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Review

BIM and GIS Applications in Bridge Projects: A Critical Review

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Abstract: In recent years, interest in BIM and GIS applications in civil engineering has been growing. For bridge engineering, BIM/GIS applications such as simulation, visualization, and secondary development have been used to assist practitioners in managing bridge construction and decision-making, including selection of bridge location maintenance decisions. In situ 3D modelling of existing bridges with detailed images from UAV camera has allowed engineers to conduct remote condition assessments of bridges and decide on required maintenance actions. Several studies have investigated the applications of BIM/GIS technology on bridge projects. However, there has been limited focus on reviewing the outcomes of these studies to identify the limitations of BIM and GIS applications on bridge projects. Therefore, the aim of this study was to review the research on BIM/GIS technology applications in bridge projects over the last decade. Using a systematic review process, a total of 90 publications that met the inclusion criteria were reviewed in this study. The review identified the state-of-the-art methods of BIM and GIS applications, respectively, at the planning and design, construction, and operation and maintenance phases of bridge projects. However, the findings point to segregated application of BIM and GIS at all phases of bridge projects. The findings of this study will contribute to guiding practitioners in selecting appropriate BIM and GIS technologies for different aspects of bridge projects.

Keywords: Building Information Modelling (BIM); Geographical Information System (GIS); Bridge Information Modelling (BrIM); bridge; application

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1. Introduction

Building Information Modelling (BIM) and Geographical Information System (GIS) are two interdisciplinary scientific fields that involve the application of computers to integrate and visualize diverse project data and provide an objective source of project information to assist managers in making project decisions. At present, BIM/GIS technology is used in several fields, including architecture, civil engineering and facilities management. This paper mainly discusses the research and application of BIM/GIS technology for bridge projects.

BIM has the potential to improve the efficiency and effectiveness of the design of mega-complex bridge projects [1]. A design guideline of 3D information models was suggested [2]. Three-dimensional bridge models enable digital mock-ups and design enhancements [3]. A modern, technologically-advanced design may be compatible with feasible solutions [4] to help governments, urban planners and other stakeholders in making bridge project-related decisions [5,6]. The use of BIM may facilitate otherwise complex projects [7] to shorten the construction time and reduce cost by minimizing trial and error [8]. The application of 4D Bridge Information Modelling (BrIM) in the construction phase benefits the project team in material delivery planning, project monitoring and control, construction schedule improvement, documentation and coordination [9].

BIM implementation may lead to 5–9% cost savings during construction through reduced change orders and rework [7] that would enhance cost-effectiveness and sustainability outcomes [10,11]. Additionally, significant benefits such as enhanced structural health monitoring may be realized through a future BIM-enabled operation and maintenance of such an infrastructure [7,12]. GIS implementation contributed to reducing the cost and increasing the accuracy and timeliness of the project and program development of major transportation infrastructure programs [13,14]. Integrating BIM and GIS may improve the efficiency of infrastructure operation management by providing a useful platform [15] that furnishes engineers and other decision-makers with detailed information about specific issues [16]. System information requirements would need to be defined by stakeholders and a unified format adopted to facilitate data exchange [17]. Semantic integration of cross-domain data is trusted to be highly automated [18] and the generated BrIM based on industry foundation classes (IFC) can be queried semantically [19]. IFC are used to exchange information; the implementation of asset management properties can facilitate a transition from document-based software to a combination of visual representation alongside the information that accompany every asset to form a basis for integration with GIS standards such as CityGML, and investigated to determine the level of information transferred between the BIM and GIS standards [20]. Managers explore more features of a bridge information model [21] at the asset management phase to aid efficient and informed decision making [22]. Information modeling is more than just a new technology—it is a new way of working [23] which has the power to totally transform the bridge industry.

Over the last decade, the application of BIM/GIS technology in the planning and design, construction, operation and maintenance as well as information exchange on bridge projects has increased significantly. The potential benefits of applying either BIM, GIS or both technologies on bridge projects cannot be overemphasized. However, the literature is limited regarding studies that have focused on reviewing outcomes of BIM and GIS applications on bridge projects. A review of these studies would lead to identifying BIM and GIS applications that are most suitable for selection of bridge location, budget allocation, and formulation of maintenance decision schemes. Additionally, a review of these studies would lead to identifying weaknesses of current methods of BIM and GIS applications on bridge projects. This information will be relevant to practitioners who are looking to apply BIM and GIS technologies to their bridge projects. Additionally, developers of BIM and GIS technologies can use this information to develop the next generation of BIM and GIS technologies to overcome the limitations of the current methods. Therefore, the purpose of this study was to review the application and potential capabilities of BIM/GIS technology in different aspects of bridge projects, and to determine the value and implications of these technologies for decision making and management of bridge projects. The vision of BIM/GIS applications for bridge projects would be to aid the development and optimization of new construction processes to reduce project duration, construction cost, site safety and environmental impact of the bridge construction. Additionally, BIM/GIS would seek to optimize operation and maintenance processes using emerging methods such as omnidirectional data acquisition to aid real-time remote condition inspection and data collection. To achieve these visions, there will be a need to develop BIM and GIS standards and formulate standardized bridge design modeling protocols and terms. Section 2 below describes the research methods used in this review while Section 3 presents the analysis in four aspects as follows: (1) planning and design stages, (2) the construction stage, (3) operation and maintenance stage, and (4) information exchange. Section 4 discusses the challenges associated with these four aspects and suggests possible directions for future research.

This study analyzed and consolidated the current state-of-the-art on the application of BIM and GIS technologies on bridge projects. This review contributes to the literature by highlighting the limitations of the current BIM and GIS applications on bridge projects. The limitations identified in this review highlight the current research gaps and will contribute to shaping the direction of future research on BIM and GIS applications on bridge projects.

Additionally, this review will guide bridge engineering industry practitioners in choosing appropriate BIM/GIS tools for relevant applications on bridge projects.

2. Research Methods

This research conducted a systematic review following the PRISMA framework to obtain a comprehensive understanding of how BIM/GIS technology is utilized on bridges. Data for this systematic review were sourced mainly from Scopus because of its broad coverage of interdisciplinary research. Google Scholar, a powerful web search engine, functioned as a supplementary tool to eliminate searching biases. "Building Information Modelling" (BIM) or "Bridge Information Modelling" (BrIM); "Civil Information Modelling" (CIM), or "City Information Modelling" (CIM); "Geographical Information System" (GIS), and bridge constituted the primary keywords. The "AND" Boolean logic was used to search for combinations of the primary keywords in either the title, abstract or keyword fields of journal articles to capture a wide range of sources relevant to the applications of BIM and GIS technologies in bridge construction and management. The time frame for the review was set to the past ten years (2011–2020) since BIM/GIS technology is a relatively new area that is largely facilitated by the development of computer science. The publication type was limited to peer reviewed journal articles to ensure that high-quality state-of-the-art research was reviewed. Figure 1 presents details of the PRISMA framework implementation in this research. A total of 135 records were retrieved from Scopus and 96 from Google Scholar. The records retained for screening after removing duplicates was 124 journal articles. After screening titles and abstracts, 113 records were retained for full-text review as shown in Figure 1. Records were retained for detailed qualitative synthesis if they collected and analyzed BIM/GIS technology implementation data on bridges. A total of 90 publications were retained for detailed review following a full-text eligibility review.

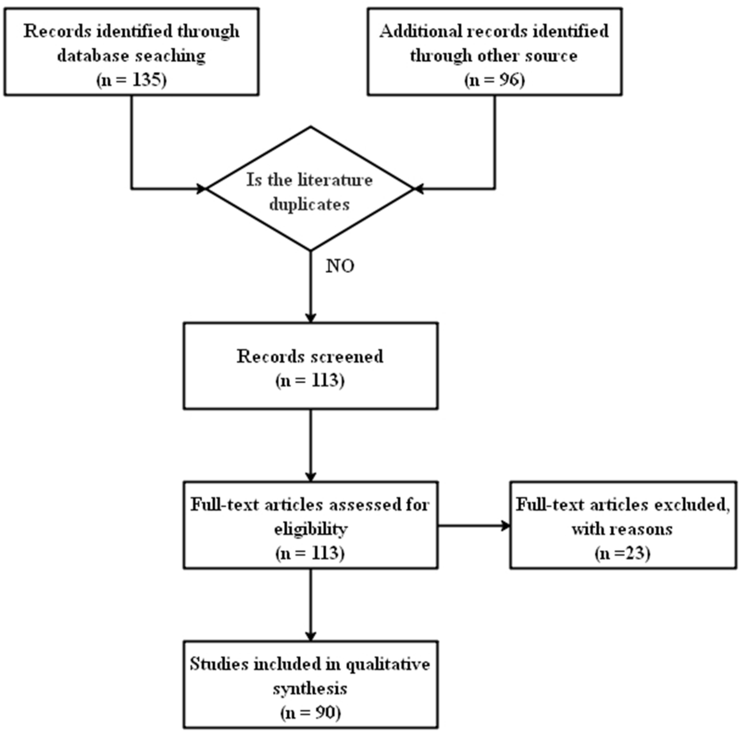

Figure 1. PRISMA flow diagram.

To analyze these publications quantitatively, Table 1 lists journals where the reviewed papers were published, including top ranking journals such as *Automation in Construction* (AIC), *Journal of Computing in Civil Engineering* (JCCE), and *Structure and Infrastructure Engineering* (SIE). The paper distribution in terms of year and journal is illustrated in

Table 1. The table shows a growing trend of research from 2011 to 2020. Table 1 also shows that the research on BIM technology (i.e., 58) is twice as much as GIS technology (i.e., 30). Only two studies investigated the combination of BIM and GIS for bridges.

Table 1. Paper distribution in terms of journal and year of publication and BIM/GIS.

Journals	Sum	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
AIC	8					1	1	1	1	3	1
JCCE	5							2	3		
AS	5								1		4
SIE	3		1						1	1	
KSCE JCE	3				1		1			1	
TRR JTRB	3		1	1	1						
PE	3	2					1				
AES	2							1		1	
Sustainability	2									1	1
JPCF	2					1			1		
ECAM	2						1				1
SEI	2		1						1		
BJRBE	2			1							1
JTE	2					1			1		
BE	2							2			
ITcon	2								2		
LNCE	2										2
IJ3DIM	2		1		1						
RESS	1									1	
Measurement	1										1
ACME	1	1									
JWEIA	1								1		
IJGIS	1					1					
SSS	1							1			
JCSHM	1						1				
JBE	1						1				
IEEE ITSM	1							1			
JCEM	1				1						
Stahlbau	1							1			
IJARS	1				1						
ACE	1									1	
AJSE	1				1						
PPSDC	1					1					
BEPAM	1										1
JOE	1									1	
EJRSSS	1						1				
IJSBE	1				1						
PEF	1				1						
JHTRD	1				1						
IAM	1								1		
ISPRS APRSSI	1									1	
JIEA	1					1					
JED	1				1						
Buildings	1										1
JRES	1										1
JEDT	1										1
JETT	1										1
JPCS	1										1
NOQO	1										1
SS	1										1
JG	1									1	
AG	1									1	
JIS	1								1		
JTG	1								1		

Table 1. *Cont.*

Journals	Sum	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
JESD	1							1			
Sum	90	3	5	2	10	6	7	10	15	13	19
BIM and GIS	2									2	
BIM	58	2	3	2	5	2	6	6	11	5	16
GIS	30	1	2		5	4	1	4	4	6	3
Sum	90	3	5	2	10	6	7	10	15	13	19

3. Analysis

Bridge engineering involves many stages throughout its life cycle; each stage comprises multiple complex processes with large project teams and relies on the efficient exchange of information [24–26]. Table 2 shows the distribution of the reviewed studies with respect to planning and design, construction, operation and maintenance, and information exchange for the last decade.

Table 2. Literature distribution of BIM/GIS applications at different stages of bridge engineering.

Technology	Planning and Design	Construction	Operation and Maintenance	Information Exchange
BIM	[1–4,8,11,23,27]	[1–3,7–11,21,28–35]	[12,16,17,34,36–52]	[11,19,20,22,36,41,44,46,53–65]
GIS	[5,6,66–68]	[69]	[13,14,70–86]	[18,77,87–89]
BIM and GIS			[15]	[15,90]

3.1. Planning and Design

Because GIS technology has the function of a macro layout, it is often used in the regional level and above scenes, as Table 3 shows that the application of GIS technology in bridge engineering at the planning stage mainly involved making need-based decisions for planning new bridges [6,66,67] to improve transportation infrastructure [6,66], traffic jam and pedestrian travel time [67]. Additionally, GIS technology combined with different multi-criteria decision-making methods were used in selecting the best geographic locations for new bridges [5] to minimize cost and also add value to the city image [4] and other benefits (e.g., tourism).

Table 3. BIM/GIS uses in planning and design.

Examples	Application Type	Key Outcome	Limitations
		Technology: BIM	
[1]	Error/clash detection	• 3D parameterized modelling of the bridge resulted in identifying several design problems, including errors in dimensions and quantity of some components. • Non-matching columns and arch rib joints identified. • Design criteria non-compliant reserved welding seams identified.	• The bridge project participants' lack of BIM knowledge might diminish the benefits of BIM implementation.
[2]	Parametric modeling	• Each bridge component (e.g., beam, pier, and abutment) modeled with basic parameters such as geometric dimensions and connected to other components by layered architecture of geometry models.	• Parametric modeling is mainly used in regular components, but it lacks the application in special-shaped components.

Table 3. *Cont.*

Examples	Application Type	Key Outcome	Limitations
[3,8]	Parametric modeling, simulation, visualization	• Three-dimensional bridge models that considered WBS and PBS-enabled digital mock-ups, design enhancement and shortened learning time of construction engineers. • Virtual assembling of the bridge resulted in identifying several errors in two-dimensional drawings. • 3D model and DMU enhances the understanding of structural configuration, especially for complicated structures.	• The effective application of three-dimensional information modeling and DMU technology in segment manufacturing and bridge transmission is still limited by many factors, such as unskilled operators.
[4]	Aesthetic	• Showed that a modern, technologically advanced design may be compatible with a solution whose elegance meets the most exacting aesthetic standards.	• Holistic consideration of the natural, human and built context of civil works generally neglected in structural engineering.
[11]	Design model integration	• Furthermore, during the bridge life cycle, this master digital model enables engineers to access and update model data for the bridge life cycle analysis and control, including minimizing tolerances during the erection stage and some unexpected damage/deterioration during operation.	• Master digital model of bridge components and the whole suspension bridge is not suitable for bridge maintenance
[23]	Visualization	• Early design phase visualization modelling generated geometry information structural analysis at later stages.	• Lack of unified modeling terms and standards in the design phase.
[27]	Parametric analysis	• Information loss reduced by exporting BrIM input databases via IFC file format. • Proposed BrIM system incorporates diverse bridge MR and R solutions into a multi-criteria decision making approach (MCDM) to derive competitive priority ratings at the conceptual bridge design stage.	• Lack of the effect of incorporating complex quality functions on prioritizing MR and R decisions for bridge components.
[28]	Conceptually plan	• By integrating 4D BrIM, assisted stakeholders' conceptual plan with cost data resources, besides user-defined input, is presented.	• Lack of invasive research on integration of bridge information modeling, fuzzy logic decision support and cost estimation system.
		Technology: GIS	
[5]	Bridge location	• GIS technology combined with five different multi-criteria decision-making methods could facilitate effective selection of pedestrian bridge location.	• Lack of dynamic analysis of the impact of bridge site selection on planning.
[6,66]	Road transport information management system	• GIS for data collection, entry, management and analysis will facilitate planning and development of road transport infrastructure and ease management and control of its facilities.	• Would need industry-wide adoption of GIS.
[67]	Transportation network	• GIS model projected 50% reduction in pedestrian travel time (i.e., minimize pollution and fuel consumption). • Reduced congestion in current bridge approaches.	• Calculation time of model is long.

Table 3. *Cont.*

Examples	Application Type	Key Outcome	Limitations
[68]	Evaluation	• Based on the strong space data management and information process of GIS, the GIS of HEBC was constructed, and its evaluation was effectively realized.	• Input and output mode of GIS data have not been fully automated.

Table 3 also shows that use of BIM technology at the design stage of bridge engineering has focused mainly on developing and using 3D bridge models to inform design decisions. The authors of Refs. [11,23] used a 3D information model to analyze the assembling process of a bridge and suggested modifications. The authors of Refs. [1–3,8] conducted the parametric modeling of a bridge and suggested a design guideline for 3D information modelling to reduce collision and other modeling problems to enhance the accuracy of 3D model design. Three-dimensional information modeling can also be used to design aesthetically pleasing bridges [4]. The authors of Ref. [27] proposed that an integrated information management system at the conceptual design stage should become the new approach to informing downstream design (and construction) processes of bridge projects. Based on the powerful spatial data management and information processing ability of GIS, Ref. [68] constructed the evaluation model of highway engineering bearing capacity (HEBC) based on GIS, and effectively realized the evaluation of highway engineering bearing capacity.

3.2. Construction

Table 4 shows applications of BIM/GIS technology at the bridge construction stage from 18 studies. Among them, only one study [69] investigated the application of GIS technology combined with fuzzy logic in the selection of better bridge construction location in the construction process. At the construction stage, Table 4 shows that research on the application of BIM/GIS technology has focused mainly on construction cost [3,7,10,29,30], scheduling [1,3,7,9,10] and visualizing the construction process on site [1,2,8,9,31–35] and is not surprising, given that these are among the key issues that project managers will generally prioritize at the constructions stage of all projects, including bridges. However, the table also shows the use of BIM/GIS technology for other complex tasks at the construction stage, including coordination [9,11], optimizing constructability [21,69], and tracking GHG emissions [69].

Table 4. BIM/GIS uses in construction.

Examples	Application Type	Key Outcome	Limitations
Technology: BIM			
[1]	Construction schedule	• Using simulation, an appropriate construction schedule and relevant construction methods were obtained. • Simulated main construction equipment to analyze the installation methods of prefabricated components and the allocation of equipment.	• Simulation based on the experience of project managers introduces subjectivity that may not be sufficient for verifying the impact of BIM on simulating the bridge project schedule.
[2]	Produce shop drawing	• Four-dimensional simulations and 3D models enhanced the engineers' knowledge of a bridge and resulted in the effective usage of resources for the construction. • Engineers used 3D models to check constructability and to produce accurate shop drawings.	• The lack of engineers' knowledge and previous project experience may reduce the benefits of using BIM technology in bridge engineering.

Table 4. *Cont.*

Examples	Application Type	Key Outcome	Limitations
[3]	Construction schedule	• Through the use of the 3D BrIM, construction period was reduced by about 4.5 months. • Efficiency of site operation was improved and the number of workers could be reduced by about 6%.	• Understanding of 3D model technology and assurance of positive effects of its application were insufficient.
[7]	Construction schedule, rework	• Use of BIM may facilitate scheduling of complex projects and saved approximately 5–9% cost by contributing to reduced change orders and rework.	• About 70% of the cost of 3D modeling may be associated with the first implementation; this front-end loading of 3D modeling cost may limit its adoption.
[8]	Risk factor	• The risk visualization system not only quantifies risk factors reasonably but also visualizes existing mathematical modes of expression.	• Category of risk factors is not applicable to a wide range of bridge engineering.
[9]	Construction sequence, schedule	• Four-dimensional visualization of the construction sequence ensured installation of piles at different locations within the constraints of the site space. • An increase in the value of planned percentage complete (PPC) ranged from 26.5 to 56.4 percent after implementation of 4D BrIM.	• Lack of quantitative evaluation of 4D BrIM application benefits.
[10]	Rework	• Six-dimensional BIM can save time by transforming 2D information to 3D information. • Collaborated within 6D BIM environment can reduce the rework amount and lead to enhancing sustainability and cost-effectiveness of outcomes.	• Lack of compatibility with complex bridge modeling would result in some unnecessary rework.
[21]	Crane location	• Choosing the best crane position using a 3D model can be enhanced by importing the crane model and simulating the erection process.	• Hybrid model needs more projects to verify its applicability.
[29]	Budget, schedule	• Four-dimensional BrIM captured the control account, planned and actual cost information, and then performed earned value calculations and determined the budget and schedule status.	• Cost evaluation model only considers direct cost, not indirect cost.
[30]	Cost estimate, review estimate	• By integrating 3D models representing a specific construction method and the BrIM model, it helps to perform detailed cost estimates and review estimates.	• Presented work is limited to the calculation of the negative cash flow only (cash out).
[31,32]	Risk location	• Linking and visualizing risk information into 3D/4D BIM facilitated the understanding of the location of each risk.	• Current open BIM standards (e.g., IFC) do not define schemas for risk management.

Table 4. *Cont.*

Examples	Application Type	Key Outcome	Limitations
[33–35]	Estimate dimension	• When compared with the dimensions obtained from manual measurement, 92.2% of the dimensions estimated by the proposed technique (automatic creation of as-built BIM of precast concrete panels by using laser scan data) had discrepancies of less than 3 mm. • The personnel cost for quality inspection was reduced by 86.7% by using the proposed technique.	• Scan data acquisition still requires manual maneuvering of the laser scanner to different locations. • Proposed technique was tested only in a controlled environment.
[53,54]	Earth filling	• A 3.95% accuracy difference found in cut and fill calculations between the proposed 3D IFC approach and the real project.	• Complexity of calculation required some assumptions to eliminate ambiguity of analysis.
Technology: GIS			
[69]	Bridge construction site	• Fuzzy logic was used in AHP to incorporate the imprecision of the expert judgments.	• Lack of dynamic analysis of the impact of bridge construction site selection on the surrounding environment.

Project participants used BIM technology to calculate the required earth filling [53,54], timely visualize of risk factors [8], select the best crane position through the visualization [21], minimize rework [7,10], track project schedule [1,3,7,9,10], and to finally reduce construction cost [3,7,10,29,30]. BIM can also generate as-built CAD drawings from as-built BIM models [2] and export them.

3.3. Operation and Maintenance

Table 5 shows the operation and maintenance applications of BIM/GIS technology in bridge projects from 41 studies. Among them, only one study [15] focused on the bridge management system (BMS) and investigated the application of BIM and GIS technologies to realize several maintenance functions, including information management, bridge detection, condition evaluation, repair and reinforcement, multi-scale visualization, and collaborative management. At present, GIS technology is mainly used for tracking bridge traffic networks [13,70–76]. This traffic network can be leveraged by disaster response systems to determine the location of the affected bridge [14,77,78] and coordinate the timely arrival of first responders, such as firefighters [70], to minimize disaster-related losses [13,74].

Table 5. BIM/GIS uses in operation and maintenance.

Examples	Application Type	Key Outcome	Limitations
Technology: BIM			
[12]	Operation and maintenance cost	• Accurately predicted the operation and maintenance cost of target projects. • Through the actual data, the effect of operation and maintenance management was verified and operation and maintenance cost was reduced.	• Actual project defects not considered.
[16]	Automatic rule checking	• Bridge maintenance regulations were translated into a machine-readable language to realize automated rule checking and eliminate unnecessary subjective errors.	• Realizing automation in all maintenance phases could be challenging. • Converting information from Revit models into ontologies without data loss may be less likely.

Table 5. *Cont.*

Examples	Application Type	Key Outcome	Limitations
[17,36]	Operation and maintenance cost	• A bridge data management system could significantly help engineers to save time and money on inspection and repairs.	• The process method is theoretical without practical proof of concept.
[34,37,38]	3D in situ modelling	• UAV was used to acquire images from all possible points of view, overcoming limited inspection accessibility and occlusions, which provides the completeness and accuracy needed for both detailed 3D in situ modelling and structural condition assessment.	• Mature shrubs will cover the structure and hinder the acquisition and imaging. • Bottom of decks on cloudy days will be difficult to capture.
[39,40]	Bridge evaluation	• BIEM (bridge information modeling for inspection and evaluation method) provides a way to collect, store, and use location based damage information from a bridge inspection by using BIM software to analyze and present that information to help make decisions by enabling the user to evaluate damages on the basis of location and providing maintenance recommendations.	• There is no automatic algorithm to extract and manage data for BIM storage or to solve the analysis structure evaluation process.
[41,42]	Maintenance scheduling	• Maintenance engineers were able to perform their daily tasks in nearly 50% less time and with 20–40% higher accuracy.	• Lack of 4D technology based on the impact of maintenance data to communication between maintenance engineers.
[43]	Bridge evaluation	• Random spatiotemporal conflict detection method can effectively calculate the random conflict probability due to the change of reconstruction task duration, and can assist decision makers to investigate different demolition start dates.	• Lack of different resource quantity constraints.
[44]	Bridge inspection	• A chain of algorithms based on a computer vision was embedded into an AR device that aims to enhance the precision and performance of inspection tasks. After, the technical damage report is fed-back to the management system and is available for assessment and discussion.	• The reliability of this inspection system will depend on the capability of the AR device and the strength of the network connection.
[45]	Bridge evaluation	• Proposed idea (unique integration of structural health monitoring and resulting dynamic information) would enable systematic visualization of condition assessment data that are collected on a continuous basis.	• Needs to be updated with the changing environment.
[46]	React to unexpected situation	• Federated model using DTM/RTM provides an information-rich resource for maintenance purposes. • Accumulated damage and repair history was retained; this significantly supports the project team to react timely against unexpected situation, as well as creating a premise to orient a long-term strategy for bridge maintenance. • Maintenance performance was significantly improved due to the federated models.	• Accuracy of mechanical twin model is not enough.

Table 5. *Cont.*

Examples	Application Type	Key Outcome	Limitations
[47]	Bridge monitoring	• Key structural performance parameters could be dynamically displayed using the developed dynamic BIM viewer. • By incorporating BIM provisions during the operational phase of an asset, significant reductions in costs could be realized through the reduction of tactile and visual inspections and maintenance.	• Feasibility of the model needs to be verified for different bridge types and their environments.
[48,49]	Bridge monitoring	• Deformation displacement curves obtained by BIM monitoring system were more in line with the actual deformation curves.	• Need the actual data to verify the reliability of the model and conclusion.
[50]	Imaging processing	• Deflection measurement error between imaging instrument and special bridge deflection measurement instrument was only 3.0% to 6.9%.	• Application lacks operation process diagram.
[51]	Bridge Management System (BMS)	• Balanced decision making proposed for bridge maintenance management strategy based on several constraints, including cost optimization and decision support from professionals.	• It is uncertain whether the objectives and requirements of all constraints are met by a balanced maintenance plan and life cycle cost.
Technology: GIS			
[13,74]	Benefit-cost	• Review is based on the results of a benefit-cost (BC) analysis that showed overall positive returns.	• Benefits of GIS in managing major transportation program assessments have not yet been validated.
[14,78]	Disaster response system	• Rapidly maintained remote monitoring sensors and surveillance facilities with AR-based assistance and correctly assessed bridges and their elements through mobile 3D graphics.	• Lack of alternative disaster management measures for disaster managers.
[70]	Fire alarm time	• Using spatial data and attribute data of bridges and fire stations, the closest fire station can be determined in addition to calculating likely arrival time of fire brigades from fire station.	• There are still some factors that have not been considered, such as wind intensity.
[71,72]	Bridge evaluation	• Storm surge modeling was coupled with bridge fragility models and GIS analysis to evaluate the potential for network disruptions.	• Influence of uncertain storm factors is not considered.
[73]	Bridge evaluation	• System developed for prior identification of vulnerable components whose failure due to a major earthquake event may have disproportional socio-economic impact.	• The threshold value (capacity) of each component needs to be modified with more cases.
[75]	Bridge evaluation	• Assessed regional network resilience by leveraging scenario-based traffic modeling and GIS techniques.	• There are limited records of bridge closure times, especially after dangerous events.
[76]	BMD	• Determined optimal intervention programs for large infrastructure networks using a linear optimization model.	• Application of mixed integer nonlinear model is not considered.
[77]	Disaster response system	• Mobile disaster response system not only reports sudden disaster information, but also offers precise disaster locations.	• The speed of information feedback still needs to be strengthened.

Table 5. *Cont.*

Examples	Application Type	Key Outcome	Limitations
[79]	BMS	• Tool developed to provide users with an intuitive, organized method for querying, evaluating, and managing bridge inspection data that are collected over time. • Emphasis was placed on developing methods for viewing high-resolution, time-aware, close-up images of bridge elements and joints.	• As the number of bridges increase in the database, it may become difficult for the user to find particular bridges in the BridgeDex-map.
[80]	Bridge Maintenance Decision (BMD)	• A central server capable of reading and displaying weather forecast data by calling GIS functions. • Dangerous road segments can be pinpointed on a digital map. This visualization function provides great convenience to decision makers during emergencies.	• The inaccurate risk index is affected by the predicted weather data.
[81]	Bridge inspection	• SPFs used for network screening activities such as identifying bridges with potential for highest estimated safety benefits.	• Models estimated herein might not be directly transferable to other states or might require calibrations before using in other states.
[82,83]	BMD	• Developed a GIS-based multi-criteria decision-making system without extra data collection effort while yielding high confidence in obtaining optimal prioritization solutions for bridge maintenance and repairs. • GIS interface can easily visualize bridge information and facilitate the decision-making process.	• Lack of dynamic analysis of the impact of bridge site selection on operation and maintenance.
[52]	BMS	• Database management system that can house basic information about a bridge, the inspection record, maintenance and reinforcement history, and images; system provides a variety of information queries and automatically generates documentation needed for a comprehensive bridge evaluation.	• More projects are needed for application.
[84]	Bridge evaluation	• Network map reconstructed using GIS data; when the intensity of ground motion is determined at the locations of a bridge, the probability of damage can be calculated from seismic fragility curves.	• GIS and ANN technologies need to be applied to more projects to verify their adaptability.
[85]	BMS	• Makes BMMS more interpretable through dynamic color coding and more sophisticated visualization techniques than the conventional tabular data format. • Geostatistical analysis was carried out in which the settlement of study areas were defined by producing color images.	• There are still some inaccuracies in local color coding.
[86]	BMD	• Decision making tool for the renovation of obsolete bridges and tunnels.	• Limited historical information about protection of old bridges.

Table 5. *Cont.*

Examples	Application Type	Key Outcome	Limitations
		Technology: BIM and GIS	
[15]	BMS	• Built a BMS for a real long-span cable-stayed bridge that incorporated GIS and satisfied main maintenance functions, such as information management, bridge inspection, condition evaluation, repair and reinforcement tracking, multi-scale visualization, and collaborative management.	• BIM model could not be connected to the finite element model, which strongly limits the structural analysis ability. • Data in the system are not mined deep enough.

For the operation and maintenance stage, Table 5 shows that the bridge management personnel developed BMS [12,14–17,36,44,45,51,52,73,77,78,84–86] based on BIM/GIS technology to facilitate bridge inspection/monitoring [14,34,37–40,43,44,47–51,77–81], bridge evaluation [12,14,16,34,37,38,41–45,48–50,52,73,75,77,78,81,85], bridge maintenance decision making [43,46,51,52,82,83] and bridge structural health recovery [14,39,45,71,72]. Bridge operation and maintenance management personnel collect timely data through monitoring equipment or manually. The data are then transferred to bridge management systems. In the system, the collected data are processed first [50] and then used for a bridge health assessment to inform operation and maintenance decisions. After completing the maintenance action, a revised bridge health status can be fed back to the bridge management system.

3.4. Information Exchange

Table 6 shows the applications of BIM/GIS technology at all stages of the bridge information exchange from 25 studies. Among them, two studies [15,90] investigated the integration of BIM and GIS technologies, Ref. [15] proposed the necessary IFC and IFD standards as the premise of unifying bridge maintenance information, and Ref. [90] realized the conversion from an IFC (BIM) to a Shapefile (GIS) through an open source algorithm. There is no standard extension of GIS in the collected literature. Table 6 shows that bridge managers operate with bridge information models based on extended standard [15,19,20,55,56], data integration [18,19,36,41,44,57–60,87,88,90] and interoperability [11,22,46,60–65,79,90]. In order to better realize the application of BIM/GIS technology in the field of bridge engineering, researchers first compile bridge BIM/IFC standards according to the requirements of bridge maintenance [19] or expand BIM/IFC in the existing standard [15,20,55,56] and gradually integrate BIM/GIS data before developing an advanced algorithm to interact with BIM/GIS data.

Table 6. BIM/GIS uses in information exchange.

Examples	Application Type	Key Outcome	Limitations
		Technology: BIM	
[11]	Interoperability	• Addressed the existing collaboration gap among different stakeholders and the discontinuity of information between the various stages of bridge projects.	• Digital models need to be updated by adding more information on their performance.
[19]	IFC standard	• Developed rules of unique identifier and information reassignment, and applied a semi-automated naming algorithm. • It was observed that information retrieval and extraction for components was possible through a semantic-based query to the generated IFC-based bridge information model.	• It is still insufficient for implementing true BIM models owing to the absence of support of IFC for bridge structures.

Table 6. *Cont.*

Examples	Application Type	Key Outcome	Limitations
[20]	IFC expansion	• Developed a system to cross-reference proposed entities, relationships and attributes with the existing structure of IFC to highlight unique information and those already described by IFC.	• Concept extension lacks physical testing with real-world data.
[22,60–62,64,65]	Interoperability	• Laser remote sensing data registration of existing bridges based on TLS and BrIM technologies.	• Application of the model is limited to situations where an accurate point cloud is available.
[36,44,59]	Storage, sharing, utilization	• NoSQL database system was employed. • BrIM was built based on 2-dimensional drawings, a 3-dimensional engineering model and a sensor description of the Telegraph Road Bridge (TRB), which is able to integrate different types of bridge information by linking related data entities.	• BrIM considers only a few standards and applications. • Requires creating data retrieval scripts.
[41]	Data integration	• Four-dimensional modeling has the potential to provide an effective means of sustainable integration of various data categories with 3D models of an infrastructure over its lifetime.	• Needs more focus on the use of interoperable and open data exchange formats.
[46]	Interoperability	• Mechanical model derived directly from the initial model through the interoperability of BIM solution which created the DTM; this can maintain the integrity of the 3D physical models.	• Data management system of network layer lacks automatic and timely update of information.
[55]	Expand standard	• Developed a process that results in a rule set to identify all possible object types in a domain. • Object can be completely and correctly classified only when the models have sufficiently small errors in the locations and geometry of the bridge components to allow the geometry and topological relationship operators to perform correctly with suitable tolerances.	• Success of the object classification process remains dependent on the quality of the geometric model.
[56]	Expand standard	• Presented taxonomy of geometrical models and notation of distinguished classes of geometry representations to enable consistent and uniform classification of all models used. • Classification system can be used for homogeneous and non-homogeneous models.	• Bridge structure representation may not meet the increasing accuracy and complexity.
[57,58]	Data integration	• Damaged data structure and semantics definitions proposed. • It is possible to either apply the proposed approach to an external IFC file and simply link it with BMS or insert an IFC representation of every specific bridge into the BMS.	• Lack of digital drawings or even the paper ones makes this task rather difficult although the registration precision is achieved.
[63]	Interoperability	• Engaged bridge industry stakeholders in vetting data exchange requirements and aided eventual compliance certification processes.	• Incomplete data exchange between two or more stakeholders.

Table 6. *Cont.*

Examples	Application Type	Key Outcome	Limitations
		Technology: GIS	
[18]	Data integration	• Determined the semantic relationship between concepts of two lightweight ontologies that facilitate formal ontology integration based on common vocabularies. • Facilitate developments of cross-domain applications.	• There are still some problems in the construction of common vocabulary, such as low efficiency and automation.
[87,88]	Data integration	• Multiple technologies integrated to enhance the accuracy and reliability of the collected data.	• There is a phenomenon of manual processing in data integration.
[89]	Interoperability	• Reconfigured the way that people interacted with spatial data that included multi-sensory engagement, multi-dimensional representation and thinking through play. • Tactile and kinetic engagement were able to interact with landscape information in a shared space.	• Needs to be applied and improved in many aspects.
		Technology: BIM and GIS	
[15]	IFC expansion	• Necessary IFC and IFD standards were proposed as supplements according to the actual maintenance needs of bridges; thus, filling the gap in BIM standards of the bridge industry in China.	• IFC has not fully expressed its bridge attribute in China.
[90]	Interoperability, data integration	• Transformation of IFC to shapefile achieved with opensource technology and is more stable and efficient than that of the DIA. • Shapefile supports 3D geometry and can be exchanged easily with other non-GIS 3D software packages. • As an open-source solution for transforming IFC to shapefile, the proposed method can contribute to the community and advance BIM/GIS integration.	• Transformation is currently unidirectional from IFC to shapefile in terms of geometry. • Efficiency of BIM/GIS integration should be further improved.

4. Discussion and Future Work

BIM and GIS modelling are new techniques that require further investigation to discover their potential benefits for all stakeholders [91,92]. The integration of both technologies is expected to revolutionize digital design in the Architecture Engineering Construction (AEC) industry [10,93]. Table 7 shows the challenges and potential solutions for the effective application of BIM/GIS technology in the bridge sub-industry of AEC based on synthesis of the limitations of the application of BIM/GIS technology from the current body of knowledge. The following four subsections expand these challenges and suggest potential solutions.

Table 7. Challenges corresponding to the four aspects of analysis and potential solutions.

Application Aspects	Contents	Challenge	Potential Solution
Planning and design	**Planning**: Plan roads (bridges), find bridge site. **Design**: Establish bridge 3D information design model.	• Technical competency. • Technology standardization.	• Converting research findings into practice oriented information. • Regularly train and assess practitioners in the application of BIM/GIS technology. • Standardizing bridge design modelling protocols and terminologies.
Construction	Cost, schedule.	• Cost evaluation model. • New construction process.	• Reasonable methods for cost estimation could be continuously explored. • Try to use BIM technology to optimize new construction processes and improve the construction schedule.
Operation and maintenance	Bridge traffic network, bridge management system, bridge inspection, bridge evaluation, bridge maintenance decision.	• Multi-factor bridge traffic network model. • BIM/GIS model compatibility. • Collection method. • Maintenance plan.	• Introduce an uncertain or dynamic traffic flow and other factors to improve the bridge transportation network model based on GIS. • BIM/GIS software should be further developed, such as API. • Omnidirectional data acquisition methods should be explored further. • Research and verification of different bridge maintenance decisions.
Information exchange	Expand standard, data integration, interoperability.	• Bridge BIM standard. • Integrate bridge BIM and GIS data. • BIM and GIS data interaction method.	• Develop/expand bridge BIM standards to meet the needs of existing stakeholders. • Study the integration content of BIM standards (such as IFC) and GIS standards (such as CityGML). • Research on data exchange format and method of BIM and GIS.

4.1. Planning and Design

It was found that most practitioners only considered BIM as a display tool and some of them had no idea about BIM [1]. With the increase in population and the evolving complexity of structural design [4], there is the need to improve practitioners' knowledge and application of BIM/GIS technology [1] to enhance the application of BIM/GIS technology at the design stage of bridge projects [4,6,11,66].

The design institutions need to regularly train and assess practitioners in the application of BIM/GIS technology [1]. At present, efforts are being made to expand the probabilistic and numerical model database of bridges, which is an important step towards formulating reasonable design rules for bridge components [27]. This can be achieved through close cooperation between key stakeholders, including architects [4], landscape designers and urban planners.

4.2. Construction

The application of BIM/GIS technology in the bridge construction process in various countries is increasing. This can promote effective and efficient management of the construction processes and contribute to further development of BIM/GIS technology for the AEC industry and particularly, the bridge sub-industry. However, there are several technical and practical problems that need to be resolved to enhance the application process of these technologies.

About 70% of the negative cost impact of some bridge construction projects may be related to the first implementation of BIM/GIS technology during construction [7]. Some bridge construction projects use BIM technology to evaluate cost inaccuracies [28–30], such as estimates limited to direct costs only [29]. Moreover, due to the lack of BIM/GIS knowledge of bridge project participants [1], the efficiency and effectiveness of BIM/GIS technology implementation may be negatively affected [3,7]. It is gratifying that the visualization of BIM/GIS technology can enhance project cognition and communication among participants in the process of bridge construction [9]; however, only a limited number of bridge projects have implemented BIM/GIS technology [9,21,28,30,69].

It is difficult to completely isolate the impact of BIM/GIS implementation, because no two construction projects are identical [7]. However, in the future, when BIM/GIS technology is used at the construction stage of bridge projects, appropriate BIM/GIS training could be conducted for participants to enhance implementation [1]. Methods of cost estimation can be continuously explored to enhance cost efficiency [28–30] by covering most indirect costs [29] so as to reduce the negative cost impact of BIM/GIS technology implementation. BIM/GIS technology implemented on existing bridges for functions such as maintenance management to aid further adaptation of these technologies for bridges and continuous improvement of the application process.

4.3. Operation and Maintenance

At present, the existing bridge transportation network models based on GIS usually adopt deterministic [71,72] or static traffic flow patterns [76], without considering the influence of other factors, such as wind intensity [70]. The benefits of GIS technology in the management of major transportation facilities have not been verified [13,74]. BIM/GIS models for bridge management have poor compatibility with other models or modules such as the finite element model [15,39,40], damage model [16], and disaster model [14,77,78] and, therefore, influences data mining. There is a growing trend using UAV and other detection technologies for bridge detection based on BIM/GIS [94]. Although these technologies have many benefits, there are some shortcomings, including the lack of overall perspective [41,42] and the impact of weather changes on data quality [14,34,37,38,77,78]; these can affect bridge evaluation outcomes [73]. Therefore, the existing evaluation models may not be directly applicable to other projects [48,49,52,81], given that they may negatively affect maintenance decisions of other bridges.

In the future, researchers could consider introducing uncertainty [71,72] or a dynamic traffic flow [76] and other factors to improve bridge transportation network models based on GIS to enhance model utility and expand the scope of application. BIM/GIS software, including API, should be further developed to improve their compatibility with other models or modules and enhance data mining for bridge management systems [15,39,40,95]. It is suggested to improve the quality of bridge detection by adding acquisition methods such as omnidirectional acquisition [41,42] and improving data processing methods. In terms of bridge maintenance decision making, more researchers and decision makers need to study and verify different bridge maintenance decision-making objectives and constraints [51], and combine with BIM/GIS technology to improve decision making.

4.4. Information Exchange

As a research prototype, bridge information models, in their current state, consider only a few standards and applications. Many data entities, which are necessary to fully support other bridge monitoring and management applications, are lacking [36]. Although BIM based on the IFC data model is the core of information interoperability, due to the lack of IFC support for bridge structure [19,36,44,59] and the target classification depending on the quality of the geometric model [55], it is still not enough to realize a real BIM model [19]. Some existing bridges lack digital drawings and even paper drawings [57,58]; hence, most of the data transmission needs to be manual [18,33–35] which would affect the efficiency of BIM/GIS integration [20,90]. BIM/GIS models have inconsistent data exchange format [41,63] and a slow information feedback speed [77], which affect interoperability between models. The poor interoperability of BIM/GIS software may hinder effective development of related software [22,41,60–65].

Regarding future work, it is important to clarify and pinpoint the requirements that each domain sets, especially if BIM-GIS integration (e.g., geometry conversion [20] and semantic mapping [20,55]) are to be addressed [20]. It is suggested that researchers could develop a more accurate bridge information model with detailed parameter information and determine the model development specifications of existing bridges to meet the needs of stakeholders [34]. It is very important to compare BIM standards (such as IFC) with the infrastructure module of GIS standards (such as CityGML) to determine the most favorable integration degree of these two fields in the field of asset management [15,20,90]. When using BIM/GIS technology, managers need to pay more attention to the use of interoperable and open data exchange formats [41] to enhance the operational efficiency of the platform.

5. Conclusions

There has been increasing interest in the bridge engineering community to use BIM and GIS for the efficient, automated and intelligent handling of different aspects of bridge projects. This research reviewed a total of 90 journal papers over the past decade and summarized the state-of-the-art applications of BIM and GIS technologies in different aspects of bridge projects (i.e., planning and design, construction, operation and maintenance as well as information exchange). Accordingly, the main challenges were identified and future work is recommended based on the following key aspects: (1) Develop BIM and GIS standards to solve the problems of bridge BIM-GIS data integration and interaction method. (2) During the planning and design stage, it is necessary to formulate standardized bridge design modeling protocols and terms to solve the problems of bridge modeling design. (3) During the construction stage, try to use BIM technology to optimize new construction processes and improve the construction schedule, as well as reasonable methods for cost estimation could be continuously explored. (4) During the operations and maintenance phase, the requirements of each management department should be clarified and identified, as well as omnidirectional data acquisition methods should be explored further to enhance the efficiency of managers in decision making. Findings of this research would serve as a guide for bridge engineering practitioners in selecting appropriate BIM/GIS technology for different phases of bridge projects. Additionally, findings of this review would contribute to further research and development to improve the application of BIM/GIS technology on bridge projects.

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