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APPLICATION OF AI AND BIM IN THE DESIGN, CONSTRUCTION, AND MANAGEMENT OF BRIDGES – A LITERATURE REVIEW

Abstract:

Bridges are critical components of transportation infrastructure, requiring efficient design, construction, and management throughout their entire life cycle. Recent advances in digital technologies have significantly influenced bridge engineering, particularly through the adoption of Building Information Modeling (BIM) and Artificial Intelligence (AI). BIM enables integrated information management and improved coordination across different project phases, while AI provides advanced tools for data analysis, optimization, and decision-making. This paper presents a comprehensive review of the existing literature on the application of BIM and AI in bridge design, construction, and operation. The review covers the use of BIM in geometric modeling, construction planning, and asset management, as well as AI-based methods for structural analysis, damage detection, and predictive maintenance. Furthermore, the integration of BIM and AI, including the development of digital twins for bridges, is discussed. Key challenges, such as data availability, interoperability, and lack of standardization, are also identified. The findings highlight the significant potential of combining BIM and AI to enhance the efficiency, safety, and sustainability of bridge infrastructure and outline directions for future research.

Keywords:Artificial Intelligence, Building Information Modeling (BIM), Bridge Engineering, Structural Health Monitoring, Digital Twin, Infrastructure Management

ПРИМЈЕНА ВЈЕШТАЧКЕ ИНТЕЛИГЕНЦИЈЕ И BIM-А У ПРОЈЕКТОВАЊУ, ИЗГРАДЊИ И УПРАВЉАЊУ МОСТОВИМА - ПРЕГЛЕД ЛИТЕРАТУРЕ

Абстракт:

Мостови представљају кључне компоненте саобраћајне инфраструктуре и захтијевају ефикасно пројектовање, изградњу и управљање током читавог животног циклуса. Недавни напредак дигиталних технологија значајно је утицао на инжењерство мостова, нарочито кроз примјену Building Information Modeling-а (BIM) и вјештаћке интелигенције (AI). BIM омогућава интегрисано управљање информацијама и унапријеђену координацију између различитих фаза пројекта, док AI пружа напредне алате за анализу података, оптимизацију и доношење одлука. Овај рад даје свеобухватан преглед постојеће литературе о примјени BIM-а и AI у пројектовању, изградњи и експлоатацији мостова. Преглед обухвата примјену BIM-а у геометријском моделирању, планирању изградње и управљању имовином, као и методе засноване на вјештачкој интелигенцији за структурну анализу, детекцију оштећења и предиктивно одржавање. Такође се разматра интеграција BIM-а и AI, укључујући развој дигиталних близанаца мостова. Идентификовани су и кључни изазови, као што су доступност података, интероперабилност и недостатак стандардизације. Резултати указују на значајан потенцијал комбиновања BIM-а и вјештачке интелигенције у циљу унапређења ефикасности, безбједности и одрживости мостовске инфраструктуре, као и на правце будућих истраживања.

Кључне ријечи:вјештачка интелигенција, Building Information Modeling (BIM), мостоградња, праћење стања конструкције, дигитални близанац, управљање инфраструктуром

1. INTRODUCTION

Bridges represent key elements of transportation infrastructure and play a significant role in economic and social development. Their design, construction, and maintenance require a high level of technical precision, as well as efficient management throughout the entire life cycle of the structure. Contemporary challenges, such as increased demands for safety, durability, and sustainability, have encouraged the adoption of advanced digital technologies in bridge engineering. Building Information Modeling (BIM) and Artificial Intelligence (AI) are increasingly being used as tools to enhance planning, design, and management processes of infrastructure assets. While BIM enables integrated management of asset-related information, AI offers advanced methods for data analysis, optimization, and decision-making. The aim of this paper is to provide a review of the existing literature on the application of BIM and artificial intelligence in bridge engineering, with a particular focus on their advantages, challenges, and future research directions.

2. LITERATURE REVIEW METHODOLOGY

The literature review was designed to provide a structured overview of the application of Building Information Modeling (BIM) and Artificial Intelligence (AI) in bridge engineering. The selection process focused on peer-reviewed journal articles and conference proceedings addressing infrastructure assets, with particular emphasis on bridge-related applications.

Studies were included if they addressed BIM- or AI-based approaches applied to at least one phase of the bridge life cycle (design, construction, operation, maintenance, or monitoring). To ensure the relevance of the findings, the review prioritized research published within the last ten years.

The selected studies were systematically analyzed and categorized according to application domain and methodological approach. This classification enabled the identification of prevailing research trends, dominant technologies, and existing research gaps.

3. BIM IN BRIDGE ENGINEERING

3.1. FUNDAMENTAL CONCEPTS OF BIM IN INFRASTRUCTURE PROJECTS

BIM represents a digital representation of the physical and functional characteristics of a construction asset, enabling the integration of geometric, technical, and organizational data within a single model. Unlike traditional 2D design approaches, BIM supports a multidimensional framework (3D, 4D, 5D), which improves coordination among project stakeholders and reduces the risk of errors.

In infrastructure projects, and particularly in bridge engineering, BIM is used for modeling complex structures, analyzing design alternatives, and efficiently managing large volumes of data throughout the entire asset life cycle.

In addition to geometric representation, BIM in infrastructure projects serves as a comprehensive information management platform that supports decision-making throughout the asset life cycle. By integrating design data with scheduling, cost, and performance information, BIM enables a more holistic understanding of infrastructure systems. This integrated approach reduces information fragmentation and improves consistency across project phases. In bridge engineering, where projects are typically large-scale and technically complex, such capabilities are particularly important. BIM also facilitates collaboration among multidisciplinary teams by providing a shared digital environment. As a result, BIM contributes to increased transparency, reduced design errors, and improved overall project coordination.

Furthermore, BIM is increasingly recognized not only as a modeling methodology but as a structured knowledge framework for the AECO industry, with defined domains, processes, and governance requirements, particularly when extended from building projects to complex infrastructure systems, where challenges related to information integration, constructor-oriented processes, and data governance become more pronounced [1], [2].

3.2. BIM IN BRIDGE DESIGN

The application of BIM during the bridge design phase enables accurate structural modeling, enhanced visualization, and more efficient coordination among different engineering disciplines. The use of BIM tools allows for early detection of clashes, optimization of structural components, and faster evaluation of alternative design solutions. Furthermore, BIM models can be linked with structural analysis software, enabling the integration of static and dynamic analyses into the design process.

Beyond visualization and clash detection, BIM supports advanced design optimization by enabling rapid evaluation of alternative structural configurations. Parametric modeling allows designers to assess the impact of changes in geometry, materials, or loading conditions with greater efficiency. This capability is especially valuable in bridge projects, where structural safety, durability, and constructability must be carefully balanced. Furthermore, BIM-based design improves communication between structural engineers, architects, and other specialists by providing a common data environment. The use of BIM also supports better documentation and traceability of design decisions. Consequently, BIM enhances both the technical quality and reliability of bridge design outcomes.

In addition, previous studies have demonstrated that the application of Bridge Information Modeling (BrIM) extends BIM capabilities beyond design coordination to include cost and time management through BIM-based quantity take-off, schedule control, and integration with Earned Value analysis, while also emphasizing the importance of synchronizing BIM data with real-time construction processes to support informed decision-making throughout the project lifecycle [3], [4], [5].

3.3. BIM IN THE CONSTRUCTION PHASE OF BRIDGES

During construction, Building Information Modeling (BIM) is widely used for activity planning, progress monitoring, and resource management. The integration of the time dimension (4D BIM) allows for simulation of construction processes and the early identification of potential issues before they occur on site. By linking digital models with construction schedules and resource data, BIM enables more effective project control. The use of 4D BIM allows stakeholders to visualize construction sequences and detect potential conflicts between activities proactively, which improves planning accuracy and reduces construction risks. BIM models can also be updated to reflect as-built conditions, ensuring consistency between planned and executed work. Furthermore, BIM-based construction management enhances communication among contractors, supervisors, and investors, collectively contributing to reduced delays, better cost control, and improved construction quality.

In addition, recent research has explored the integration of advanced damage detection methods into BIM. For instance, Hong-lei Yang [6] proposes an enhancement of classical neural networks for detecting damage during bridge construction and integrates the improved recognition algorithm into the BIM framework for automated damage detection. This approach demonstrates the potential of combining AI techniques with BIM to further improve monitoring and quality control on construction sites. Moreover, BIM has been successfully applied to construction safety planning by integrating temporary structures such as scaffolding into automated hazard identification and prevention processes, enabling early detection of safety risks and improved safety communication through BIM-based simulation and visualization environments [7].

3.4. BIM IN BRIDGE OPERATION AND MAINTENANCE

In the operational phase, BIM serves as a digital repository that consolidates inspection records, maintenance histories, and performance data. This centralized information base supports more informed maintenance planning and prioritization of interventions. By linking condition data with specific structural components, BIM enables targeted maintenance actions rather than generalized interventions. This approach can significantly extend the service life of bridge structures and reduce lifecycle costs. Furthermore, BIM supports long-term asset management by facilitating data continuity from design to operation. As a result, BIM contributes to more sustainable and efficient bridge infrastructure management.

Recent studies have demonstrated that BIM-based inspection and evaluation frameworks can be used to systematically capture, assess, and analyze bridge damage and structural performance by linking inspection data directly to digital bridge models, thereby enabling more efficient condition assessment, load rating, and long-term management of bridge inventories [8].

The role of BIM across different phases of the bridge life cycle is schematically illustrated in Figure 1.

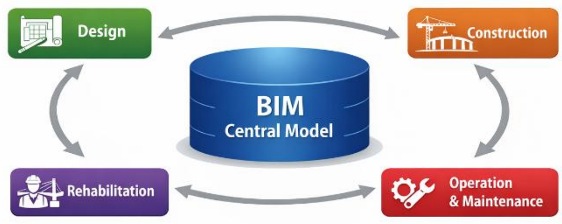

Figure 7. BIM-supported information flow throughout the bridge life cycle (Source: Developed by the authors based on literature review).

4. APPLICATION OF ARTIFICIAL INTELLIGENCE IN BRIDGE ENGINEERING

4.1. ARTIFICIAL INTELLIGENCE METHODS IN CIVIL ENGINEERING

Artificial intelligence encompasses a range of methods, including machine learning, neural networks, deep learning, evolutionary algorithms, etc. These methods enable the processing of large datasets and the identification of complex patterns that are not easily detectable using traditional analytical approaches.

In civil engineering, AI is applied for the optimization of design solutions, risk analysis, and automation of decision-making processes.

Building on these capabilities, AI methods support data-driven modeling of complex civil engineering systems characterized by uncertainty and nonlinear behavior. In infrastructure projects, AI is increasingly used to analyze large volumes of monitoring, inspection, and operational data, enabling more accurate performance assessment over time. The ability of AI models to learn from historical and real-time data allows continuous improvement of predictions related to structural response, degradation, and failure risk. Moreover, AI-based tools facilitate scenario analysis and optimization under multiple constraints, supporting informed decision-making at different stages of the project life cycle. When integrated with digital design and information management platforms, AI enhances coordination between technical analysis and management processes. Consequently, the application of AI contributes to more efficient, resilient, and adaptive civil engineering solutions.

4.2. AI IN BRIDGE DESIGN AND ANALYSIS

The application of AI in bridge design enables optimization of structural dimensions, material properties, and construction costs. Neural networks are frequently used to approximate complex calculations and to predict structural behavior under various loading conditions.

AI-based methods contribute to faster development of design solutions and a reduction in the time required for structural analysis. AI techniques support multi-objective optimization by simultaneously considering structural safety, serviceability, durability, and economic constraints. This enables engineers to explore a wider design space and identify balanced solutions that may not be evident through conventional trial-and-error approaches. AI-based surrogate models can also be integrated with parametric design environments, allowing rapid evaluation of design alternatives in early project stages. Furthermore, AI facilitates sensitivity analysis by identifying key parameters that have the greatest influence on structural performance. Such insights support more informed engineering judgment and risk-aware design decisions. Overall, the integration of AI into bridge design processes enhances both efficiency and decision quality.

4.3. AI IN STRUCTURAL CONDITION MONITORING AND DAMAGE DIAGNOSIS

One of the most significant applications of artificial intelligence (AI) in bridge engineering is structural condition monitoring. By analyzing data obtained from sensors, cameras, and inspections, AI models can detect damage, assess its progression, and indicate potential risks, enabling early detection of structural issues and reducing maintenance and rehabilitation costs. AI also facilitates the transition from reactive to predictive maintenance strategies, using historical and real-time data to forecast damage and plan maintenance interventions optimally. In predictive maintenance frameworks, AI supports the prioritization of actions by estimating the probability and consequences of different damage scenarios, allowing infrastructure managers to allocate resources effectively and focus on critical structural components. AI-based condition assessment also reduces reliance on manual inspections, which are often time-consuming, subjective, and limited in frequency. Integrating AI with real-time monitoring systems further allows continuous evaluation of structural performance under changing environmental and operational conditions, improving the reliability of safety assessments and reducing the likelihood of unexpected failures.

Recent research has demonstrated how AI can be integrated with BIM for bridge monitoring and diagnostics. Kwon et al. [9] proposed an IFC-BIM framework that uses artificial neural networks to predict bridge behavior under complex loads and detect anomalies by comparing measured and predicted values, linking sensor data to BIM objects. Borin and Cavazzini [10] developed an automated image-based workflow for mapping spalling in reinforced concrete elements, combining Mask R-CNN for defect detection, photogrammetry to generate accurate point clouds, and Scan-to-BIM processes to transfer detected pathologies into the BIM model. Huang et al. [11] proposed a BIM framework for diagnostics and prognosis, employing data-driven SHM algorithms to map strain distributions in 3D models and estimate the remaining service life of bridge components. Li Y. et al. [12] explored partially automated analyses using UAVs, digital records, and databases, while Li R. et al. [13] improved crack detection efficiency and accuracy using UAV-mounted cameras and deep learning models. Han W. et al. [14] combined long-term sensor data with predictive models and SHM systems to evaluate structural condition and durability. Zhang et al. [15] applied AI methods for routine visual inspections, field measurements, and reporting according to FHWA national standards. Kumar D. et al. [16] utilized impact-sounding methods, acoustic signals such as Power Spectral Density and Hilbert-Huang Transform, field measurements, and AI techniques for detecting concrete delamination.

Together, these approaches illustrate how AI, SHM, and BIM integration enable more accurate, efficient, and predictive maintenance of bridge infrastructure, reducing the reliance on manual inspections and extending service life while enhancing resilience.

5. INTEGRATION OF BIM AND ARTIFICIAL INTELLIGENCE

Artificial intelligence (AI), when combined with Building Information Modeling (BIM) and sensor technologies, offers significant potential for enhancing bridge infrastructure management. Kumar and Agrawal [17] synthesize the state of the art and highlight challenges in integrating UAVs, high-resolution cameras, AI algorithms, and BIM platforms for bridge monitoring and maintenance. Similarly, Araya-Santelices et al. [18] demonstrate that the synergy of AI, UAVs, and BIM technologies can improve the efficiency of inspections and support decision-making in bridge maintenance, although standardization and interoperability remain key challenges. The combination of databases, machine learning techniques, and BIM provides a promising path toward automation and support in both the design and maintenance of bridges, yet further research is needed to fully implement these approaches in practice [19].

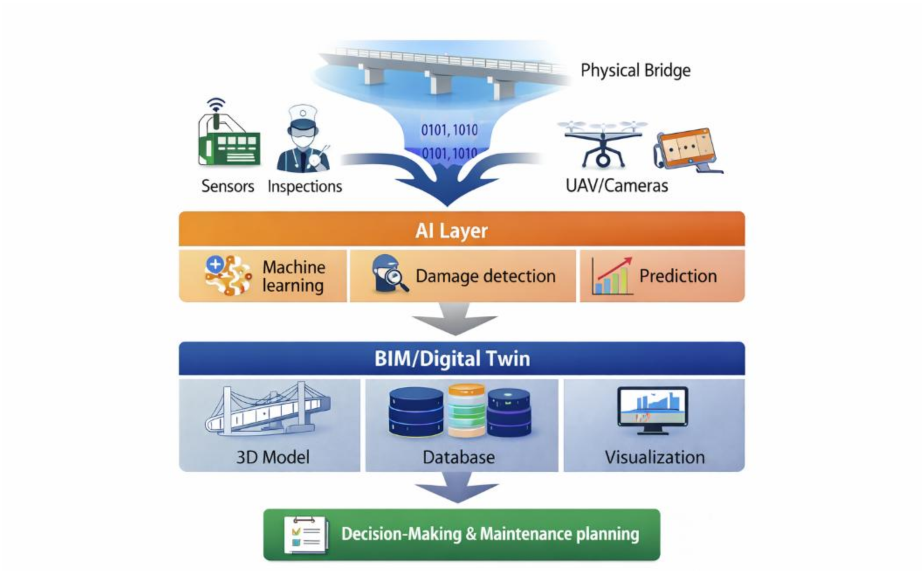

Figure 8. Conceptual framework for BIM–AI integration in bridge management (Source: Developed by the authors based on literature review).

When integrated with the previously discussed AI and BIM methods for structural monitoring, these studies underline the potential of a holistic, data-driven framework for predictive maintenance. Such approaches can reduce reliance on manual inspections, enable continuous condition assessment, and support optimized resource allocation, ultimately improving the service life and resilience of bridge infrastructure.

The conceptual integration of BIM, artificial intelligence, and monitoring data for bridge management is presented in Figure 2.

5.1. DIGITAL TWINS OF BRIDGES

The integration of BIM and AI has fostered the rapid development of digital twin technology in bridge engineering. A digital twin is a dynamic, virtual representation of a physical bridge that is continuously updated with real-time data from sources such as structural health monitoring sensors, inspection reports, weather data, and traffic loads. Unlike static BIM models, digital twins provide a living, data-driven model reflecting the current condition, performance, and operational behavior of the bridge. Digital twin technology applied to bridge infrastructure is shown in Figure 3.

Digital twins enable continuous monitoring and predictive analysis of structural condition, allowing engineers to simulate various loading scenarios, environmental impacts, and potential degradation over time. AI algorithms can, for instance, predict the progression of fatigue cracks or corrosion in critical structural components, enabling proactive maintenance planning, prioritization of resources, and reduction of unexpected failures. Additionally, digital twins support scenario testing and decision-making for both design upgrades and rehabilitation strategies. By integrating AI-driven predictive models with BIM-based structural models, engineers can optimize interventions for cost-effectiveness, safety, and longevity while facilitating collaboration among designers, contractors, operators, and regulatory authorities throughout the bridge life cycle.

Recent studies demonstrate these capabilities in practice. A BIM-centered digital twin system proposed by Xiong et al. [20] integrates sensor-equipped robotics for defect localization, computer vision for defect quantification, SQL-based data storage, and visualization of enriched BIM models on a web platform for maintenance decision-making. Li et al. [21] applied digital twin frameworks for monitoring large and complex bridges, combining analytical models, visualization tools, and SHM technologies. Similarly, Kang et al. [22] employed real-time sensors integrated with BIM platforms to enable continuous condition assessment and informed maintenance planning.

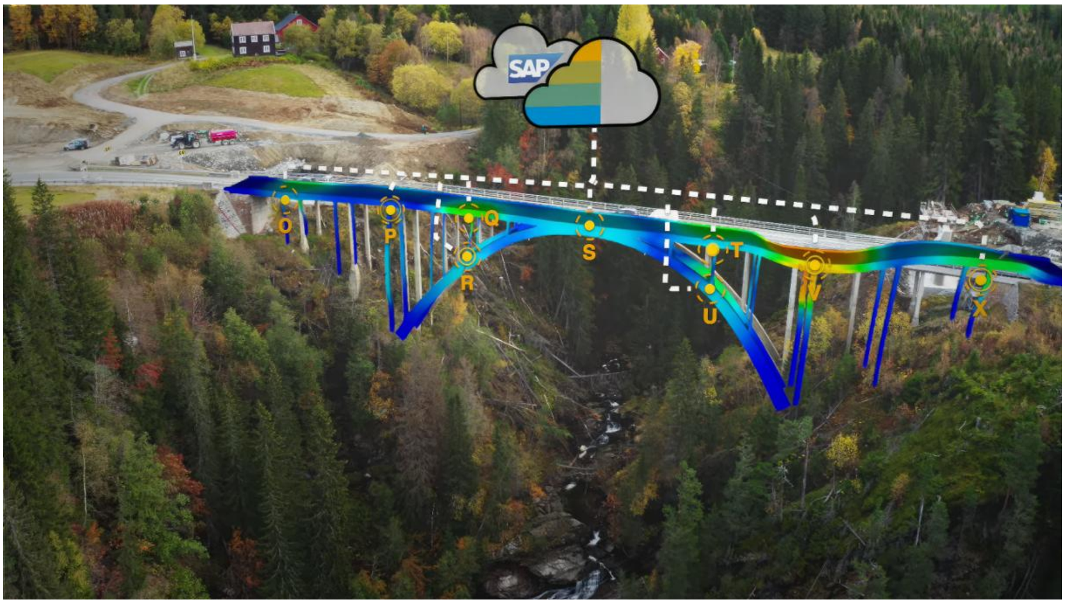

Figure 9. Digital twin technology applied to bridge infrastructure [23].

5.2. PROCESS AUTOMATION IN BRIDGE MANAGEMENT

The combination of BIM and AI enables significant automation of decision-making processes in bridge management. Routine tasks such as scheduling inspections, analyzing structural health data, and generating maintenance reports can be automated, reducing human error and freeing engineering resources for more complex analyses. When integrated with BIM models, AI algorithms can continuously evaluate structural performance by analyzing sensor data and inspection records, enabling automated risk assessment, early warnings for critical deterioration, and optimized prioritization of maintenance activities. Cost optimization can also be achieved by simulating multiple intervention strategies and selecting the most efficient option based on predictive analytics.

Moreover, process automation supports long-term infrastructure sustainability by facilitating data-driven lifecycle management. Digital twins, when combined with AI, can model the impact of traffic growth, climate change, or material degradation on bridge performance, informing proactive reinforcement or retrofitting strategies. Centralizing all relevant information in an integrated digital platform also improves communication between stakeholders, ensuring that decisions are based on accurate, real-time data.

Recent research highlights the potential of these approaches. Huang et al. [24] demonstrated how design and construction phase data, combined with deep learning and BIM models, can enhance model efficiency and accuracy. Ghodoosi et al. [25] applied advanced AI-based methods to optimize maintenance planning, while Zhang et al. [26] employed natural language processing and AI to analyze existing inspection reports and extract actionable insights. These studies collectively show that integrating BIM and AI not only enhances operational efficiency but also improves safety, reduces maintenance costs, and extends bridge service life through predictive, automated, and data-driven management.

6. CHALLENGES AND LIMITATIONS OF AI AND BIM IMPLEMENTATION

Despite their numerous advantages, the implementation of AI and BIM in bridge engineering faces several significant challenges. One of the main obstacles is the lack of standardization. Different software platforms often use proprietary formats and data structures, which can hinder the seamless exchange of information between BIM models, AI algorithms, and other engineering tools. This lack of standardization can result in compatibility issues, duplication of effort, and potential errors during project execution.

Another key challenge is the limited availability of high-quality and comprehensive data. AI models rely heavily on large datasets for training and accurate predictions, yet in many cases, historical bridge data, inspection records, or sensor measurements are incomplete, inconsistent, or not digitized. The scarcity of reliable data reduces the accuracy of predictive models, damage detection algorithms, and performance simulations.

High initial implementation costs also pose a barrier, particularly for small and medium-sized engineering firms. The integration of BIM and AI requires investments in software, hardware, training, and ongoing maintenance, which can be financially demanding. Additionally, the complexity of these technologies necessitates interdisciplinary expertise, combining knowledge from civil engineering, computer science, data analytics, and structural health monitoring. Many organizations currently face a shortage of personnel with such multidisciplinary skills.

Organizational and regulatory factors further complicate implementation. Existing legal frameworks, construction codes, and contract structures are often not aligned with digital workflows, AI-assisted decision-making, or fully integrated BIM practices. Resistance to change within organizations, insufficient awareness of the benefits, and lack of clear guidelines for integrating these technologies into existing processes can delay or limit adoption.

Finally, cybersecurity and data privacy issues represent emerging challenges. The increased reliance on cloud-based platforms, digital twins, and AI-driven data analytics introduces risks related to unauthorized access, data corruption, or misuse of sensitive infrastructure information. Ensuring robust cybersecurity protocols is essential to protect both operational and structural data.

Overall, while AI and BIM offer transformative potential for bridge engineering, addressing these technical, organizational, and regulatory challenges is critical to realizing their full benefits and enabling widespread adoption.

7. FUTURE RESEARCH

Future research in the field of bridge engineering should place strong emphasis on the further development and practical implementation of digital twins. This includes improving the bidirectional integration between physical bridge assets and their digital counterparts, enabling continuous data exchange throughout the entire life cycle. Particular attention should be given to the coupling of BIM-based models with real-time monitoring data in order to achieve more accurate and up-to-date representations of structural condition and performance.

Another important research direction involves the integration of advanced sensor networks and Internet of Things (IoT) technologies with AI-driven analysis frameworks. The use of heterogeneous data sources, such as strain gauges, accelerometers, vision-based inspection systems, and environmental sensors, offers significant potential for enhancing structural health monitoring and early damage detection. Future studies should focus on data fusion techniques and robust AI models capable of handling large-scale, noisy, and incomplete datasets.

Further advancements are also required in the development of AI algorithms for predictive modeling and decision support. This includes improving the transparency, reliability, and generalization capability of machine learning and deep learning models applied to bridge assessment. Explainable AI approaches represent a promising research area, as they can increase trust in AI-based decisions and facilitate their adoption by engineers and infrastructure managers.

In addition, future research should address interoperability and standardization issues related to BIM and AI integration. The development of unified data standards and open platforms would significantly enhance information exchange between different software tools and stakeholders. Finally, there is considerable potential in the development of smart bridges, where BIM, AI, and sensing technologies are fully integrated to support automated inspection, optimized maintenance planning, and sustainable infrastructure management over the entire bridge life cycle.

8. CONCLUSION

This paper has presented a comprehensive literature review on the application of Building Information Modeling and Artificial Intelligence in bridge engineering, with a particular focus on their roles across the entire bridge life cycle. The reviewed studies demonstrate that BIM provides a robust digital framework for integrated information management, while AI introduces advanced capabilities for data analysis, optimization, and predictive decision-making. Together, these technologies enable a shift from traditional, fragmented approaches toward more integrated and data-driven bridge engineering practices. The analysis confirms that their combined application has the potential to significantly improve efficiency, safety, and sustainability of bridge infrastructure.

The findings further indicate that the integration of BIM and AI is particularly impactful in the areas of structural design optimization, construction planning, and structural condition monitoring. AI-based methods support multi-objective design optimization and predictive analysis, while BIM ensures consistency and continuity of information from design through operation and maintenance. The emergence of digital twins represents a key advancement, enabling continuous performance assessment, scenario simulation, and proactive maintenance planning based on real-time data. In addition, process automation supported by BIM–AI integration enhances decision-making efficiency, reduces human error, and supports optimized lifecycle management of bridge assets.

Despite the demonstrated benefits, the literature also highlights several challenges that limit widespread adoption, including data availability and quality issues, lack of interoperability and standardization, high implementation costs, and organizational and regulatory constraints. Addressing these challenges is essential for fully realizing the potential of BIM and AI in bridge engineering practice. Future research should focus on the development of standardized data frameworks, explainable and robust AI models, and improved integration of real-time monitoring data within BIM environments. Strengthening collaboration between academia, industry, and public authorities will be critical for translating research advancements into practical and scalable solutions. Overall, BIM and AI constitute a fundamental technological foundation for the development of intelligent, resilient, and sustainable bridge infrastructure systems.

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