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Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations

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ABSTRACT

Transportation infrastructure is a critical component to a nation's economy, security, and wellbeing. In order to keep up with the rising population, there is a great need for more efficient and cost-effective technologies and techniques to not only repair the infrastructure, but also to advance and expand the transportation infrastructure to sustain the growing population. Building Information Modeling (BIM) has been widely adopted in the building industry, and its established methods and technologies show enormous potential in benefiting the transportation industry. The purpose of this paper is to present a literature review and critical analysis of BIM for transportation infrastructure. A total of 189 publications in the area of BIM for transportation infrastructure were reviewed, including journal articles, conference proceedings, and published reports. Additionally, schemas and file formats from 9 main categories and 34 areas related to transportation infrastructure were reviewed. An application was developed to collect, store, and analyze the publications. Various algorithms were developed and implemented to help in the automation and analysis of the review. The goal of this paper is to provide a comprehensive, up-to-date literature review and critical analysis of research areas regarding BIM for transportation infrastructure to further facilitate research and applications in this domain. Based on the results of the analysis, current topics and trends, applications and uses, emerging technologies, benefits, challenges and limitations, research gaps, and future needs are discussed. Significantly, the contribution of this paper is providing the foundation of current research, gaps, and emerging technologies needed to facilitate further research and applications for both academia and industry stakeholders to develop more efficient and cost-effective techniques necessary to repair, advance, and expand the transportation infrastructure. Furthermore, the results show that the use of BIM for transportation infrastructure has been increasing, although the research has mainly been focusing on roads, highways, and bridges. The results also reveal a major need for a standard neutral exchange format and schema to promote interoperability. Most importantly, the continuing collaboration between academia and industry is required to mitigate most challenges and to realize the full potential of BIM for transportation infrastructure.

1. Introduction

Transportation infrastructure can be viewed as the backbone for any nation, since reliable, safe, and efficient movement of goods and citizens significantly helps the economic and social development. With the ever-increasing growth in population paired with the ageing of the transportation structures, there is a great need for more efficient and cost-effective technologies and techniques to build, maintain, monitor, and repair the structures. There has been a significant push for the development and utilization of innovative technologies in the transportation sector, in which many of the proven technologies and methods from the building industry have been adopted. One method that particularly excelled in the building industry is known as Building Information Modeling (BIM). BIM, as defined by the U.S. National Building Information Model Standard Project Committee, "is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle; defined as existing from earliest conception to demolition" [1]. Confusion and misunderstanding occurs when BIM is seen solely as 3D model of a facility with added features and functions; however, BIM is about the *information* and the 3D model is just one way of representing the information. Therefore, the advent around centralized information creation, sharing, and management has created new paradigm shift in the

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Architecture, Engineering, Construction, and Operations (AECO) industry, driving the traditional design approach into more information-centric collaboration. The term BIM has various uses and connotations, such it is defined as a product, a collaborative process, and a facility life cycle management requirement [2]. The intention of BIM was to be able to capture all the information and aspects of the design and construction of a facility, so it can be utilized for the operation and maintenance (O&M).

BIM has been widely adopted in the building industry for a few decades; however, the use of BIM in transportation infrastructure has been slow in its adoption and application [3–5]. Industry and academia are increasingly putting effort into adopting BIM for other non-building civil infrastructure, but so far, there has not been a comprehensive review of the effort specifically aimed at transportation. Previously, there have been other literature reviews of BIM in the areas of existing buildings [6], managerial areas of BIM [7], BIM as a collaborative platform and data management applications [8], civil infrastructure facilities [9, 10], infrastructure with a constructor perspective [11], and a scientometric review of global BIM research [12]. These provide an elaborate overview of BIM for their respected focuses, but an extensive review of BIM for transportation structures, such as bridges, highways, and roads have still been lacking. Therefore, the purpose of this paper is to provide a comprehensive, up-to-date literature review of the application and usage of BIM for transportation infrastructure. The goal of this paper is to provide a critical analysis of research areas regarding BIM for transportation infrastructure to further facilitate research and applications in this area. This paper provides a complex analysis of the reviewed articles, including current topics and trends, applications and uses, emerging technologies, benefits, limitations and challenges, research gaps, and future needs. Additionally, the paper aims to provide alignment for future work and collaboration that can exploit the full potential of computer technologies and applications that have been realized in the building industry. Significantly, this paper provides the foundation of current research, gaps, and emerging technologies needed to facilitate further research and applications to develop more efficient and cost-effective techniques necessary to repair, advance, and expand the failing transportation infrastructure.

2. Terminology and classification

2.1. Synonyms of Building Information Modeling (BIM)

Before the term "BIM" was coined, the idea stemmed from building product models, an early development of utilizing the newly invented computers to produce parametric information in development of product models as the electronic representation of buildings for data exchange and collaboration. Currently, BIM incorporates the traditional 3D computer-aided design (CAD) model of a building with all the information and properties about that building such as design plans, product information, schedule sequencing, and operations. Prior to consolidation of software-based information modeling of bridges, paper-based numerical modeling of structure of bridges was the normal practice [13]. Interestingly, the earliest research discovered in this review fitting the definition of BIM for transportation infrastructure was the development of a microcomputing system for bridge management [14]. Moving from a paper-based workflow to an electronic/computer workflow has led to the rise of Bridge Information Modeling (BrIM), which is an extension of BIM that focuses on bridges [15]. Although bridges and buildings are similar in that they are both structures and have similar features, they vary greatly in terms of construction, operation, and classification of parts. There are needs to generate BrIM models, which is distinguished from BIM, because bridges have some unique features like roadway alignment and girder camber, which play important roles in design, construction, and fabrication. In addition, the majority of resources are spent on operation and maintenance (O&M) throughout bridge life-cycle including but not limited to bridge inspection, permitting, load rating, while the emphasis of building lifecycle is on the stages before handover.

Prior to the adoption of BIM for civil infrastructure, software tools and methods were explored to help with the development and deployment of civil projects, specifically with digital project delivery. The Federal Highway Administration (FHWA), along with the American Association of State Highway and Transportation Officials (AASHTO), American Road and Transportation Builders Association (ARTBA) and the Associated General Contractors of America (AGC) have defined this as Civil Integrated Management (CIM). *"Civil Integrated Management (CIM) is the collection, organization, and managed accessibility to accurate data and information related to a highway facility"* [16]. Since BIM is a life cycle asset requirement, the definition of CIM was recently expanded to include this. Therefore, an updated definition is the following [17];

> *"Civil Integrated Management (CIM) is the technology-enabled collection, organization, managed accessibility, and use of accurate data and information throughout the life cycle of a transportation asset. The concept may be used by all affected parties for a wide range of purposes, including planning, environmental assessment, surveying, design, construction, maintenance, asset management, and risk assessment."*

The acronym "CIM" has also been used to mean civil information and construction information modeling, which have been mainly used in internationally and within industry modeling [10, 18]. Recently, due to the confusion, the moniker CiM with the lower case "i" has been adopted by recent participants for civil information modeling to describe the process that is equivalent to BIM [19]. Additionally, CIM has also meant Computer-Integrated Management (CIM) [20], Construction Information Modeling (CIM) [21], and Construction Information Management [21]. Regardless of the name and acronym, the purpose that these terms represent are clear: the utilization of technology to develop and share information for the life cycle of a building, structure, or asset. Table 1 summarizes the current acronyms discovered in literature.

2.2. Categories of BIM for transportation infrastructure

Civil infrastructure is a facility, structure, or utility needed to support human civilization and activities. Table 2 is a modification from [10] that defines five domains of civil infrastructure expanded into thirteen categories. Specifically, the transportation infrastructure is a subset of civil infrastructure that can be expanded into 8 categories. Distinct classification of individual items can be difficult since some can fall into one or more categories. Examples include: a road can be built on top of a levee or dam; subways can be part of rail and mass transit; and roads can be used for both vehicles and pedestrians. The mode of transportation can also dictate what specific category it falls under, e.g. car, train, airplane, bus, or bicycle.

2.3. Vertical and horizontal construction

Building Information Modeling has been predominately used for buildings and other vertical construction, e.g. hospitals, schools,

Table 1
Acronyms and meaning for various information modeling terms.

Acronym	Meaning
BIM	Building Information Modeling
BrIM	Bridge Information Modeling
CAD	Computer-Aided Design
CIM	Civil Integrated Management
CiM	Civil information Modeling
CIM	Computer-Integrated Management
CIM	Construction Information Management
CIM	Construction Information Modeling
VDC	Virtual Design and Construction

Table 2
Categories of civil infrastructure

Categories of civil infrastructure		Domains
1)	Bridges	Transportation infrastructure
2)	Roads and highways	
3)	Railways	
4)	Mass transit	
5)	Tunnels	
6)	Aviation and airports	
7)	Ports, docks, and harbors	
8)	Non-motorized vehicle and pedestrian pathways	
9)	Power generation	Energy infrastructure
10)	Oil and gas	
11)	Mine	
12)	Utility	Utility infrastructure
13)	Recreational facilities	Recreational facility infrastructure
14)	Water and water facilities	Water management infrastructure
15)	Dams, canals, locks, and levees	

stadiums, high rises, etc. This is mainly due to the fact that vertical construction is whole different process than horizontal construction (e.g. bridge, road, tunnel, etc.), in which each has different operations, components, and techniques from planning, through construction, to operation and maintenance [15]. For example, highways and bridges largely rely on terrain (e.g. GIS data) and heavy earth moving operations, while buildings do not (although some is required). Cultural, management, and contractual factors also differentiate between the two [22]. Additionally, horizontal projects are typically public projects that are owned and operated by government entities (e.g. DOTs), which have different financing (e.g. taxes and bonds) and legal restrictions (e.g. bidding and contracting) versus private projects. One major differencing factor between a building (vertical) and a transportation (horizontal) structure that this paper asserts is the coordinate system that is used in the design, planning, and construction of that structure. Vertical construction uses the Cartesian coordinate system as a single reference, while horizontal construction uses multiple stations and alignment curves for references. This difference has been a major barrier for direct adoption and application of traditional BIM software for transportation, since traditional CAD design tools primarily use Cartesian coordinate system. However, this distinction may cause a blur between the horizontal and vertical structures for transportation infrastructure that utilizes a building component, which includes dams, ports, and terminals. Nonetheless, transportation infrastructure that predominately uses horizontal construction is considered in this literature review, although others are mentioned as well.

3. Review approach

3.1. Originality

Since BIM for transportation infrastructure has been a relatively new in academia and industry, there has yet to be a comprehensive literature review on this topic. Having a comprehensive literature review is important to continue the research and development in an aligned and orderly fashion. Additionally, a major contribution of this paper is that it surveys and identifies publications from industry and governmental agencies, such as the state departments of transportation (DOTs). Therefore, having a mix of academic, industry, and governmental publications is critical to the advancement of innovations and technology for transportation infrastructure.

The scope of this literature review pertains of any published works relating with BIM for transportation infrastructure. Any publications that fit the definition of civil integrated management (CIM), which was previously defined, would be included in this review. One major delimitation is that the review only includes research and applications that directly applies to transportation infrastructure, i.e. "actual application" versus "potential applications." Therefore, the review portion only contains articles that have been tested or validated for the use on transportation infrastructure. Another delimitation is that this review excludes computer modeling techniques, such as statistical analysis, strengths of materials, and probabilistic techniques that does not utilize information modeling as defined earlier.

3.2. Methodology

This review takes a four-step approach: 1) identify academic journals and databases; 2) create query of keywords; 3) collect, store, and filter relevant articles; and 4) perform data analysis.

3.2.1. Identify academic journals and databases

The first step is to identify the academic journals and databases that may contain any relevant material for this review. Table 3 displays the information of the academic journals that were searched in the review process. Since many of the CIM efforts are outside of university research, it is important to identify the databases and publications of all stakeholders, including state departments, government agencies, professional associations, and industry companies.

3.2.2. Create query of keywords

The second step was to search and locate any publications relating to BIM for transportation infrastructure. Since there are various nomenclatures that can fall under the topic of BIM for transportation infrastructure, a list of all the possible combinations of the keywords to address this topic was created. For example, BIM for transportation infrastructure covers a wide array of topics and published articles might not include the keyword "BIM." Therefore, we broke down the topics into subtopics that fall under the umbrella term "BIM." These topics include Bridge Information Modeling (BrIM), 3D modeling applications for infrastructure, BIM for transportation, Civil Integration Modeling (CIM), Civil information Modeling (CiM), Computer Aided Design (CAD) for infrastructure, and any other information modeling or technological advancements aimed at transportation infrastructure. For example, internet search engines (e.g. Google Scholar) and academic/applied databases were searched with broad terms and queries. It was more efficient to start with a broad, top down search approach and then decipher what publication were related to the scope, versus starting with a restricted search. It was important to identify literature that is relevant to the scope, but does not contain adequate keywords. Many older articles may not include the terms "BIM" or "BrIM" since these terms are relatively new, but would be within the realm of the scope (e.g. structure analysis software for bridges). Additionally, other articles might include non-BIM specific technologies for transportation structures.

3.2.3. Collect, filter, and store relevant articles

It is important to err on the side of collecting too many articles that include some non-relevant to this literature review, which could be filtered out, rather than collecting too few, which could result in missing some. This literature review utilized both academic and public databases, such as SCOPUS, EBSCO, and Google Scholar for a broad approach that searches multiple journals simultaneously. Next, the review searched the individual publisher databases that have multiple journals and conference proceedings (e.g. Elsevier, ASCE, TRB). Finally, the review indexed each cited reference of relevant publications to review the history of the publication.

Once a publication was found, the abstract and keywords were reviewed to check whether or not it was relevant to the review. If the publication was relevant, an analysis was preformed, which included a written synopsis (outline, review, significance, etc.). Both the publication and synopsis were stored on a secure, central server. In order to help manage and store the large number of publications gathered for

Table 3
Examined journals categorized by scope.

Category	Journal title	Publisher
Built environment (AECO) (Reviewed journals: 24)	Advances in Structural Engineering	*Sage Publishing*
	Journal of Asian Architecture and Building Engineering	*J-Stage*
	Automation in Construction	*Elsevier*
	Canadian Journal of Civil Engineering	*NRC Research Press*
	Computer-Aided Civil and Infrastructure Engineering	*Wiley*
	Construction and Building Materials	*Elsevier*
	Engineering Structures	*Elsevier*
	Gerontechnology	*International Society for Gerontechnology*
	HKIE Transactions	*Taylor & Francis*
	International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering	*World Academic of Science, Engineering and Technology (WASET)*
	International Journal of 3D Information Modeling	*IGI Global*
	International Journal of Project Management	*Elsevier*
	International Road Federation (IRF) Examiner	*IRF Global*
	Journal of Harbin Institute of Technology	*Harbin Gongye Daxue/Harbin Institute of Technology*
	Journal of Computing in Civil Engineering	*ASCE*
	Journal of Construction Engineering and Management	*ASCE*
	KSCE Journal of Civil Engineering	*Springer*
	Journal of Management in Engineering	*ASCE*
	Practice Periodical on Structural Design and Construction	*ASCE*
	Proceedings of the Institution of Civil Engineers - Municipal Engineer	*ICE Publishing*
	Structural Engineering International	*IABSE*
	The Open Construction and Building Technology Journal	*Bentham Open*
	eWork and eBusiness in Architecture, Engineering and Construction	*Taylor & Francis*
	Bridge Structures: Assessment, Design and Construction	*Taylor & Francis*
Civil infrastructure (Reviewed journals: 4)	Journal of Infrastructural Systems	*ASCE*
	Journal of Bridge Engineering	*ASCE*
	The Baltic Journal of Road and Bridge Engineering	*Thomson Reuters*
	Structure and Infrastructure Engineering	*Taylor & Francis*
Informatics and computer technology (Reviewed journals: 16)	Advanced Engineering Informatics	*Elsevier*
	Advances in Engineering Software	*Elsevier*
	Applied Computational Intelligence and Soft Computing	*Hindawi*
	Applied Soft Computing	*Elsevier*
	Archives of Computational Methods in Engineering	*Springer*
	Computers & Structures	*Elsevier*
	Expert Systems with Applications	*Elsevier*
	Facilities	*Emerald Publishing*
	IFMA Facility Management Journal	*International Facility Management Association (IFMA)*
	Journal of Computational Science	*Elsevier*
	Journal of Information Technology in Construction	*International Council for Research and Innovation in Building and Construction (ICB)*
	Journal of Applied Computing in Civil Engineering	*J-Stage*
	Neurocomputing	*Elsevier*
	Simulation Modeling Practice and Theory	*Elsevier*
	Smart Structures and Systems	*Techno Press*
	Visualization in Engineering	*Springer*
Civil and mechanical engineering (Reviewed journals: 3)	Applied Mechanics and Materials	*Trans Tech*
	Archives of Civil and Mechanical Engineering	*Elsevier*
	Mechanical Systems and Signal Processing	*Elsevier*
Energy, sustainability, and environment (Reviewed journals: 5)	Energy	*Elsevier*
	Energy and Buildings	*Elsevier*
	International Journal of Sustainable Built Environment	*Elsevier*
	Renewable and Sustainable Energy Reviews	*Elsevier*
	Sustainability	*MDPI*
Geotechnology (Reviewed journals: 3)	ISPRS International Journal of Geo-Information	*MDPI*
	Geotechnical Special Publication	*ASCE*
	Journal of Rock Mechanics and Geotechnical Engineering	*Elsevier*
Emerging technologies (Reviewed journals: 3)	International Journal of Advanced Robotics Systems	*Sage Publishing*
	Journal of Intelligent and Robotic Systems	*Springer*
	Measurement	*Elsevier*
Remote sensing and computer vision (Reviewed journals: 3)	ISPRS Journal of Photogrammetry and Remote Sensing	*Elsevier*
	Journal of Sensors	*Hindawi*
	The Egyptian Journal of Remote Sensing and Space Science	*Elsevier*
Transportation engineering (Reviewed journals: 2)	Journal of the Transportation Research Board	*TRB*
	Journal of Transportation Engineering	*ASCE*
Safety (Reviewed journals: 1)	Safety Science	*Elsevier*
Waste management (Reviewed journals: 1)	Waste Management	*Elsevier*

the review, an application programmed in Excel VBA (Visual Basic for Applications) was developed to automate the storage, retrieval, and analysis of the references. The main functions of the applications include the entry of each publication, assignment of relative categories/keywords, exportation of references, and execution of various analysis techniques. Additionally, an import/export feature to EndNote was

Table 4
Frequency of the top 20 keywords extracted from the articles in the analysis.

Extracted from list of keywords (count)	Extracted from abstract (count)
BIM (20)	Information (113)
Building information modeling (11)	Data (81)
Bridge (9)	Construction (76)
IFC (8)	Bridge (71)
Bridge information modeling (7)	Infrastructure (58)
Interoperability (7)	Management (54)
Bridge inspection (7)	BIM (52)
CIM (6)	Information modeling (52)
Bridges (5)	System (52)
Building information modeling (BIM) (5)	3D (50)
Building information modelling (5)	Maintenance (41)
Structural health monitoring (5)	Bridges (36)
Automation (4)	Building Information Modeling (34)
NoSQL database (4)	Analysis (32)
Structural health monitoring (SHM)	Engineering (32)
Visualization (4)	Monitoring (30)
Alignment (3)	Building Information Modeling (BIM) (25)
Big data (3)	Framework (25)
Collaboration (3)	Technology (25)
Data management (3)	Road (24)

scripted to promote sharing of references. A major function of this application was to collect pertinent data about the article needed for the analysis. Examples of the data collected include the abstract, keywords, citation information, and detailed methods. For this review article, detailed methods collected include uses and applications, phase of the life cycle, structure type (e.g. road, bridge), technology, schema, benefits, and limitations. Various algorithms were developed that automated sorting, classifying, and producing results. Algorithms were also developed for text abstraction from the articles that was used to perform keyword searches and analysis. There was a combined total of 478 unique words listed as keywords in the articles that were analyzed in this review. These keywords were then used to search the abstracts of all the articles in this review. Table 4 lists the most frequent keywords found in the listed keywords section of the article (left column), and the most frequent keywords found in the abstract (right column). The numbers in parentheses (count) signifies how many articles that specific keyword was found in. It is important to note that not all of the articles had either a list of keywords or abstract. Since some of the keywords appeared in multiple spellings or formats, as shown in the table, all variations were grouped together prior to the analysis portion of the review.

Due to the applied methodology of selecting from published works, this review excludes any ongoing research in the topic that have not been published or made known. However, since the recent research of BIM for transportation have been driven heavily by industry, this literature review includes funded projects by government, organizational, and industry that resulted in a publication of a report. Blogs, magazine articles, webpages etc. that are not published as an official document were not included in the analysis (although they may be included for references in this article).

3.2.4. Perform data analysis

The analysis was broken down into two groups: 1) academic, which includes journal and conference publications, and 2) non-academic, which includes industry reports, manuals, etc. The intent of keeping them separate was to avoid bias in the analyses since there may be reports or studies that are not published. Fig. 1 displays the breakdown of the literature that was reviewed based on the publication type and year. A total of 189 publications in the area of BIM for transportation infrastructure were analyzed in the review, including journal articles, conference proceedings, and published reports. Other sources, such as dissertations, magazines, web sites were excluded from the analysis, but were included in the overall article. Since there are various topics under BIM for transportation infrastructure, Fig. 2 displays the frequency of the main keywords that were either in the listed keywords or abstract of the publication. The main keywords in Fig. 2 are the topics of this paper, which include Bridge Information Modeling (BrIM), CIM, BIM for infrastructure, BIM for transportation, BIM (specifically) for transportation infrastructure. Since there are various spellings and formats, each keyword includes the list of variations. As shown in Figs. 1 and 2, there has been a major increase in research on this topic. Additionally, Fig. 2 shows the lag with the classification of the topics. The categories of models are further broken down based on the type of information model (Table 5).

4. Applications and uses of BIM for transportation infrastructure

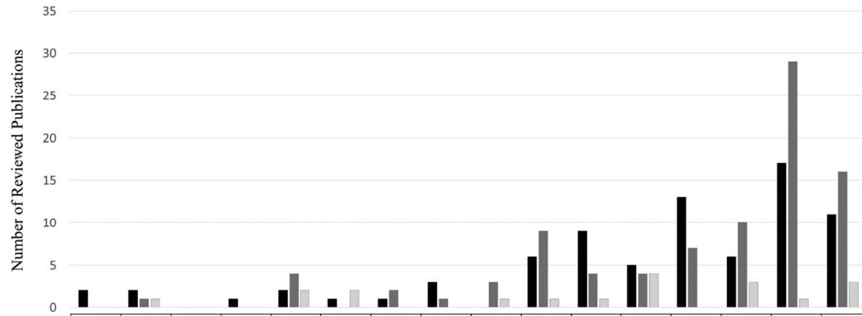
While the application of BIM in the building sector is expanding every day, its utilization in transportation infrastructure has still been limited and slow in the application [4, 5]. Civil Integrated Management (CIM) has been mostly used for operation and management sector, while Civil information Modeling (CiM) has focused on the 3D virtual modeling of transportation infrastructure in the design phase. Recently, there have been diverse attempts and studies in the area of CiM, both from industry and academia. Industry professionals mostly explored different applications of CiM (Table 6) while the academics focused on a specific type of infrastructure and concluded their results as data schema models [10].

4.1. BIM expansion and maturity

Building Information Modeling (BIM) is a growing trend in the Architecture, Engineering, Construction, and Operations (AECO) industry. Initially, BIM was designed to be applied in the building sector, but it is expanding into other areas of construction which it was not originally designated for, such as civil infrastructure [10, 11, 23]. It is believed that the use of BIM in infrastructure is nearly three years behind from its use for buildings, but evidence show that recently the use of BIM in infrastructure is increasing [11] (see Fig. 1). The use of BIM in the United States has a long history with extensive research in this area, but Europeans are also achieving maturity in BIM rapidly. The UK, Germany, and France are now using BIM as a favorable technology for design and management of their infrastructure. There is a significant growth in adoption of BIM for infrastructure between 2012 and 2017 in Europe, and the rate of BIM implementation for infrastructure projects has been raised from 20% to 52% in this period [24].

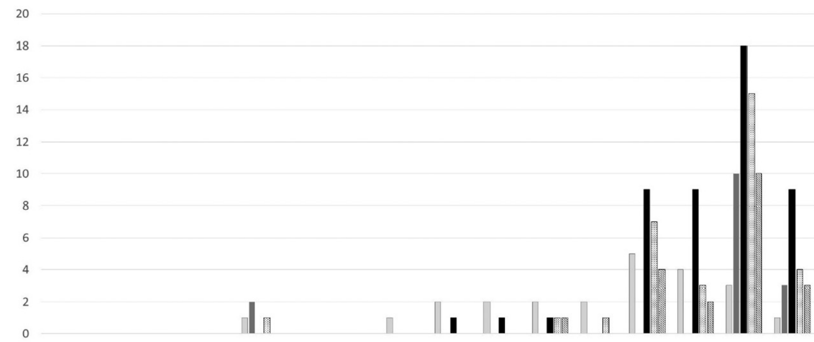
4.2. Revenues

While it seems that spending on bridge information modeling (BrIM) can impose a considerable cost to the project at its initial stage, findings show that this cost is worth paying as it brings significant revenues during construction of the project. Minehane et al. [25] stated that BrIM expenses are only a fracture (1.5–15%) of savings which will be brought to the owner through its application during the project. Using BIM or BrIM instead of traditional documentation methods will help stakeholders build up financial and technical benefits. An accurate cost estimation for components of bridges can help all stakeholders to make a better prediction and plan. It helps the process of capturing and storing data in accuracy and exhaustiveness while reducing the required time and human efforts. This information could later be used as reliable data for more detailed analysis that will make more savings in future projects. Evidence show that BIM can mostly help governments in infrastructure projects. Public sector owns the majority of road and transportation infrastructure system; hence government and owners are the most benefited parties by implementing BIM in infrastructure projects [23].



	<2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
Total Reviewed Publication	2	4	0	1	8	3	3	4	4	16	14	13	20	19	47	30	189
■ Journal Article	2	2	0	1	2	1	1	3	0	6	9	5	13	6	17	11	80
■ Conference Proceeding	0	1	0	0	4	0	2	1	3	9	4	4	7	10	29	16	90
□ Report	0	1	0	0	2	2	0	0	1	1	1	4	0	3	1	3	19

Fig. 1. Frequency of reviewed publication based on type and year.



	<2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
Total Articles with Main Keywords	0	0	0	0	4	0	0	1	3	3	5	3	25	18	56	20	138
BrIM	0	0	0	0	1	0	0	1	2	2	2	2	5	4	3	1	23
CIM	0	0	0	0	2	0	0	0	0	0	0	0	0	0	10	3	15
BIM for Infrastructure	0	0	0	0	0	0	0	0	1	1	1	0	9	9	18	9	48
BIM for Transportation	0	0	0	0	1	0	0	0	0	0	1	1	7	3	15	4	32
BIM for Transportation Infrastructure	0	0	0	0	0	0	0	0	0	0	1	0	4	2	10	3	20

Fig. 2. Frequency of main keywords listed in the abstract based on year.

Table 5
Publications regarding BIM for transportation infrastructure based on model type.

Model type	Publication
As-built	[4, 5, 25, 33, 42, 55, 64, 69, 72, 76, 147]
Bridge Information Modeling (BrIM)	[11, 20, 21, 25, 29, 31, 35, 36, 39–41, 43, 60, 66, 68, 69, 76, 83, 84, 87, 88, 94, 96, 97, 101, 103, 104, 112, 114, 117, 118, 121, 125, 128, 129, 135, 139, 141, 143, 160, 196, 229]
Building Environment Information Modelling (BEIM)	[67]
Building Information Modeling (BIM)	[3–5, 10, 11, 18, 19, 23, 26, 30, 36, 38, 40, 42, 44, 45, 55, 57–59, 67, 71, 78, 79, 81, 82, 85, 86, 90, 91, 93, 94, 96, 99, 106, 109, 110, 113–116, 124, 127, 131, 132, 136, 139, 140, 149–152, 154–156, 158, 160–162, 197, 230, 234, 236, 238]
CIM	[18, 72, 109, 120, 148]
Civil Information Modeling (CiM)	[3, 19, 21, 63, 64, 66, 88, 90, 91, 115, 126, 159]
Digital Terrain Model (DTM)	[66, 67, 71]
Finite elements	[94, 111, 134, 139, 236]
Geometric modeling	[59, 73, 111, 147, 151, 232]
Multi-scale model	[57, 73, 107, 236]
nD	[32]
Numerical modeling	[14, 27–29, 31, 34, 36, 37, 39, 50, 51, 65, 97, 108, 119, 133, 134, 143, 155, 159, 236]
Parametric models	[25, 73, 100, 101, 107, 109, 125, 139, 153, 157, 232]
Product model	[91, 100, 101, 107, 136, 142, 158, 160, 196, 225–227, 230, 234, 239]
Tunnel information model	[236]
VDC	[10, 63, 69, 72, 162]

4.3. Risk management

BIM can be applied as a systematic risk management tool to control risk and improve safety. Risk management and safety analysis is possible through 4D planning phase of the project where the order and duration of tasks are defined and justified. Application of BIM can help general contractors to reduce their risks and diminish the associated costs [26]. It can greatly help in identifying uncertainties in bridge construction [27]. BIM helps professionals to reduce trial and errors in construction phase that enhances productivity while diminishing risks associated with time and cost. The risks could also be visualized, simulated and quantified through BIM capabilities [26]. Bridges could be threatened by flood and other natural hazards and scouring is a crucial risk for bridges that can result in failure and collapse. BIM can help in

Table 6
Publication of applications and uses of BIM for transportation infrastructure.

Application or use	Publication
Accelerated bridge construction (ABC)	[121, 124]
Adoption	[5, 10, 29, 71, 85, 127]
Advantages and disadvantages	[10, 18, 19, 23, 42, 45, 63, 72, 75, 79, 83, 85, 103, 104, 124, 132, 148, 225, 238]
Analysis	[5, 30, 40, 41, 56, 57, 59, 60, 78, 99, 101, 108, 121, 133, 135, 136, 161, 239]
Appraisal	[14]
Appraisal and assessment	[14, 42, 131]
Asset Management	[8, 10, 36, 51, 55, 58, 59, 65, 87, 106, 124, 131, 137, 148, 154, 159, 238]
Automation	[41, 44, 64, 65, 86, 107, 111, 120, 129, 144, 155]
Best practices	[45]
Bill of Quantities (BOQ)	[71, 96]
Bridge Management System (BMS)	[41, 136, 239]
Cash Flow	[96]
Clash detection	[5, 10, 11, 18, 29, 30, 63, 68, 69, 71, 72, 97, 116, 132, 149, 161, 162]
Collaboration	[8, 18, 25, 26, 45, 57, 71, 73, 82, 93, 94, 99, 101, 112, 113, 162, 236]
Constructibility	[71]
Cost Estimation (5D)	[5, 10, 11, 18, 26, 29, 32, 39, 57, 71, 72, 80, 86, 96, 97, 99, 103, 110, 112, 119, 128, 129, 158]
Data management	[8, 36, 37, 43, 60, 136, 239]
Decision making	[8, 32, 61, 68, 93, 95, 99, 112]
Deterioration	[28, 51, 53, 134, 137]
Digital mockup	[29, 118]
Environmental impact	[87, 92, 154, 155]
Facility management	[99, 154, 156, 238]
Framework	[93, 236]
Health monitoring	[14, 25, 27, 28, 33, 36, 41, 44, 50–54, 65, 76, 134]
Inspection	[14, 27, 36, 41–44, 48–50, 55, 59, 61, 76, 77, 88, 89, 126, 141, 143]
Interoperability	[3, 10, 11, 18, 21, 26, 29, 36, 38, 58, 60, 67, 72, 76, 78–81, 83, 86–88, 91, 93, 94, 100, 101, 105, 112, 114, 118, 124–126, 136, 139, 149, 151–153, 163, 197, 225–227, 230–232, 234, 236, 239]
Legal and law	[80, 147, 148, 241]
Lessons learned	[30, 57, 85, 238]
Load ratings	[5, 44, 60, 101]
LOD	[10, 18, 29, 45, 57, 61, 63, 71, 78, 100, 107, 115, 116, 136, 140, 148]
Maintenance	[10, 14, 25, 44, 77, 137, 155]
MEP	[30, 154, 156]
Monitoring	[5, 11, 27, 37, 42, 51–54, 56, 59, 60, 64, 65, 76, 94, 144, 156, 236]
Policy and organization	[5, 23, 117, 130, 132]
Quantity take-off	[21, 69, 97, 119, 120, 136, 140]
Safety	[5, 11, 18, 25, 27, 29, 31–39, 42, 45, 46, 91, 138, 141]
Scheduling (4D)	[5, 10, 11, 26, 29, 30, 32, 39, 57, 61, 63, 68–73, 80, 86, 95–97, 99, 103, 112, 117]
Seismic Design	[121]
Sequencing	[68, 71]
Simulation	[4, 29, 50, 57, 63, 66, 68, 70, 79, 94, 95, 99, 131, 236]
Structural Analysis	[40, 108, 133, 134]
Surveying	[5, 40, 66, 76, 128, 143]
Sustainability	[57, 70, 85, 87, 92, 110, 114, 130, 132, 138, 154, 155, 162]
Thermal monitoring	[58, 155, 156]
Traffic	[47, 63, 68, 95]
Virtual assembly	[67]
Visualization	[4, 8, 29, 32, 37, 40, 41, 57–61, 63, 68, 69, 71, 73, 76, 78, 80, 81, 86, 95, 96, 99, 101, 110, 111, 116, 124, 139, 144, 147, 148, 151, 153–156, 159, 226, 232, 234, 236, 241]

monitoring and modeling the dynamic responses from monitoring equipment to diminish the risk of scouring on bridge structure [25, 28]. Shim et al. [29] developed a 3D model of a bridge in Korea to illustrate how BIM can help in identification and quantification of the project risks. Sarkar [30] developed a BIM model to study the principals of risk management for urban infrastructure projects with a focus on subway in India, and found that BIM can reduce the risks by increasing the collaboration between stakeholders during construction phase and save considerable amount of money.

4.4. Safety control

Safety is a major priority in the AECO industry and BIM can maintain a high level of safety for the prevention of disaster [18, 31, 32]. Regular maintenance with BIM can keep the infrastructure at acceptable level of safety [33, 34]. BIM can help in evaluating the structural safety of bridges [5, 35, 36] and reliability in performance [27, 37]. Design and evaluation of roadside facilities, including the road lighting with BIM, can significantly increase the safety of roads and tunnels [38]. The location of mobile cranes [39] could be assessed and optimized to enhance the safety of the site and job process [40]. BIM can be used for choosing safest construction methods, and planning site activities to avoid space conflicts. BIM can help in detailed visualization of bridge, that can help in tracking and assessing the structural condition of bridge components to prevent failure and hazard [41–45]. Jian et al. [46] investigated other areas of transportation and concluded that safety of marine transportation infrastructure and harbors could also be improved with BIM as it can be a reliable tool for regular maintenance planning.

4.5. Integration with technology

During the past decade, technology has made a revolution in the planning, design, construction, and management of infrastructure. Technology has helped government and infrastructure managers to navigate away from traditional and human-based activities into automatic operations to enhance the precision, quality, and safety of the project. Some of the most important technologies that have been applied in infrastructure planning, design, construction, and management phases are as follows.

4.5.1. Unmanned systems and robotics

Unmanned aerial systems (UAS) have changed the work procedure from manual to automatic where robots and drones are iconic instances. Drones can be equipped with different cameras, radars, laser scanners, infrared, thermal, and other types of sensors. Their real-time data transfer feature eliminates the need for data storage devices and help in the comprehensiveness of data collection process. They could also be used for training purposes while enhancing the safety [47]. Drones could significantly help in inspection of traffic operation [47] as well as structural health monitoring of infrastructure [48]. Robotic systems for underwater applications, known as unmanned marine systems (UMS), are being used and considered for post-disaster bridge inspection and other activities [49].

4.5.2. Sensing technologies and sensors

The use of wired and wireless sensors increased the precision of operation and management activities while prevented human-errors and increased safety. Large amount of data that could be captured through sensors can help in establishment of more reliable databases that enhance the quality of management and maintenance of highways [8]. Further analysis on these data, including development of numerical modeling [50] and machine learning [51], can help in the advancement of the level of utilization of the data. Captured data can also help in structural health monitoring of infrastructure [27, 50, 52–57], which could also be integrated with BIM for further analysis [58, 59].

4.5.3. Cloud computing and mobile services

Online databases and cloud servers [43, 60] reduce the hardware dependency and provide the opportunity for accessing unified and up-to-date models, as well as their associated data that could be easily accessed through mobile devices and tablets. Cloud computing services are scalable and could be designed for responding to different needs that makes them more desirable for users and developers of services. Despite the benefits of cloud computing services, their adoptability is highly dependent on economic, social, and technological development of countries. eGovernment concept is based on development and advancement of eServices and is being used for management and control of transportation, public healthcare, and education systems. Development of these systems promotes the development of smart city concept. Security and antifragility of cloud computing services are crucial concerns in this concept [9, 55, 60, 61].

4.5.4. Laser scanning and photogrammetry

Laser scanning and light detection and ranging (LiDAR) have made a revolution in inspection and as-built documentation of infrastructure due to higher accuracy and speed of operation [42, 55, 62–64]. Laser scanners measure the travel time of laser beams to locate and capture the surface of objects in the space [42]. Through stitching different captures, laser scanners produce a point cloud model of the infrastructure that has a high precision and resolution, and could be used for modeling, diagnosis, and analysis of infrastructure [65]. Laser scanning technology can be applied through the life cycle of infrastructure. As an example, laser scanners can scan the surface of the road regularly during the construction phase to help in monitoring the project progress based on their schedule. Drones are currently simplifying the laser scanning process and Mobile Lidar. Airborne Lidar scanners are other new generations of advanced laser scanning technologies [64]. Currently, the cost of laser scanning technologies is the main hurdle for their development, specifically for small-scale constructions, while photogrammetry technologies are still an affordable substitution. Image processing and photogrammetry could save time and money, while enhancing safety and accuracy [42, 64, 66, 67]. According to the large scale of transportation infrastructure, the selected method should be able to scan a large area with reasonable level of precision [64].

4.5.5. Virtual Design and Construction (VDC)

Virtual design, prototyping, and simulation of infrastructure have brought numerous benefits to infrastructure design and management industry through better utilization and visualization of data. VDC can help through the whole life cycle of the infrastructure. It can help in enhancing the quality of feasibility studies, comparison of different scenarios in design, visualizing construction process, studying the operability of the project, and project documentation. Planning and scheduling phase of infrastructure projects could be easier and more precise by using this system. Resource management is much easier through visualization of the work progress. VDC can also help in facility management by providing a realistic model of the facility that helps the facility managers [68–73] The modeling of infrastructure and lately their development into multi-scale 3D city models have enhanced the understating, collaboration, and efficiency of planning for infrastructure planners and designers [57, 73].

4.5.6. Augmented and virtual reality

Augmented reality (AR) and virtual reality (VR) technologies elevate the level of benefits that could be obtained from 3D models. The model that has been produced by 3D software or laser scanners can be explored in a real environment, and layers of information could be added to them. These technologies help in extending the vision from the project and can help in planning and inspections on the site. AR and VR improve the communication and help in integration of ideas. As the level of skills and perceptions of participants may be different during project meetings, working in this environment helps in providing a better understanding of projects and simplifies communication between different stakeholders. In this technology, data could be augmented to 3D models or pictures/videos to help conveying the ideas. The augmented data could be in a format of text, audio, static and dynamic 2D/3D. Different platforms are now being used and combined for development of AR and VR models that include 3D modeling software, game engines, Software Development Kits (SDKs), libraries of functions, and Mid/Low level languages. These technologies require special hardware including a powerful computer, Hand Held Display (HHD) or Head Mounted Displays (HMD), projector, haptic and sensors. Thus, their cost could be a challenge for their development. Other major implementation challenges of these technologies are the complexity of surroundings and quality of received signals from sensors that have been embedded on site [57, 69, 73].

4.5.7. Global positioning systems (GPS) and geographic information systems (GIS)

Global positioning systems (GPS) have improved the accuracy of coordinates and geographical information and helped in precise implementation of projects. Integration of GPS data into geographic information systems (GIS) helped in establishing a unified and visual database that could have better representation of data and enhanced the quality of communication and decision makings [74–77]. Fusion of GIS and BIM capabilities opened new visions in infrastructure management that amplified their performance and efficiency. Controlling and monitoring of roadside utilities in ground transportation infrastructure including geotechnical, structural, and drainage data are significantly more efficient. This fusion has also helped in better planning of airports, ports, and pipeline infrastructure [5, 8, 11, 57, 67, 73, 78–82].

5. Life cycle analysis of BIM for transportation infrastructure

BIM can effectively help in managing the whole life cycle of buildings and infrastructure from planning and design through construction and maintenance [20, 26, 31, 33, 34, 36, 61, 68, 69, 83–91]. BIM helps in providing a comprehensive visual-database that could be used through the whole life cycle of the infrastructure. The data that have been collected and stored during the design and construction phase of the infrastructure can be effectively used for their operation and maintenance phase. BIM models can store considerable amount of information through the life cycle of the infrastructure [10]. Other life cycle assessments are possible through BIM capabilities. BIM can help in evaluation of sustainability and energy consumption through the life cycle of transportation infrastructure. This analysis could yield important data for electricity consumption of roadside lighting facilities, and amount of fuel consumed for maintenance equipment [92].

Bridge Information Modeling (BrIM) can help the organization and flow of data through the life cycle of bridges that helps in collaboration and interoperation [42, 83, 93]. BrIM can help in the management of the discrete events though the life cycle of bridges. Information exchange is a significant instance where BrIM can help in managing complex processes and enhance the quality of life cycle management. Shirole et al. [83] conducted a study to develop standards for neutral data exchanges throughout the bridge life cycle, in which resulted in an overview of tools and technologies for reliable electronic exchange of bridge data, identification of the data needed to support bridge life cycle activities, and an integrated prototype system that connects existing commercial software for all major phases of bridge life cycle. Hammad et al. [61] developed a mobile-based bridge life cycle management system (MMBLMS) in a 4D environment that could store the data for further uses and analysis about bridges. Jeong et al. [94] indicated that data have fundamental role in bridge management through its life cycle and BrIM could be a reliable tool for storing and managing the data. Li et al., Liapi, and Marzouk and Hisham [69, 95, 96] presented case studies to show how BIM helps decision makers to utilize the data and evaluate different alternatives expeditiously and select the most appropriate option for design, construction, and maintenance of highway and bridges. Marzouk et al. [97] stated that a data-rich BrIM

Table 7
Publications of BIM for transportation infrastructure based on the life cycle phase.

Phase	Publication
General phases	[3, 5, 8, 19, 42, 57, 61, 67, 78, 82, 93, 99, 104, 106, 107, 116, 125, 127, 130, 136, 148, 151, 153, 162, 163, 197, 227, 234]
Life cycle	[8, 10, 11, 20, 21, 25, 28, 29, 32, 34, 36, 39, 41, 42, 50, 57, 61, 66, 72, 80, 81, 83, 84, 87, 89–93, 96, 97, 131, 135, 138, 139, 142, 148, 161]
Planning	[14, 23, 26, 33, 35, 39, 45, 57, 67–70, 73, 78, 86, 93, 95, 104, 112, 119, 121, 125, 128, 129, 146, 160, 248]
Design	[10, 14, 18, 20, 21, 26, 27, 30, 31, 33, 35, 38, 41, 45, 50, 56, 57, 63, 66–69, 71, 72, 78, 86, 90, 91, 95, 96, 99–101, 103–105, 107–109, 111, 112, 114–116, 118, 121, 125, 128, 129, 133, 136, 138–140, 149–151, 153, 157, 158, 161, 196, 199, 225–227, 229, 239]
Estimating	[96, 120, 136, 140]
Detailing	[101, 125, 139]
Fabrication	[20, 118, 125, 139]
Earthwork grading	[75, 144]
Construction	[5, 10, 18, 20, 21, 23, 26, 30, 32, 39, 40, 45, 63, 64, 68, 69, 72, 75, 76, 86, 92, 95, 103, 110, 117–121, 124–126, 128, 136, 139, 144, 158, 159, 162, 199, 236]
Handover	[238]
Operation and maintenance (O&M)	[4, 8, 14, 20, 21, 25, 27, 28, 31, 33, 35–37, 40–44, 46–52, 54–56, 58–61, 65, 66, 70, 72, 76, 77, 80, 81, 88, 89, 94, 99, 103, 105, 106, 124, 126, 134, 135, 137, 141–143, 146, 152, 154–156, 238]
Renovation and rehabilitation	[4, 44, 133, 137]
Demolition	[138]

model can significantly help in decision making through the life cycle of bridges. Different applications of BIM for management of transportation infrastructure for the various life cycle phases (Table 7) are discussed in more detail in the following sections.

5.1. Planning

In addition to life cycle analysis, strategic planning and management of project tasks are possible and even easier with BIM [98]. Usually, there are different alternatives for construction of transportation infrastructure. BIM can help in assessing different scenarios by providing visual qualitative and quantitative information that helps in selection of the best scenario to minimize the time and cost of the project [69, 99].

BIM can help in optimizing the location of facilities that can help their accessibility and operability during the construction phase. Marzouk and Hisham [41] developed a hybrid model and integrated that with a BrIM model to find the optimum location of mobile cranes during the construction of a bridge. Application of BIM from planning stage can simplify communication while enhancing collaboration between different stakeholders [57]. Applying time (4D) and cost (5D) planning in enormous infrastructure projects can make greater values. Value earned through the BIM adoption has a direct relation with complexity and scale of the project. The more complex and larger the project is, the more benefit is earned [24]. Abdelwahab [71] used BIM for evaluation of constructability and mobility plan of two highway projects that could later help in construction phase of the project.

5.2. Design

BIM has helped in real-time evaluation of design criteria and rule-checking and has supported the quality of design [21, 26, 57, 71, 72, 98, 100–107]. BIM can help in different phases of design that includes preliminary design, detailed design, and design optimization [108]. It improves the quality of design and provides a better visual representation of the infrastructure and increases collaboration [26]. In addition to significant improvements in the design process, reduced omissions and errors, and subsequent reduction of conflicts and coordination problems in construction site are of the most favored benefits of using BIM in infrastructure from the design stage [102]. Data uploading and dynamic figure modification features in BIM provided the context for simultaneous reviews of design [109] that can help reducing waste as well as improving quality during the construction and support sustainable construction and development [110]. Internal business benefits and improvements in project process and earned benefits are recognized to be the main drivers for adoption of BIM in infrastructure sector. These benefits encouraged major construction companies in the U.S. and across the Europe to start or expand the use of BIM in design and construction of their infrastructure projects with a significant rate of increase [24].

Bridge structural design and analysis is the initial phase of bridge life cycle, and BrIM can greatly help in this phase [31, 69, 102, 109]. Ji et al. [111] is one of the early efforts on using computer capabilities for 3D modeling of box girder bridges and stated that this approach simplifies and accelerates the geometric design phase while increasing the accuracy. Markiz and Jrade [112] used BrIM capabilities to implement a fuzzy logic algorithm for the design of concrete bridges to enhance the total cost of the bridge and facilitate interoperability. Obergriesser and Borrmann [113] presented a framework called infrastructural information delivery manual (IDM) which helps in better collaboration in process of design and analysis of geo-mechanical infrastructure and enhances workflow and data exchange. Kim et al. [86] used object-oriented 3D modeling for highway alignment and calculation of cut and fill portions. Huang et al. [109] used BrIM capabilities for design and alignment of railway tracks. Lee et al. [114] used BIM for design of railway bridges.

BIM capabilities in project visual scheduling (4D) and automatic and detailed cost estimations (5D) made a revolution in building process from the design stage. By application of BIM for infrastructure design, management of the project in scheduling and procurement has been enhanced and resource waste has been reduced [39, 69, 71].

Level of development (LOD) and level of information (LOI) are the most important criteria in design phase that can significantly influence the project delivery and its quality [115]. LOD defines the expected level of precision in representation of different elements of a 3D model of building and infrastructure [61]. LOD could be simply described as a standard of communication and statement of requirements between owners, designers, and contractors [63, 116]. Application of LOD in infrastructure projects is different than in buildings. In buildings, LOD is usually focused on the interior specifications, but in infrastructure projects, it focuses on exterior specification including geometric details and semantic information [10, 78], which helps in better understanding of dependencies between geometric elements [100]. Sankaran et al. [63] identified LOD as a major challenge in the highways and infrastructure detailed design phase.

5.3. Project planning and scheduling

After project owners reach to a common consent on the design of the project, work breakdown structure (WBS) needs to be produced to start planning for the construction phase of the project and identify the required resources, and the required amount of budget. The following subsections discuss the various aspects of project planning and scheduling in greater detail.

5.3.1. Sequencing

BIM can help in sequencing construction work to organize crews, avoid clashes, and increase productivity in construction phase. Mawlana et al. [68] proposed a methodology for optimal sequencing and phasing of construction/re-construction of elevated highways that prevents spatiotemporal clashes. Abdelwahab [71] applied BIM in two road design processes and validated the sequence of construction tasks to reduce changes and their associated risks for the projects.

5.3.2. Resource management

Low efficiency and resource waste are serious problems in traditional construction systems [110], and this deficiency gets more crucial when the size of the project increases. BIM can increase productivity [26] and help the workflow by increasing the efficiency and preventing waste of time and resources during construction [69]. Due to the limitations of using resources in bridge construction, scheduling for their optimum use as well as preventing waste is a priority. Zhou and Wang [70] simulated the construction process of a bridge to find the resource needs, plan for raw materials requirements, and reduce waste of resources, based on the needs of the project according to its timeline. Li et al. [69] assessed relationships among plant, equipment resources, and temporary platforms with the use of Virtual Prototyping Simulations (VPS). Li et al. [69] also utilized this technology for assessment of different scenarios and alternatives in the planning phase, aiming to help planners attain optimal plans for bridge construction projects.

5.3.3. Scheduling

BIM has proved to help in the optimization of project scheduling through 4D visualization, where many researchers confirmed its efficiency compared to old manual and semi-manual methods [23, 68, 70, 71, 95, 117]. Visual scheduling of projects can help in identifying the concurrent tasks that could cause a conflict or clash during the construction phase, and also helps in traffic scheduling and management during the construction of infrastructure [95]. Since 4D scheduling helps in efficient resource management to prevent waste, Zhou and Wang [70] have integrated construction schedule and resource management in a 4D environment to be applied on a BrIM model for bridge construction projects. The proposed methodology for dynamic 4D modeling of bridge construction process helped in better management of the project, as well as enhancement of resource consumption. Liu et al. [102] applied 4D visual scheduling methods for thorough study of a bridge construction project and could illustrate the efficiency of BIM in comprehensive scheduling of mega-complex bridge construction projects. Application of BIM is not just limited to visual representation of work schedule and resource requirements. Different project management methods could be applied and evaluated through the 4D environment capabilities of BIM. Marzouk et al. [103] developed integrated project delivery (IPD) guidelines in a 4D BrIM environment to illustrate the benefits of this shift in comparison with traditional design and delivery methods. Marzouk and Hisham [97] then combined earned value management (EVM) methods and BrIM capabilities in 4D environment to help in increasing the efficiency of project status reports by providing more precise information about budget and status of bridge construction project at any specific date.

5.3.4. Cost estimation

After clearing the work sequence and its scheduling, it is possible to perform the cost estimation through the time line of the project. Construction of bridges requires a high load of work with the considerable amount of expenditure [70]. Construction cost is one of the most important criteria in the construction of transportation infrastructure, and poor planning can threaten the success of the project [86]. Due to the need for large investment and limited amount of budget, constructing bridge and road infrastructure requires effective techniques in resource management and process scheduling [70, 118]. BIM can help in preparation of more precise quantity take-offs (QTO) for estimating the amount and cost of excavation and filling in road and bridge construction [119, 120]. Accurate cost estimation in these projects can help in effective budgeting and prevent delays and confusions significantly. Cost estimation process could be more accurate with BrIM functionalities while providing great potentials for further analysis in a shorter time [69, 96]. The information could be used for cost and time management in approximate and detailed scale [97]. While the QTO feature can greatly help in infrastructure projects, the level of its application is a variable of local market budgeting system, proper pushing strategies, supportive environment, and existence of reliable cost database and compatible software [120]. Assessment and comparison of different alternatives for construction of roads, bridges, and other infrastructure is easily possible with BIM. Kim et al. [86] evaluated three alternatives for construction of a road by comparing the time and cost of each alternative and could suggest the most cost-effective alternative with higher level of precision and confidence.

5.4. Construction

While enhancing the workflow, 3D visualization of the BIM model can help in the construction phase of highway bridges to increase collaboration and communication [11, 36, 45, 95, 117, 121–123]. Application of BIM in design of infrastructure and bridges helps in review and optimization of constructability of the project, which helps in reducing the errors and omissions and conflicts, while increasing the quality and smoothening the construction process [102]. Mawlana et al. [68] described how BrIM could help in re-construction of a complex elevated highway to avoid spatiotemporal clashes between demolition of old section and erection of new section, while maintaining the safety of the passing traffic. Virtual construction of infrastructure helps designers to find and resolve clashes in the design phase, which has had a huge impact during the actual construction of the facility by preventing re-work and time and cost over-runs [10]. It also shortens the learning time of construction engineers and crew [118]. Using BIM during construction of infrastructure and bridges can reduce the number of requests for information (RFIs) and change orders (COs) [124]. BIM can help in producing detailed bill of materials [118] and improve the financial performance during the construction phase [103]. Fanning et al. [124] stated that using BIM for construction of two bridges in Denver could approximately save 5–9% of construction costs. Monitoring of construction with BIM can help in prevention of contract disputes during the construction [64]. As the design and construction documents are linked in the BIM model, evaluation of alternatives and change management is easier during construction [124]. BIM can help in organization of massive and repeating activities in mega infrastructure projects [117]. Using BIM can be a significant help in construction of bridges. Parametric modeling of bridges can improve the quality of design and prevent unnecessary and duplicate information, which benefits construction, erection, and fabrication crew, as well as designers and owners [125]. Matsumura et al. [126] reported that application of BIM in construction of a bridge in Tokyo-Gaikan expressway in Japan could improve the reliability of construction process, enhance the understanding of structural complexity of the project, and help the workflow. Matsumura et al. [126] also indicated that development of level of detail (LOD), and utilization and transfer of the processed data after the project completion were their crucial issues. Application of BIM for construction of infrastructure is receiving more attention and support from governments [127]. In Finland, “5-D Bridge Consortium” focused on research and development (R&D) of methods for digital construction of bridges and tries to establish a national standard for it [128, 129]. The South Korean government supported studies for virtual construction of infrastructure [29, 98]. China [130], Germany [131], the United Kingdom [132], and Czech Republic [45] have recently initiated the use of BIM for transportation infrastructure on pilot projects.

5.5. Maintenance

Transportation infrastructure needs constant monitoring to remain at the acceptable operational level. Currently, a considerable number of bridges need repair and maintenance, and due to their number, there is a crucial need for a rapid system to evaluate and analyze their health condition [76, 133]. Deterioration is a major concern for bridges. Highway bridges can be threatened by deterioration and deflection in their service life, which may affect their performance and safety [34, 134]. Bridge aging is also another growing problem for U.S. Department of Transportation (US DOT) [14]. Aging affects the reliability, safety, and serviceability of these infrastructures and upturns concerns for efficient methods of maintenance [27]. As the information could be collected and stored through the life cycle of the bridge in the BrIM models, it can effectively help in the maintenance of the bridge later and keep the ideal operation while avoiding any need for major repairs, and enhancing bridge safety as well [33, 35, 36, 103]. Eventually, BrIM could assist in reducing the maintenance costs, while improving the quality and efficiency [59].

5.6. Structural health monitoring (SHM)

Recent sensing technologies and sensors also help designers for automated receival of infrastructure data. Responses received from sensors are used to detect any anomalies or deterioration issues that can later cause damage to the structure. This process is known as Structural Health Monitoring (SHM), which can help decision makers to diagnose and make early plans and actions about any possible damages in bridge structure [27, 28, 50, 54, 59, 60, 134]. Structural Health Monitoring is very important in the reliable operation of transportation infrastructure. Specifically, BrIM can help in SHM of bridges through registering the received data from sensors and automate the data capturing process to help the industry navigate away from tedious person-based activities into automated trends [51, 56, 134, 135]. Data analysis in the 3D environment can help conduct various structural tests and visualize structural responses that help in better understanding of the structural behavior of bridges [50]. Elnabwy et al. [53] used Real Time Kinematic-Global Positioning System (RTK-GPS) to monitor the oscillation and deformation of steel-deck bridge. McGuire et al. [44] used BIM software to analyze the inspection data and introduced a methodology for assessment and tracking of the structural condition of bridges. Catbas et al. [27] combined SHM and probabilistic structural analysis to evaluate how sensor-based structural monitoring can minimize uncertainties that are associated with parameters that are hard to be quantified in bridge modeling. Jeong et al. [60] developed a framework to integrate BrIM and SHM for enhanced monitoring of bridges by using OpenBrIM standards to receive, store, and analyze the data which have been captured through sensors.

5.7. As-built data registration and documentation

BIM can help in detailed geometric design [31], as well as organization and integration of information and as-built data [5, 33, 35]. BIM can produce engineering documents, such as bridge inspection and assessment reports, hydraulic calculation records, and geological survey reports [136]. Integration of capturing technologies such as laser scanning with BIM can help in the as-built documentation of current structures [76], as well as underground facilities [79] and enhance monitoring of their operation. It could also be used for documentation of old buildings and heritages. Minehane et al. [25] used 3D scanning and BrIM for documentation of a decommissioned historical viaduct.

5.8. Renovation and rehabilitation

Renovation of transportation infrastructure is usually expensive, while the available budget for their rehabilitation is limited [137]. Utilization of cost effective methods are imperative to improvement of the failing transportation infrastructure. Petzek et al. [138] used BIM for renovation of two railway bridges and concluded that refurbishing could be more economical than re-building this facility. BIM can help in development of efficient strategies for rehabilitation of bridges by collecting the required information about the specifications of the deterioration and load-rating of different elements through the time [44]. BIM can help in evaluation of infrastructure renovation by enhancing the structural analysis for evaluation of new loads and post-rehabilitation analysis [133], which ultimately increases the reliability of rehabilitation strategies.

5.9. Behavior modeling and prediction

The data collected throughout the life cycle of a structure through a BIM model can be used for behavior modeling and prediction. These data could have been acquired from inspection visits, sensors, or by calculations using historical condition rating methods. Stored data can later be used for developing methodologies to construct the deterioration model of the structure [134]. Having robust data frame and database, prediction of future behavior and needs of infrastructure is possible and could be a decisive factor in maintenance and management process. Okasha and Frangopol [34] developed a detailed and integrated computational framework to help in better management of highway bridges through their life cycle. Elnabwy et al. [53] used the outputs of RTK-GPS to model the behavior and deformation of steel-deck bridge. Shim et al. [26] proposed a data schema for better interoperability of design and construction processes in bridges via BIM. Marzouk and Hisham [41] designed a framework to integrate BIM and advanced analysis methods to analyze the condition of bridge structures and present it as an enhanced type of bridge management systems (BMS). Development of these frameworks can generally help in: 1) analysis of system performance and component interaction; 2) evaluation and update of life-cycle performance; 3) optimization of maintenance plans; and 4) ability for instant update and analysis of information upon receiving of new data [34].

6. Transportation infrastructure

Transportation infrastructure have a key role in social and economic development of countries and applying new methods for improving their design and operation is to be expected. Considering the capabilities, BIM could be a great method for increasing the quality of infrastructure through their life cycle. Evaluation of industrial case studies shows that among industrial projects, BIM for civil projects has mostly been implemented in energy infrastructure projects and tunnels were the least [10]. A recent study claims an opposite finding. According to the responds from the sample companies who have been asked across the UK, Germany, France, and the US, majority of them are using BIM for tunnels (86%), bridges (79%), rail/mass transit (77%), and roads (76%) [24]. Table 8 lists the publications of BIM applied to various transportation structures, and the following sections have more focused details.

6.1. Bridges

BIM for bridges is widely becoming a competent tool in bridge construction and engineering industry [109]. As stated before, BIM capabilities have been applied for the design of bridges, known as Bridge Information Modeling (BrIM), which could be applied through their whole life cycle [20, 68, 97, 111, 139]. BrIM is not just a geometrical representation of bridges, but is an intelligent virtual 3D model of the bridge as it contains all information about every component for its whole life cycle [34, 39, 140]. It improves the quality and accuracy of drawings, as well as constructability, and enhances collaborations [26, 68]. BrIM can also be used for advanced analysis including

Table 8
Publications of BIM for transportation infrastructure based on the structure.

Structure	Publication
General infrastructure	[3, 10, 11, 18, 42, 45, 57, 63, 66, 67, 72, 80, 86, 90–92, 100, 101, 113, 124, 127, 131, 148, 157, 162, 197, 227, 229, 241, 248]
Transportation infrastructure	[3, 5, 8, 23, 30, 45, 57, 64, 67, 72, 73, 78–80, 85, 87, 92, 101, 106, 107, 116, 120, 124, 127, 130, 132, 148, 153, 157, 162, 226, 227, 238, 241]
Airport	[10, 67, 161]
Bridge	[10, 11, 19–21, 25–29, 31, 33–37, 39–44, 48–56, 58–61, 63, 65, 68–70, 76, 83, 84, 88, 89, 93, 94, 96, 97, 99, 101, 103, 104, 108, 111, 112, 114, 116–119, 121, 124–126, 128, 129, 133–143, 148, 150, 152, 196, 229–232, 239]
Geotech and earthwork	[64, 67, 75, 79, 86, 106, 113, 120, 234, 236]
Port and harbor	[10, 46, 162, 163]
Rail	[10, 30, 32, 45, 54, 72, 82, 109, 114, 137, 138, 149–153]
Road and highway	[4, 5, 8, 10, 11, 20, 23, 34, 40, 47, 54, 55, 63, 68–72, 77, 79, 80, 86, 92, 95, 97, 99, 100, 113, 116, 117, 120, 126, 132, 137, 144, 146, 148, 149, 152, 199, 226, 227, 229]
Subways	[30, 32, 57, 73, 78, 81, 107, 147, 154–156, 162, 241]
Transit hub	[32, 45, 57, 110, 147, 154–156, 162, 241]
Tunnel	[10, 38, 81, 87, 100, 150, 152, 153, 157–160, 229, 234, 236]

integration, surveying, and machine control [128].

6.1.1. Bridge inspection

There are more than 600,000 bridges across the United States that need to be inspected biennially [44]. Manual inspection and data collection is not a completely reliable method as it highly depends on humans, which may be inexperienced, incomplete, or subjective [55, 141]. Sometimes data capturing could be difficult, risky, dangerous, and prone to errors, such as in the case of where post-disaster bridge inspections are needed. Hence, there is a need for an alternative way of capturing data, where the role of human is minimized. Inspection data could be captured through strain and displacement sensors [42, 50, 51, 56, 134, 135], wireless sensors [52], robotic technologies [141], RFID tags [142], Unmanned Aerial Systems (UAS), [47, 48], or unmanned marine vehicles (UMV) [49]. Laser scanning is another tool for automatic inspection of bridges to construct a point-cloud model of the bridge [65, 76, 143]. This technology has recently received much attention. The data that have been acquired through laser scanning can be stored in BrIM model for further analysis in order to continually monitor and detect any defect or imprecision in elements of the bridge [76].

BIM could be used as a reliable database for storing the inspection data. Tanaka et al. [88] utilized BrIM and industry foundation classes (IFC) to propose an information model for supporting enhanced inspection of bridges. Al-Shalabi et al. [43] used a BrIM model for practicing bridge inspection and validated their new methodology through using cloud-based BrIM models for inspection of two bridges in Iowa. Their findings indicate that, despite many challenges in BrIM implementation for inspection purposes, many of the industry professional and DOT authorities believe that BrIM can significantly help the current inspection process while reducing its associated costs and decrease the maintenance and repair operation costs. DiBernardo [36] reviewed the current process of data collection in bridge inspection and presented a framework for storing, organizing, and analyzing the data with BIM capabilities, aiming to illustrate the potentials of BrIM for existing bridges.

6.1.2. Bridge management systems (BMS)

Bridges need an efficient management system to maintain their operability. Bridge management is a multi-step effort which requires the cooperation of different stakeholders including owners, structural designers, fabricators and repair technicians [36]. Coordination of work among different teams and organizations in such large-scale projects is so important, while is a complicated process [11, 137]. A bridge management systems (BMS) offers a systematic approach toward management and maintenance of bridges network that organizes all the management and maintenance activities. BMS can effectively help to reduce the major repairs through effective preventive management. By using this system, decision makers can select between different alternatives from interim repairs to major construction or replacement of the bridge. It offers an optimized solution for maintenance decision makers to design a set of activities that increase the benefits while decreases redundant costs [14, 35]. Sung et al. [89] developed a framework for recording the data during the inspection and evaluation of bridges in Taiwan that can significantly help in their management for resiliency in post-disaster conditions.

Data are very important elements in BMS [34, 35], and there are distinct types of data sources in bridge management. Currently, the use of these data is limited and isolated. BrIM can effectively help in integration of this data in BMS [11]. BrIM can help in sharing and integrating the data for better management of bridge, which also helps in operation, maintenance, and safety [33, 34, 39, 94].

6.2. Roads and highways

BIM can help in design, planning, and maintenance of roads and highways [20, 53, 62, 74, 142, 144–146]. Okasha and Frangopol [34] used BIM for development of a platform that helps in management of highway bridges during their life cycle. BIM can help in planning and detailing as well as sequencing and managing the workflow [86]. Highway design follows a set of rules and codes which needs to be repeated along the entire road. These repeating tasks could be automated by using BIM capabilities. Mawlana et al., Liapi, and Patt [68,95,145] used 4D information modeling techniques for optimization of sequencing and scheduling of highway construction process that could significantly help in optimization of resource usage and prevention of waste. Chen and Shirole [20] used 3D bridge information modeling for accelerating the design process and expedite the project delivery. Kim et al. [86] developed an object-oriented visual model to determine the optimum alternative when designing highway alignment. This process is tedious and time-consuming in traditional designing approach, but BIM helped them in saving a considerable amount of time in the design phase and prevent extra costs to project. They later developed their research into integration of BIM and GIS for faster and more precise calculation of cut and fill operations [147]. Sankaran et al. [148] stated that while BIM can help in addressing design needs, asset management, and work flow, lack of legal resources and clarities is still a hurdle in development of BIM in public projects. They declared that development of technical and managerial skills is an inevitable step for adoption of BIM in design and construction of highways.

6.3. Railways

BIM can be used for railway bridges and track alignment in both design and operation [109, 149, 150]. Huang et al. [109] assessed the help of BIM in handling change orders received for railway track alignment designs that could greatly save time and effort by preventing tedious and time-consuming repeating tasks. BIM can help in more

Table 9
Data formats and schemas for infrastructure.

Categories	Data covered by the schemas	Name [reference]	Last updated	Base schema
Transportation	Surface transportation, government entities	NIEM [223]	2017	XML
	Survey/roadway design, transportation construction/materials, highway bridge structures, and transportation safety	TransXML [172]	2007	XML
	Traffic control	NTCIP [176]	2016	N/A
		TCIP [177]	2016	XML
		TMDD [178]	2016	N/A
	Traffic modeling	TMML [179]	2014	XML
		TrafficXML [180]	2004	XML
	Traffic signal	Host hardware environment [181]	2017	N/A
	Weather forecast, natural disasters, geographical regions, etc.	RWML [182]	2009	XML
Building	Building and construction industry data	IFC [183]	2016	STEP, XML
	Structural steel project data	CIS/2 [184]	2003	STEP
	Structural steel procurement process	steelXML [185, 186]	2015	XML
	Structural steel elements (e.g. section, plates)	SDNF [187]	2013	ASCII
	Structural analysis and design	ISM [188, 189]	2012	XML
	Building project data (proposals, submittals, request for information, etc.)	BCF [190, 191]	2017	XML
		agcXML [192]	2014	XML
	Building project handover and asset management	COBie [175]	2013	XLS
Bridge	Steel bridge construction and fabrication	SBCDM [193]	2010	XML
	Bridge alignment	IFC-bridge [194, 230–233]	2013	STEP, XML
	Bridge design to construction	IFC bridge design to construction [169]	2016	STEP, XML
	Bridge life-cycle	OpenBrIM [168]	2017	XML
Civil	Roadway	IFC-alignment [194]	2015	STEP, XML
		IFC-road [226–228]	2015	STEP, XML
	Track and railway	IFC-railway [109, 114, 151, 152]	2011	STEP, XML
	Tunnel	IFC-tunnel [101, 157, 158, 160, 234, 235]	2016	STEP, XML
Geospatial	Civil and survey	LandXML [198]	2014	XML
	Spatial and non-spatial geography	GeoXACML [200]	2011	XML
		GML [201]	2012	XML
		GeoSciML [202]	2017	XML
	Geographic annotation and visualization	KML [203]	2015	XML
	Virtual 3D city	CityGML [204]	2012	XML
	Water observation	WaterML [205]	2014	XML
		GroundWaterML [206]	2017	XML
	Indoor space	IndoorGML [207]	2018	XML
Geotechnics	Geotechnical and geoenvironmental information (e.g. borehole, soil testing, construction site information)	DIGGS [208–210]	2012	XML
		Geotech-XML [211]	2002	XML
Graph and image	Exchanging data among computer-aided design (CAD) systems	DXF [212]	2007	ASCII
		IGES [213]	1996	ASCII
		STEP [214]	2016	STEP
	3D (Lidar) point cloud	LASer [215]	2013	ASCII
		ASTM E57 [216]	2018	N/A
	3D scenes and models	FBX [217]	2018	ASCII
	Virtual reality	VRML and X3D [218]	2015	XML
	Augmented reality	ARML [219]	2015	XML
Safety	Transportation accidents	CRML [220]	Inactive	XML
	General safety issues (vehicle registration, injury surveillance, emergency management system)	FARS [221]	2015	Binary and CSV
Recreation	Recreation facilities across the country	RecML and AIRS XML [222]	2016	XML

accurate cost estimations, which will prevent project losses in bridge projects [23]. Aroch et al. [54] used BrIM for modeling and storing information about structural and dynamic tests on a railway bridge. Cheng et al. [10] stated that the lack of research on evaluation of environmental impacts of railways on their neighborhood with BIM is still a gap. Lee et al., Gao et al., and Seo et al. [114, 151, 152] developed IFC properties to address the BIM modeling needs of railway bridges. Ding et al. [32] evaluated the BIM capabilities for nD modeling of city rail transit to help the management process during their construction phase. Shirole et al. [82] reviewed the benefits of combination of GIS and BIM capabilities for railways that can help in decision support and integrity in the construction phase. Zak and Macadam [45] used BIM for modeling and modernization of a railway station in Czech Republic. Jubierre and Borrmann [153] evaluated a rule-based BIM modeling approach for modeling of a suburban railway tunnel in Munich, Germany, and their findings proved that this method can be applied for detailed design and modification of railroad tunnels, while flexibility and consistency of the model has been retained. Marzouk and Abdelaty [154–156] did series of comprehensive research on application of BIM for subway infrastructure and environmental monitoring.

6.4. Tunnels

Recently, BIM has been used in to improve the use of data for better design and management of shield tunnels. Due to the high amount of information in shield tunnel design, construction, and maintenance, BIM could be employed for storing and managing these data [18, 157–159]. To address the need for more consistent modeling of shield tunnels and their elements, Borrmann and Jubierre [160] developed a multi-scale product model for shield tunnels that conducts the required relation between semantic and geometric details of tunnel that eventually helps the exchange of data.

6.5. Airport

Digital modeling and simulation of airports can help in better design and operation of them while is in correspondence with passenger needs and behavior. Considering the complexity of airport terminals, BIM-based design of airports can reduce design errors, prevent waste, and save considerable amount of time and money [161]. Design and evaluation of airports with BIM can help in more detailed simulation of building blocks, find conflicting areas and enhance the quality of design to benefits the passengers by reducing their wait time. Using BIM for design and planning of Cathay Pacific terminal in Hong Kong International Airport has helped in better coordination of work during design and construction [162]. Compared to bridges and tunnels, application of BIM for design and planning of airports has still been limited and there is a vast context for developing research in this area [10]. BIM can also help to expand the evaluation of airport design from the terminal building to the surrounding environment and in-depth energy modeling. Development and fusion of BIM-based design software and geospatial modeling software could significantly help in better management of the infrastructure assets. Integration of BIM and GIS on case studies on Denver and Los Angeles airports shows that this integration can help in better spatial management of the infrastructure [67].

6.6. Port and harbor

Similar to airports, research on application of BIM for design, planning and management of ports and harbors has still been very limited. BIM can considerably help in registration of inspection records as well as preparation of efficient maintenance plans. Planning with BIM can help in monitoring and controlling of aging and structural corrosion in ports and harbors and help in assessment of different repair alternatives [46]. Using BIM can also help in planning of ports and harbors for better operation, so they could response to the demand dynamically and increase their efficiency. Beetz et al. [163] developed approaches for the integration and interoperability for spatial data for the construction of quay walls in harbors.

7. Formats, schemas, and applications

7.1. Schemas

Various data formats and schemas used for interoperability have been developed, proposed, and utilized for infrastructure related industries (Table 9). A data format is a specific protocol of how the data is stored and retrieved, and a schema is how a computer language or database is organized and structured. Ji. et al. [101] stated that an open source and neutral data format could be the best approach for enhancing the data exchange process. There have been a few research projects to develop a neutral file format for bridge information models [164–169]. Several research projects [170, 171] reviewed formats and schemas relating to the AECO industry and have categorized them in nine categories: transportation, building, bridge, civil, geospatial, geotechnical, graph and image, safety, and recreation facility. Other projects surveyed existing schemas and methods for the improvement and management of transportation information [172–174]. The majority of the formats and schemas are based on a markup language, such as the eXtensible Markup Language (XML). Other formats and schemas are based on standard information exchanges, such as EXPRESS language, which is the formal language of Standard for the Exchange of Product model (STEP), and the American Standard Code for Information Interchange (ASCII) data. Excel spreadsheet (XLS) can be used, such as in the Construction Operations Building Information Exchange (COBie) [175]. A coarse-grained overview of these data formats and schemas are presented below. Table 9 displays the latest updates to the data formats and schemas, which suggest that some of the recent ones are currently utilized, while some are not. For example, TransXML has not gained as much traction as IFC, and CRML, which was developed for transportation safety, is no longer active.

TransXML is an umbrella of XML schemas for transportation data. It covers four major business areas: survey/roadway design, transportation construction/materials, highway bridge structures, and transportation safety. Other transportation-related data formats and schemas were developed or utilized for traffic control [176–178], traffic modeling [179, 180], traffic signal [181], and miscellaneous traffic information including weather forecast, natural disasters, geographical regions [182].

Industry Foundation Classes (IFC) [183] are used for exchanging building and construction industry data. It is considered as the de-facto data exchange standard in building industry. IFC provides three data formats: 1) an IFC data file using the STEP physical file structure; 2) an IFC data file using the XML document structure; and 3) a compressed IFC data file. Other building-related data formats and schemas cover structural steel project data [184], structural steel procurement process [185, 186], structural steel elements (section, plates, etc.) [187], structural analysis and design [188, 189], building project data (proposals, submittals, request for information, etc.) [190–192], and building project handover and asset management [175].

To facilitate BrIM, building-related data schemas such as IFC were borrowed to exchange bridge project data. However, because IFC was intentionally designed for buildings and was unable to define bridge related geometry in early versions, bridge-based data schemas were developed for steel bridge construction and fabrication [193] and bridge life-cycle [168]. The latter was developed based on object-oriented programming concept and parametric modeling. It is able to describe bridge-specific geometry such as alignment and camber. IFC were extended to describe data in civil fields, such as roadway [169, 194], bridge [169, 195, 196], railway [109], and tunnel [158, 160]. Kang [197] proposed a BIM-integrated object query method using LandXML and IFC to obtain required objects from the BIM model.

Geospatial-related data schemas were developed to cover data for civil and survey [198, 199], spatial and non-spatial geography [200–202], geographic annotation and visualization [203], virtual 3D city [204], water observation [205, 206], and indoor space [207]. Geotechnical-related data schemas were developed for exchanging geotechnical and geoenvironmental information including soil testing, laboratory, and construction site information [208–211]. Graph and image-related data formats were developed for exchanging data among computer-aided design (CAD) systems [212–214], data for 3D (Lidar) point cloud [215, 216], and data for 3D scenes and models [217–219]. Safety-related data schemas were developed for exchanging data used for transportation accidents [220] and fatal traffic crashes [221]. Recreation-related data schema was developed for exchanging data about recreation facilities across the country [222].

With all the variety and substantial increase of heterogeneous data and models, it is becoming more apparent for the need of standard information models to establish standardized terms and definitions [15]. Originally established to support U.S. government and justice entities, the National Information Exchange Model (NIEM) has expanded to include a Surface Transportation domain to support information sharing among transportation regulators, operators, and stakeholders, in addition to law enforcement, courts, health, and emergency management [223]. Although it is not as detailed or refined as IFC, NIEM has a great potential to serve as a high-level information model to serve as central data dictionary that other schemas can utilize, especially since it relates to government related entities, domains, and procedures. This is important since a vast majority of transportation projects are governmental owned and operated.

7.2. Efforts to implement other infrastructure into IFC

Although initially intended for buildings and vertical construction, there have been various international efforts by buildingSMART International (bSI) groups to use and expand IFC for other infrastructure models (bridges, roads, tunnels etc.). In order to increase the scope to include infrastructure development, buildingSMART created the Infrastructure Room in 2010 to serve as the center of various international groups implementing IFC for infrastructure. Since then, various projects were undertaken, and the most recent progress is summarized below. More information about the current progress of the projects can be found at the homepage of the buildingSMART International User Group and the bSI Infrastructure Room [224]. Amann et al. [225] developed IFC4 standard guidelines to store alignment data so the model could be used as a reliable data exchange standard for modeling infrastructure, including roads, bridges and tunnels. The following sections discuss the major IFC expansion projects for transportation infrastructure.

7.2.1. IFC alignment

In order for roads and bridges to be modeled, one critical piece of information needed is the alignment. However, IFC lacked an entity to represent alignment, and thus a major "IFC Alignment" initiative was undertaken since without the entity modeling infrastructure that requires it would be nearly impossible. The main achievements of the IFC alignment 1.0 are as follows [225]:

- Ability to exchange alignment information from planning to design, to construction, and finally to asset management phase.
- Ability to link alignment information to other project information such as cross sections and full 3D geometry of construction elements (realized by upcoming IFC-Bridge and IFC-Road projects).
- Ability to query alignment information providing data such as linear referencing for positioning.
- Ability to allow open data access of alignment information from asset management databases.
- Ability to map IFC alignment models to InfraGML (developed by OGC), and LandXML (latest InfraBIM version from buildingSMART Finland).

This project has been the baseline for the other ongoing projects, such as IFC-Road and IFC-Bridge, since it provides the data model for 2D and 3D alignment information for spatial location of infrastructure assets. As of July 2015, the IFC alignment 1.0 has been accepted as a buildingSMART Final Standard. Research investigating IFC alignment include [149, 225–227] Additionally, other research projects are focusing on alignment for BIM, but is not using IFC as the schema [109, 150].

7.2.2. IFC-road

In 2015, another IFC-Road proposal was submitted to bSI for the "Development of International IFC model extensions and data exchange standards for planning, design, cost estimation, scheduling and construction of roads and associated structures and earthworks" [228]. Lee and Kim [229] discussed the limitation of IFC regarding infrastructure product models and proposes extensions to include road. Since IFC has not been suitable for sharing product data models of infrastructure construction (e.g. roads, tunnels, and bridges), Amann et al. [227] presented an extension to help improved the sharing capabilities. As part of the "Infrastructure Alignment & Spatial Reference System" (P6), Amann et al. [227] demonstrated how IFC can be extended for use in road design applications by presenting IFC Alignment model and future expectation to develop *IfcRoadJunction*. Huang and Wu [226] further expanded IFC alignment to include an automatic rule checker that can assist planners with checking alignment design rules and an export module for 2D/3D roadway alignment geometry information.

7.2.3. IFC-bridge

The French chapter of bSI has been leading the efforts to produce the first IFC-Bridge extension [230]. IFC-bridge was further expanded to include parametric geometry [231, 232]. However, many issues that have been identified that impede the adoption of IFC-Bridge into the IFC schema. Therefore, the European research project V-Con has now taken over this work, and is collaborating with an additional French working group, MINnD Concepts [233].

7.2.4. IFC-tunnel

Yabuki [234] is one of the earliest published research projects to develop a product model for tunnels by expanding IFC to create IFC-Shield Tunnel. Other research followed suit to further expand IFC for tunnels [78, 81, 157, 160, 229]. Yabuki et al. [158] developed an IFC-based product model for shield tunnels and applied it to an ongoing shield tunnel project in Tokyo. They developed a product model based on a standard IFC to produce IFC-ShieldTunnel. The developed conceptual model had objects for representing different members and components of the tunnel, as well as geology information and organization of layers. Hegemann et al. [235] developed an IFC product model for a tunnel boring machine. Recently, a tunnel information modelling framework is presented in order to support management and provide simulations of mechanized tunneling via a tunnel boring machine [236].

7.2.5. IFC-railway

As an initial stage study to effectively apply Building Information Modeling (BIM) to railway infrastructure, Lee et al. [114] proposed a measures and method to extend IFC for railways. Gao et al. [151] introduced IFC-Railway, a data model which aims to achieve the cross-platform and cross-discipline data interoperability in railways. Seo et al. [152] presented an information model to expand IFC-Railway to include railways, including linear, orbital, roadbed, bridge, and tunnel railways

7.2.6. IFC Infra overall architecture

With the overlapping efforts of IFC development proposing separate solutions (e.g. IFC-Bridge, IFC-Road, etc.), there is a need to align the efforts. Therefore, in order to harmonize the diverse proposals and provide a sound foundation, a plan was proposed to create a common architecture, called "IFC Infra Integration Framework." The overview of the various infrastructure components can be seen in Fig. 3. Currently in the proposal phase, the objectives of the framework aim to achieve [237]:

- Analysis of the currently available drafts of the IFC infrastructure extension initiatives with respect to joint/overlapping areas project, including
  - The IFC-Road project by the Korean chapter
  - The IFC-Rail project by the Chinese chapter
  - The IFC-Bridge project led by the French chapter
- Definition of jointly used data structures as a common basis, including
- Provision of modelling guidelines for bSI Infrastructure extension projects
- Ability to map common infrastructure information between InfraGML (developed by OGC) and enhanced version of IFC
- A foundation for standardized data exchange during the entire life cycle, including requirements, design, construction, operation, maintenance and destruction/recycling.

8. Limitations, challenges, and recommendations

While BIM can help in better management of data, there are some obstacles ahead integrating into transportation infrastructure (Table 10). Differences in scale is a considerable problem in modeling infrastructure (e.g. long span steel bridge). Scales could vary from centimeters to kilometers, so they could hardly be modeled in an individual model [107, 160]. Hence, they should be modeled in separate models and linked together. Borrmann and Jubierre [160] introduced a novel methodology for the design of a multi-scale product model that conducts consistent relations between semantics and geometrical

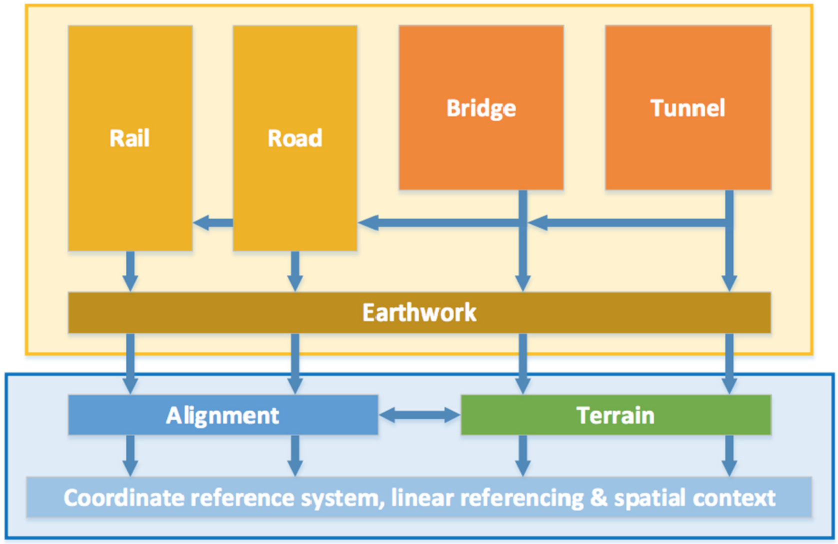


Fig. 3. buildingSMART International overview of different infrastructure components and their dependencies [224].

Table 10
Common challenges and barriers for implementing BIM for transportation infrastructure.

Challenge	Publication
BIM is expensive	[8, 55, 66, 106, 132]
BIM limitations	[5, 44, 55, 57, 58, 61, 80, 93, 100, 106, 107, 124, 132, 148, 153, 238]
Complex project	[25, 71, 112, 124, 126, 153]
Damaging portable electronic devices	[43]
Data loss	[21, 101, 136, 239]
Data quality	[21, 65]
IFC limitations	[29, 78, 83, 101, 104, 105, 113, 136, 151, 152, 226, 227, 231]
Implementation	[18, 38, 43, 63, 83, 85, 103, 120, 124, 126]
Institutional barriers	[8, 11, 43, 63, 72, 85, 238]
Integration	[11, 38, 40, 63, 126, 135]
Lack of knowledge	[8, 55, 63, 72, 75, 85, 141, 153, 238]
Lack of resources	[43, 55, 63, 75, 141]
Lack of standards	[3, 8, 82, 104, 120, 124, 132, 238]
Large model or too much data	[32, 60, 86, 132, 147, 153, 236]
Legal fears	[72, 75]
Manual effort	[42, 44, 55, 107]
Model or program type	[75, 101, 120]
Other challenge	[5, 18, 20, 23, 26–28, 31, 34, 35, 37, 39, 40, 46–52, 54–57, 63, 69, 76–78, 81, 82, 84, 87, 89–91, 97, 108, 110, 114, 115, 117, 119, 128, 129, 131, 133, 136–138, 140, 143, 146, 148–150, 152, 157–160, 196, 199, 229, 241, 248]
Resistance to change	[72]
Scale	[69, 160]

entities of the model.

As BIM and IFC were not originally intended for non-buildings, there will be challenges encountered when applying BIM to transportation infrastructure. Additionally, there are challenges still faced within the building industry that will be inherent when adopting the technologies for the transportation industry. These challenges are categorized into five sets of challenges: technical, process-related, mindset-related, legal, and return on investment (ROI).

8.1. Technical challenges

There are many technical and technology-related challenges that prevent full adoption of BIM. Some of these technical challenges include the differences and lack of fully adopted BIM work flow for infrastructure [23], differences in scale and LOD of the infrastructure model compared to normal BIM model for buildings [100], lack of interoperability and information sharing among software and technology [104], and the requirement for higher performance hardware to handle large volumes of data [31]. Overcoming the technical challenges can encourage the implementation and utilization of other advanced technologies with BIM for enhancement of infrastructure development [9]. Al-Shalabi et al. [43] conducted a survey of DOTs about the implementation of BrIM for bridge condition documentation for inspection. The survey discovered that technological implementation is one major challenges that DOTs encountered, which included the expensive initial cost, time required to develop the model, low cell phone signals in remote locations, and issues with the equipment. Liu and Gao [238] conducted a survey of BIM currently utilized in FM field of Urban Railway Transportation industry at the process level. Among the familiar challenges faced with BIM implementation into the transportation industry (lack of knowledge, lack of funding, large files/data etc.), the biggest challenges identified for BIM application in FM practices are the definitions of data requirements, and to identify by whom and when the data should be provided throughout the project life cycle. Moreover, Liu and Gao [238] stated "due to BIM models always undergoes dramatic changes during project stages in terms of variety of versions, level of detail, model purpose, and responsibilities of different parties for integrating various discipline models, the owners face much more challenges when using BIM for FM." Borrmann et al. [78] pointed out that "a challenge to be tackled in the future is the consistent application of the Level of Detail (LoD) concept on nonlinear infrastructure facilities, such as underground." Most of the technology-related challenges will be mitigated by the improvements to the technology over time (updated software, better functionality, improved features, etc.). The challenges around using the technology can be solved with proper training and education. In regard to the well-accepted data exchange schema and interoperability, it is recommended that there is consensus and support around an industry information standard, such as IFC, NIEM, or a hybrid method. For example, terminology and definitions can be defined in a high-level information model (e.g. NIEM) that could be utilized in the model view definitions (MVDs) defined by IFC.

Among all the technical challenges, lack of interoperability is still one of the major challenges faced in the AECO industry, in which a large number of research and government projects are attempting to solve it. Interoperability can be defined as the ability of one system (e.g. software application, workflow, process, ontology, etc.) to work with other systems without any effort on the part of the end user of the system, especially when exchanging information between the systems [15]. Moreover, fully interoperable systems would not contain errors, omissions, or data loss when the information is transferred from application to application. Interoperability of heterogeneous software and platforms is still a significant concern [158]. Data exchange is also an important requirement in the establishment of large infrastructure data models, as they should be exhaustive in representation of semantics as well as geometrics. There are a variety of commercially available software tools for various aspects of modeling and development of structures, for example planning, design, detailing, estimating, fabrication, construction project management, and operations and maintenance. However, the development of various computational tools for supporting the various aspects of a structure were typically addressed in standalone fashion without sufficient regard for complications arising from multiple data sources [83]. These specialized software products are typically "stove-piped," meaning they lack interoperability and information sharing with other software products [84, 171]. Transportation infrastructure projects require frequent communication, and without improved software interoperability these projects can become bogged down with requests for information (RFIs) [104]. Even on the same project, heterogeneous computer platforms cause many problems during transferring and sharing numerous data generated [239].

In 2002, the cost of inadequate interoperability in the AECO industry in the United States, alone, has been estimated at over $15 billion per year [240]. With the increase in software tools and technology, this conservative amount over a decade ago could be substantially higher in today's dollars. Furthermore, the absence of efficient interoperability among 3D modeling solutions substantially refrain users from reaping remarkable benefits [240]. Section 7 previously discussed the various schemas, formats, neutral exchanges, and efforts to achieve interoperability. It is important for academia, industry, and government oversight to continue these efforts to improve interoperability and the exchange of information. It is recommended that there be an industry wide consensus on a standard exchange for BIM for transportation infrastructure, as well as an official or government oversight. Having a unified standard, such as how IFC is for building industry, will alleviate many of the issues stemming from non-interoperable systems. Additionally, as the Gallaher et al.'s [240] study was over a decade ago, there needs to be another study of with an updated cost of inadequate interoperability in the AECO industry, including transportation, to measure the status of the recent developments for interoperability.

8.2. Process-related challenges

Process-related challenges include need of streamlining the business process of existing transportation infrastructure industry after BIM is applied, change of role and responsibility of infrastructure project stakeholders, and update of contract to specify the role and responsibility of stakeholders. Lack of standards, methods and contractual languages for BIM have been a significant challenge [3, 8, 82, 104, 120, 124, 132, 238]. There are many tools, software, and formats that work great standalone; however, utilization and understanding each is time consuming and can potentially lead to errors and disrupt the business process. Therefore, it is recommended that developing and following strict standards and definitions would help streamline the business process, such as outlined in [15].

8.3. Mindset-related challenges

Mindset-related challenges include how to encourage a collaborative approach to delivery infrastructure projects, how to train infrastructure project stakeholders to use BIM related application, and how to address the concerns that applying BIM to infrastructure will result in reduced staffing and labor. Institutional barriers, such as the resistances or lack of resources to change, are also big challenges to the adoption of BIM [8, 11, 43, 63, 72, 85, 238]. Education and training about the technologies and methods is important to help reduce such limitations. Reviewing case studies and outcomes of projects is recommended to help get a better sense of the technologies and methods, as well as increasing trust and confidence.

8.4. Legal challenges

Legal challenges include lack of agreement on the legal clauses about use of digital signatures, stamps, and deliverables, integrity of data during transmission, confidential information, and difficulties in updating insurance policies to cover responsibilities of stakeholders [43, 170, 241]. Gristina et al. [80] discussed legal issues and challenges surrounding the implementation of 3D GIS-based road inventories called Road Cadastre, an Italian road inventory as established by law. For example, one need that Gristina et al. [80] stated is that "the physical model for the Road Cadastre should consist of a network-based, multi-user, client-server system, based around a relational database (whose structure is also defined by the Act and is partially based on a pre-standard version of CEN/TC [241] and a GIS, which allows the representation of the map of the area and the graph of the road network at three different levels of detail (LoD)." To address the legal challenges, top ranked legal and liability issues were specified [242], and key questions that should be considered when drafting design and construction contracts are listed [243]. Based on the issues and questions, actionable items were proposed to update the legal framework (e.g. model ownership, allocation of risk, intellectual property, insurance and traceability) for BIM adoption for US bridge industry [170] and US building industry [6]. The current legal issues surrounding the ownership and liability of the data in the building industry will also be seen in the transportation industry. Future needs to address these issues, such as stating the ownership and liability of the data in contracts [243], are imperative for the smooth adoption of BIM technologies in the transportation industry. One recommendation is the creation of BIM execution plan for each project, which will specifically outline the ownership, rights, and duties of all parties creating and using the data.

8.5. Return on investment (ROI) challenges

Return on Investment (ROI) challenges include increased investments for acquisition of BIM enabled software, acquisition of hardware to operate the software, upgrading the current IT systems, educating engineers, changing current project delivery methods and deliverables, etc. As BIM technologies can be costly, initial investment has been a concern for some stakeholders [8, 55, 66, 106, 132]. There are a few industry leaders that have the capital to become early adopters to show the benefits of the technologies. The push-pull effect of the market will eventually reduce the costs and increase the accessibility for the rest of the industry to implement. Implementing BIM for every aspect of the transportation may not be beneficial, so it is recommended that various ROI and cost savings analyses be conducted to determine how to best implement the technologies.

9. Research gaps

As the potential applications of BIM in the transportation industry are vast, many gaps could exist since adopting BIM into the transportation industry is relatively new. Based on the reviewed literature, the following are significant instances of research gaps and suggestions in application of BIM in infrastructure.

Fig. 4 displays the number of articles in the analysis that focused on applying BIM to a specific transportation structure. It is important to note that more than one structure could have been focused in a single publication (e.g. BIM for bridges and highways). Additionally, general infrastructure refers to methods that do not focus solely on one specific type of structure, but could be generally applied to infrastructure. While

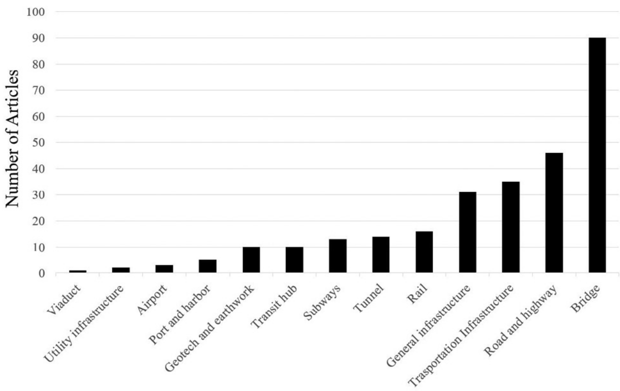


Fig. 4. Frequency of articles based on transportation structure.

the research on BIM for transportation structures have been increasing, the focus has mainly been on roads, highways, and bridges. Its application for tunnels, ports, airports, viaducts, and the other types listed in Table 2 are still limited. Development of BIM for these structures could help in improving their operation management and maintenance while preventing waste. It is understandable that certain types of projects, e.g. sidewalks, may not see the full benefits of modeling in BIM for the traditional purposes (clash detection, O&M, etc.). However, understanding the greater picture of Smart Cities holds great potential in using BIM technologies, and incorporating all transportation infrastructure is integral for sharing information among all aspects of cities. For example, embedding sensors or solar panels into sidewalks and other structures could benefit greatly by utilizing BIM to link to other aspects of Smart Cities.

A major gap is the lack of one standardized neutral exchange format for sharing information among the various software. Although there are many research efforts to accomplish this, e.g. IFC, the final standard is still limited to major transportation structures (roads, bridges, rail, and tunnels). One recent method is the use of common domain knowledge in the forms of ontologies and the Semantic Web. Ontologies could help with the development of IFC that could potentially increase the comprehensiveness of information in a BIM model as well as software interoperability. The utilization of ontologies for transportation infrastructure is gaining more momentum, but there are still many areas needed to be developed.

As reviewed previously, project management methodologies including Earned Value Management (EVM) and Integrated Project Delivery (IPD) have been applied and studied with BIM capabilities. Integration of other project management methodologies with BIM for infrastructure is a considerable gap that could bring significant values for infrastructure projects. As an example, for project risk management, there are various types of risks during the project that could be assessed by advances methodologies and computational models (e.g. Monte Carlo simulation) to analyze and provide a deeper view about them. BIM can help in visualization of risk assessment and analysis results for different stakeholders that can eventually help in enhancement of project success.

As-built documentation of infrastructure is a key process in facility management at the operation phase of the project. While there have been some efforts to use laser scanning technology, study and evaluation of capabilities of other capturing technologies, as well as the methodologies for analyzing the captured data could be an interesting topic for future research. Furthermore, research could focus on investigation of data for behavior modeling of the infrastructure, as well as the investigation of methods to make BIM models reliable tool for enhanced management of existing facilities.

Accurate project status reports are vital for finishing the infrastructure projects within time and budget. BIM capabilities could be further assessed and tailored specific to different infrastructure project needs. Researching and addressing the information gaps and designation of BIM-based reports for more comprehensive management of the infrastructures projects in the future are of the significant research gaps.

Legal issues about infrastructure, specifically public infrastructure, are still ambiguous and hinders further development and adoption of BIM applications and methods for infrastructure projects. Focusing on finding and addressing legal issues could be a great collaborative research between AECO and the legal/law industry.

As stated in Section 4.5, BIM could be integrated with advanced technologies to automatically enhance efficiency and safety of construction process in projects that require working in elevations. The fusion of advanced technologies with BrIM and CiM can help in early identification of hazard indicators and increasing the safety of infrastructure construction. Considering the high risks of clash and falls during the construction of elevated bridges in complex projects such as interchanges, further research on automated approaches can fill safety gaps in this area. Overcoming technological shortcomings and challenges for utilization and fusion of advanced technologies with BIM could be a collaborative topic between electrical and civil engineering researchers.

Finally, using BIM for the assessment of environmental impacts of infrastructure development is an important area that have received little attention. BIM capabilities could be developed to provide a comprehensive knowledge about the sustainability of the project.

10. Emerging technologies

The literature review process has led to the discovery of various emerging technologies. Information and communications technology (ICT) are shaping how the world interacts with the built environment every day [244]. It is expected that future roads will be equipped with different sensors, vehicles will communicate with each other as well as the infrastructure, and Internet of Things will help their management. The use of electric cars will be increased, and the pavement can provide inductive charging for them. Self-healing materials will be used for pavement maintenance, and robots will be massively used for inspection purposes to keep the infrastructure in good and reliable condition [71]. Zhao [12] found that mobile and cloud computing, laser scan, and augmented reality (AR) are receiving considerable amount of attention and research. According to these prospects in improvement and advancement of technologies, it is expected that more research would be focused on the adoption and integration of technology for infrastructure management in the future. This evolution is enhancing the management process, while increasing its efficiency to benefit all stakeholders. Although not the direct scope of BIM for transportation infrastructure, the following sections are worth mentioning due to the great impact they have in the use of information for transportation, as well as the potential integration with BIM.

10.1. Technology improvement and fusion with BIM

Sensing technologies currently utilized in the transportation have been discussed in Section 4.5.2. As technology becomes more advanced, available, and affordable, further research on the expansion and utilization of the information captured from embedded sensors in infrastructure can significantly help in advancement and automation of infrastructure management. BIM can be integrated with sensing technologies [6] that could be developed for monitoring and visualization of the leading indicators for safety [245] and increasing the safety during erection of highway and bridges sections. Furthermore, the fusion of sensing technologies with BIM can enable context-aware systems, which are critical in localization-based applications [246]. Context-aware systems are systems that can interact with surroundings and detect their location and environment automatically. Global positioning system (GPS) and Radio Frequency Identification (RFID) are two prevalent technologies that can be utilized to provide the true location and time, and BIM can provide the context of the location and elements needed for context-aware systems [246]. In addition to RFID technology storing more data to help in better operation and management of infrastructure through their life cycle, RFID can provide real-time information about location and identification of equipment, material, and workers that could be accessed during construction, which helps in better management of construction processes and support decision making [245, 247]. During the operation phase, the data could be stored in BIM to be utilized throughout the whole life cycle of the infrastructure, which could efficiently help in operation and maintenance (O&M) phase. Ultimately, the fusion of technologies and BIM enable new research opportunities and applications, which ultimately have the potential to reduce the time, money, and amount of resources spent on manual inspections and increase the quality, accuracy, and safety of maintenance services needed for transportation infrastructure.

10.2. Internet of things (IoT)

The world is filled with devices that are connected to share information, from phones, cars and buildings. The internet of things (IoT) can be beneficial to the transportation industry, where a network between vehicles and infrastructure communicate and transfer data that benefits the whole transportation network. Intelligent and automatic management of transportation infrastructure with the IoT guidelines is a significant research gap at the moment, and there could be great research efforts in this area to push the technology-based management of infrastructure forward. Development of IoT applications is necessary for supporting the development of smart cities.

10.3. Smart cities

Smart highways and infrastructure are integral parts of Smart Cities. With development of IoT research efforts, more cities are now being planned for smart and intelligent infrastructure. There is an increasing demand for adoption of Smart City guidelines and even governments considered incentives for further research in this area to foster this evolution, aiming to increase the quality of life for their citizens as well as the sustainability and resiliency of their cities [248]. Following the IoT research results, Smart Cities and intelligent infrastructure could be considered as the potential area for further research.

10.4. Big data

With recent influx of smart and connect technologies and sensors, the generation and utilization of mass and complex data has evolved into a new concept called Big Data. Movement and tracking of vehicles generates large amount of information every day that could be considered as “Big Data”. Traffic volume, type of vehicle, driving habits, and fuel consumption are some examples of these information. Data could be collected from different sources, analyzed, and used for different planning purposes. As example, they could be used for structural health monitoring and maintenance of bridges [51], or assessment of pavement performance for better maintenance. Aziz et al. [8] categorized the information under roadway, roadside, and road edge categories, and mentioned that as this information is bulky. Thus, there is a need for a compatible and reliable platform for their efficient utilization in infrastructure management. Enhancement of the compatibility of frameworks with Big Data and their development could be a more focused trend in the future.

10.5. Unmanned aerial systems (UAS)

Current applications and practices of UAS has been extensively discussed in Section 4.5.1. According to the applicability, flexibility, and operability of UAS, it is expected that research on their application in transportation infrastructure construction will continue to grow and help the industry in the future.

10.6. Augmented and virtual reality

Augmented reality (AR) and virtual reality (VR) technologies have elevated the level of benefits that could be achieved from 3D models. Their application in buildings and vertical construction industry is expanding every day, but still limited in infrastructure and horizontal construction while there is a vast context for their utilization in this sector for modeling, maintenance, and management of infrastructure.

10.7. Intelligent transportation systems (ITS)

Intelligent transportation systems (ITS) have helped the transportation industry in different sectors during the recent years [249]. The real-time traffic data that are being provided through ITS devices could help in exhaustiveness of the model data, and more analysis could be conducted on infrastructure models. As reliable data are the main part of BIM, it is expected that integration of BIM and ITS data would become a more practicing subject in the future.

10.8. Enhanced bridge management systems (BMS)

Bridge management systems (BMS) have changed the method of management of bridges since its introduction by helping to unify and organize the information about bridges that could later be used for maintenance and management of bridges [39, 239]. According to the proven benefits of BIM and BMS in organization of data, it is expected that their integration would be a subject of more research in the future.

10.9. Standardized neutral exchange format

There have been significant efforts leading towards a standardized neutral exchange format to enable interoperability for BIM for transportation infrastructure. It is envisioned that there will be the ability to share information seamlessly and efficiently without data loss or corruption. Although there are various methods to do so [15], the most prevalent is the creation of a nonproprietary, standardized, and neutral exchange format. Section 7 discussed the various formats, schemas, applications, and specific developments to enable interoperability among software in more detail. The need for interoperability among the transportation sector has been growing, and the number of projects focusing on interoperability have been increasing over the last few years. It is expected that the industry foundation classes (IFC) will be continually expanded to include transportation infrastructure, while other exchange models (e.g. NIEM) and methods (e.g. ontologies) are explored.

11. Conclusion

Transportation infrastructure is an integral part of economic growth and social improvement of every country which requires efficient and tailored management for the whole system. Aging and deterioration of infrastructure are two major problems of a nation’s transportation network. Traditional inspection and management systems are now inefficient due to extensive expansion of this network, and there is an immediate need for shifting toward a modern and automated management systems. Using Building Information Modeling (BIM) in correlation with emerging technologies for the management of infrastructure can help in more reliable, sustainable, and safer performance of the network while decreasing maintenance costs and risks while bringing considerable revenues for all stakeholders. Having a comprehensive understanding about this technology, applications, advantages and disadvantages, advancements and limitations can help owners, designers, and other transportation authorities to have better knowledge and select the best set of automated and strategic plans for enhanced management of the infrastructure network through its whole life cycle. This paper presented a comprehensive literature review and critical analysis of publications about Building Information Modeling (BIM) for transportation infrastructure. A total of 189 publications in this area were reviewed and analyzed, including journal articles, conference proceedings, and published reports from both industry and academia. Additionally, schemas and file formats in 9 categories and 34 areas related to transportation infrastructures were reviewed. The findings of the analysis were presented with an overview of the various domains, applications, data formats and schemas, and uses for BIM in the transportation infrastructure. The results showed that there has been an increase in research and application of BIM for transportation infrastructure, although limited to mainly roads, highways, and bridges. The analysis also resulted in the current status of research, the usage of BIM for transportation infrastructure, emerging technologies being utilized, and major gaps in research still needed to be ascertained. Finally, this paper presented limitations and challenges faced in the transportation industry, discussed the major need for interoperability and the current efforts to obtain interoperability, and provided recommendations to promote future research.

The major contribution of this paper is that the results and review provide the foundation to facilitate further research and applications for both academia and industry stakeholders. This is key in developing more efficient and cost-effective techniques needed to repair, advance, and expand the transportation infrastructure. In order to provide consensus, this paper summarized and clarified common synonymous terms for BIM used in industry, categorized the major types of transportation infrastructure, and highlighted the differences between horizontal and vertical construction. In addition to the many challenges and limitations needing to be addressed, this article identified several major research gaps, including the development of methods to register and analyze the inspection records with BIM capabilities, a standard neutral file for the interoperability of heterogeneous data types, application and assessment of project management methods through BIM capabilities, enhancement of as-built data capturing and documentation with BIM for behavior modeling, identifying the project needs in project status reports and development of BIM models, utilization of BIM for assessment of infrastructure project development on the environment and sustainability evaluation, and identifying legal issues and liabilities with the usage of BIM. Furthermore, the results show that despite the limitations and gaps, the use of BIM for transportation infrastructure has been increasing. Thus, a standard neutral exchange format and schema are needed, and that the continuing collaboration between academia and industry is required to mitigate some challenges to realize the full potential of BIM for transportation infrastructure.

BIM has been a paradigm shift in the building industry, including life cycle processes, project delivery, and technological advancements. The vision is to expand all the great the advancements of BIM into the transportation industry. Although there are various differences between the two industries, the transportation industry is at a great advantage since it can utilize all of the benefits, while learning from and improving the challenges and short comings experience in the building industry. Additionally, the benefits and successes realized in the building industry can encourage transportation stakeholders to invest in BIM, which will further the acceleration of adoption for transportation. As academia generally has a leading edge on technological developments over industry stakeholders, it is imperative for industry and academia to continue the research and development collaborations that have enabled the development of many of the current technologies. Specifically, since most of the transportation projects are owned and operated by the government, namely the FHWA and the state DOTs, it is also important for the government entities to buy into BIM for transportation. DOTs have moved toward more technology-driven management strategies including civil integrated management (CIM) and e-construction, thus incorporating BIM is not that far off in the future. The first step will be finding the practical applications of utilization of BIM in infrastructure management, where this utilization can help in solving a problem and shifting to an easier operation and management approach. Furthermore, due to the high number of infrastructure elements, another step would be focusing on developing methods that can help in prioritizing operation and maintenance tasks. As an example, there are more than 600,000 bridges in the United States, and many are in poor and unsafe condition. Therefore, there is a major need for developing methods that can assess and address the imminent hazards to prioritize the budget allocations, which are often scarce. Finally, as the owners and operation managers are used to traditional and paper-based documentation and management methods, their training is an essential step in supporting the technology-driven approach. Identification of stakeholder needs, and the extent of required training, is another crucial step in future research. There exists a need for a training and education model that is simple, yet efficient, in order for the stakeholders to embrace it. Therefore, designing a context for BIM training and technology adoption for industrial practitioners would be another research effort in the future.

This paper presented an exhaustive review of publications in the topic of BIM for transportation infrastructure. Although the attempts were to find any and relating publications (as deemed by the methodology section), there is still a possibility that some may have been unintentionally missed. For example, some publications may have been published directly to a host website or may not have active DOI's, which would not have been recorded in any of the databases utilized. A major limitation of this study was the difficulty to locate industry and government (e.g. state DOTs) reports and publications, as they are not as well stored on databases compared to academic publications. Therefore, a future review to collect and survey industry and government is needed. Other studies and reviews will be needed in the future to research, report, and quantify the success of implementation of the emerging technologies presented in this paper.

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