritisation, particularly for high-impact but low-probability risks, the Analytic Hierarchy Process (AHP) was subsequently applied. Pairwise comparisons were conducted to develop a weighting coefficient, and the resulting weighting RPN values were used as the final risk prioritisation metric.

3D bridge model was developed in Autodesk Revit based on 2D design drawings. Risk data, including Essential details such as Task ID, Group ID, Dimensions, and weighted RPN values, were stored in an external database and dynamically linked to the BIM model using Dynamo visual programming. Risk attributes were assigned to corresponding model elements through instance parameters, enabling element-level representation of risk information. Risk levels were visualised within the BIM model using colour-coded indicators, allowing users to quickly identify critical structural components and construction activities. The visual integration embedded risk intelligence directly into the BIM model, facilitating improved understanding and communication among project stakeholders.

To enable time-based risk analysis, the developed BIM model was imported into Autodesk Navisworks, where construction activities were manually defined and linked to the corresponding model elements using the timeline tool. This integration generated a 4D model that visualised construction sequencing alongside evolving risk levels. The 4D simulation allowed project teams to observe when and where critical risks were probably to occur during the construction activities. Any task or element mismatches identified during simulation were corrected by updating the Revit model and re-importing it to Navisworks, ensuring consistency between design, schedule, and risk data. This iterative process served as a validation mechanism, confirming the accuracy of task assignments and the reliability of risk visualisation.



System for integration of Risk Management and Visualisation in Bridge Construction

Results

The application of the proposed BIM enables a risk management framework for the case study, which produced several key outcomes related to risk identification, prioritization, visualisation, and decision support. The results demonstrated the effectiveness of combined FMEA-AHP risk

assessment tools with 3D and 4D BIM for managing uncertainty in bridge construction projects.

A total of 35 critical risks were identified during the design and construction phases of the project through document review and expert consultations. These risks were systematically structured using the proposed Risk Breakdown Structure (RBS), covering 16 main risks. These organised classifications provide a comprehensive and transparent overview of potential risk sources and their relationships to different project tasks.

Initial Risk Priority Numbers (RPNs) were calculated using the FMEA method based on Severity, Occurrence, and detectability scores. The following application of the AHP refined these results by introducing weighting coefficients derived from the expert pairwise comparisons. The integration of FMEA and the AHP approach yielded weighted RPN values that more accurately reflected the relative importance of risks, particularly those associated with high potential impact but low probability of occurrence. This enhanced prioritisation supported more reliable identification of critical risks requiring immediate attention.

The integration of weighted risk information into the BIM environment enabled element-level visualisation of risks using colour-coded indicators. Within the 3D model, high-risk components and activities were clearly visible, improving understanding and communication among project stakeholders. Compared to traditional risk registers, this visual representation provided clearer insight into the spatial distribution of risks and their association with specific structural elements and construction tasks.

The integration of the BIM model with the construction schedule enabled 4D risk simulation, allowing risks to be visualised as they develop over the construction timeline. The simulation highlighted periods of heightened risk exposure, particularly during significant construction stages. In addition, the 4D environment also supported verification of task- element relationships, as inconsistencies identified during simulation were corrected through iterative model updates. This process improved schedule reliability and enhanced proactive planning by allowing for reduction measures to be considered before high-risk activities commenced.

The results indicate that the proposed framework improves decision-making by providing timely visual and task-specific risk information. The early identification of essential risks reduced the probability of rework, schedule disruption, and inefficient resource use. These outcomes contribute directly to sustainability objectives by minimising material waste, reducing energy-intensive corrective actions, and supporting more efficient construction sequencing, and confirm that integrating quantitative risk assessment with BIM-based

visualisation enhances project control, collaboration, and sustainability performance in bridge construction projects.

Discussion

The results of this study demonstrate that the integration of Building Information Modelling (BIM) with structured risk management significantly enhances the ability to manage uncertainty in bridge construction projects. Integrating FMEA–AHP-based risk prioritisation into a 3D and 4D BIM environment transforms risk management from a document-based approach to a dynamic and visual decision-support process. This transformation represents a significant improvement over traditional methods, which typically depend on standalone risk registers with limited integration into the design and construction process. One of the key contributions of the proposed framework is its methodological integration. Although FMEA and AHP are well-established risk assessment techniques, their practical effectiveness has traditionally been constrained by static outputs and limited communication among project stakeholders. . By combining weighted Risk Priority Numbers (RPNs) with BIM elements using Dynamo, the framework enables risk data to be spatially and temporally contextualised. This integration allows project stakeholders to visualise not only which risks are most critical, but also where and when they are likely to occur. Such capability supports more proactive and informed decision-making, aligning with previous findings that emphasise the value of visualisation in managing complex construction risks. The use of 4D risk simulation enhances the practical value of the framework. By combining risk information with construction sequencing, the model identifies periods of increased risk exposure during critical phases of construction. This time-based insight allows participants to anticipate potential disruptions and implement mitigation measures before risks occur. Compared with traditional scheduling tools, which typically focus on time and cost alone, the integrated 4D risk simulation provides a more comprehensive understanding of project dynamics, improving coordination and reducing the probability of schedule conflicts and rework. From a sustainability perspective, the findings indicate that BIM-enabled risk management contributes to more efficient use of resources and improved environmental performance. Early identification and prioritisation of risks reduce design errors, construction rework, and unnecessary site activities, which in turn lowers material waste and energy consumption. The ability to visualise risk evolution over time also supports better planning of construction operations, helping to minimise disruptions and extend asset life. These outcomes align with the broader objectives of sustainable infrastructure development, encompassing economic efficiency, environmental responsibility, and social value through safer and more reliable bridge assets. In addition to technical improvements, the proposed framework has important implications for innovation and engineering entrepreneurship. The integration of digital risk intelligence within BIM creates opportunities for new value-adding services, such as data-driven risk consultancy, performance-based project delivery,

and predictive maintenance planning. By leveraging digital tools to manage uncertainty more effectively, civil engineers can move beyond traditional design-focused roles and adopt entrepreneurial approaches that emphasise innovation, strategic decision-making, and value creation. This shift is particularly relevant in complex infrastructure sectors, where competitive advantage increasingly depends on digital capability and risk-informed management. Taken together, these findings indicate that the proposed BIM-based risk management is not merely a technological enhancement but a strategic enabler of innovation and sustainability in bridge construction. The framework provides a practical pathway for integrating quantitative risk assessment with digital construction technologies, supporting both improved project outcomes and the development of entrepreneurial engineering practices.

Conclusion

This study proposes an integrated BIM-based risk management framework designed to support sustainable and innovative bridge construction. By combining Failure Mode and Effects Analysis (FMEA) with the Analytic Hierarchy Process (AHP) and embedding the resulting weighted risk data into a 3D and 4D BIM environment, the framework transforms risk management from a static, document-based activity into a dynamic, visual, and decision-focused process. The validation using a real bridge construction project demonstrates that the proposed framework is both practically feasible and effective in enhancing risk visibility, facilitating coordination among stakeholders, and promoting proactive planning throughout the construction process. The findings confirm that integrating quantitative risk assessment tools with BIM-based visualisation enhances decision-making by allowing stakeholders to identify the location and timing of critical risks clearly. The use of element colour coding and time-based simulation improves communication across multidisciplinary teams and supports early intervention, reducing the probability of schedule delays, cost overruns, and rework. These improvements contribute directly to sustainability objectives by enhancing resource efficiency, reducing waste, and supporting safer construction practices throughout the design and construction phases. From an innovation perspective, the proposed framework highlights the potential of digital risk integration to enable new value-creating opportunities in infrastructure delivery. By using BIM as a platform for risk-informed decision support, civil engineers can develop data-driven consultancy services, performance-based delivery models, and advanced maintenance strategies. This shift encourages engineers to move toward more entrepreneurial roles, where digital expertise and strategic risk management serve as key sources of competitive advantage within the infrastructure sector. Despite its contributions, the study has certain limitations. The framework is validated through a single case study, which may limit the generalisability of the findings. Future research should apply the proposed approach to multiple bridge projects in different geographical and regulatory contexts to further test its robustness. In conclusion, this research

contributes both theoretically and practically by providing a replicable framework that integrates BIM and risk management to improve sustainability, innovation, and resilience in bridge construction projects. The findings support the broader digital transformation of civil engineering and provide a foundation for future research and practice in risk-informed, technology-driven infrastructure delivery.

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