



| | |
|--|--|
|  |  |
| © Article authors. This is an open access article distributed under the Creative Commons Attribution-NonCommercial-NoDerivs licens. (http://creativecommons.org/licenses/by-nc-nd/3.0/). | ISSN online 2545-2819 ISSN print 0800-6377 |
| DOI: 10.2478/ncr-2021-0020 | Received: Dec. 10, 2021 Revision received: June 22, 2022 Accepted: June 23, 2022 |

Asset Management of Existing Concrete Bridges Using Digital Twins and BIM: a State-of-the-Art Literature Review



Vanessa Saback
M.Sc., Ph.D. Student
Luleå University of Technology (LTU)
Department of Civil, Environmental and Natural Resources Engineering
Luleå University of Technology, 97187 Luleå, Sweden
e-mail: vanessa.saback@ltu.se



Cosmin Popescu
Ph.D., Associate Senior Lecturer (LTU)
Department of Civil, Environmental and Natural Resources Engineering
Luleå University of Technology, 97187 Luleå, Sweden
Researcher (SINTEF Narvik)
SINTEF Narvik AS, Narvik, 8517, Norway
e-mail: cosmin.popescu@ltu.se



Thomas Blanksvärd
Ph.D., Associate Professor
Luleå University of Technology (LTU)
Department of Civil, Environmental and Natural Resources Engineering
Luleå University of Technology, 97187 Luleå, Sweden
e-mail: thomas.blanksvard@ltu.se



Björn Täljsten
Ph.D., Professor
Luleå University of Technology (LTU)
Department of Civil, Environmental and Natural Resources Engineering
Luleå University of Technology, 97187 Luleå, Sweden
e-mail: bjorn.taljsten@ltu.se

ABSTRACT

The need to optimize investments in bridge maintenance has created a demand for improved bridge management systems (BMS). Outdated practices in bridge inspection and constant advances in information technology have also contributed to this demand. The use of Digital Twins (DT), although well established in other industries, is still incipient for asset management and structural analysis of bridges. There is a great deal of research on Building Information Modelling (BIM) for bridge inspection, but its post-construction potential is still under-explored. This study presents a state-of-the-art review of the literature on asset management for bridges using digital models such as BIM and digital twins. The review was conducted using a systematic approach. Despite the rapid increase in research on DT and the amount of existing research on BIM, several gaps remain to be addressed, such as the lack of consensus about the definition of digital twins, which has led to wrongful categorisation of digital models as DT. The complex data flow and software compatibility required to develop a functional DT have hindered the exploitation of their full potential so far. The integration of BIM post-construction to BMS and existing automation technologies can also significantly improve current practices of bridge management.

Key words: digital twins, bridges, bridge maintenance, bridge management systems, BIM, review.

1. INTRODUCTION

Bridge structures have long theoretical life spans. Most bridges on the national road networks of the European Union were built within the last 50 years, although some are much older [1]. Deterioration and failures have increased in the already aging bridges due to consistent growth in automobile traffic, environmental exposure, and internal defects such as corrosion of rebars and concrete degradation. In addition, the loads currently applied to many bridge structures greatly exceed those envisaged when they were designed [1]. National guidelines require regular bridge inspection and evaluation to ensure that their operation remains safe and efficient. The processes of managing and scheduling these evaluations, recording and handling bridge data, and making maintenance recommendations have become known as bridge management [2].

Asset management is defined here as the set of activities through which an organization assures the maintenance and optimization of costs, performance, safety, and sustainability of its assets throughout their life cycles. Asset management can be applied to both tangible assets (buildings, infrastructure, equipment) and intangible assets (financial assets, intellectual property, human capital), whereas facility management focuses on maintaining the services that support the organization's primary business and activities.

Bridge management is an essential part of long-term asset management that is applicable to all existing bridges, old and new [3]. The main purpose of a bridge management system (BMS) is to preserve the asset value of the infrastructure by optimizing costs over a bridge's lifespan while ensuring user safety by offering a sufficient quality of service [1]. The expansion of physical infrastructure and improvements in technology have prompted authorities to seek ways of managing maintenance activities more efficiently [4]. In recent decades, the scope of bridge management has grown, and the objective of maximizing the value of maintenance spending to

protect investments in bridges has been added to the primary goal of protecting the safety of the traveling public [2, 4]. As a result, the search for more efficient management methods, the appeal of new technology, and efforts to reduce maintenance spending have created a demand for optimized BMS.

Some recent developments in Information Technology (IT) have led to changes in bridge management, through improvements in the quality of inventory and inspection databases as well as the control that can be exerted over deterioration, forecasting, and management models [5]. The proliferation of Industry Foundation Class (IFC) alone has had a major impact on how current tools and methods are developed in research and development [6]. Digital technologies across the board are advancing at an ever-increasing pace, taking advantage of the Internet of Things (IoT) and Artificial Intelligence (AI) agents (data analytics, machine learning, deep learning, etc.) [6].

An approach that has proven useful in many different industries involves the use of Digital Twins (DT). The basic idea behind the DT approach is that a digital informational construct representing a physical system can be created as an entity in its own right, providing a “twin” of the information embedded within the real physical system that is linked to the real system over its entire life cycle [7]. Despite extensive discussion in the literature, no consensus regarding the features and scope of digital twins has yet been established [8]. As a result, the term “digital twin” is often used to describe 3D digital models that lack the relevant data flows. Moreover, despite a growing body of research, the AEC/FM (Architecture, Engineering, Construction/Facility Management) sector still lags behind the manufacturing and aerospace sectors in terms of the maturity of development of digital twins [9].

This context was the main motivation for this state-of-the-art review of the literature on asset management for concrete bridges using digital models such as Building Information Modelling (BIM) models and digital twins. A great deal of research has been done on the use of BIM for inspecting bridges, so the discussion of BIM here focuses on synthesizing the most recent research and summarizing information on best practices. Digital twins, on the other hand, have been studied less extensively, especially in the context of asset management in the construction industry. This review of DT therefore focuses on summarizing the work that has been done and identifying gaps in the literature meriting further exploration.

This review is divided into eight sections: Introduction, Methodology, Bridge Inspection, Bridge Information Modelling (BrIM), Digital Twins, Bridge Management Systems, Discussion, and Conclusion. The methodology section explains the procedures used when conducting the systematic review of the literature. Sections three through six present an overview of key findings from the literature pertaining to their subjects and link those findings to the main thread of the review. The material reviewed in the preceding sections is then discussed in the seventh section, and the conclusions and recommendations for future studies are presented in the final section.

2. METHODOLOGY

This section explains the methodology used when conducting the systematic state-of-the-art literature review. The process was divided into three main steps: (i) defining the search strings, (ii) performing searches in the selected database, and (iii) assessing the retrieved articles. The search strings were defined based on keywords identified in primary references retrieved during

a preliminary exploratory literature review. The most commonly recurring keywords in the primary references were divided into five subject groups; each subject group was then assigned a set of strings as follows:

- BIM: ("BIM" OR "Building information modelling");
- Bridges: ("Bridge information modelling" OR "BrIM" OR "Bridge" OR "Bridges");
- Digital Twins: ("Digital twin" OR "Digital twins" OR "DTM");
- Management/inspection: ("Facilities management" OR "Facility management" OR "inspection" OR "monitoring");
- Maintenance: ("Maintenance" OR "Assessment").

16 different searches were then performed in Scopus [10], the selected database, in April of 2020. The search results were only limited by year; the acceptable range was set from 2010 to 2020 to ensure that only publications that could be considered to represent the state-of-the-art were retrieved. Each search used a combination of three (ten combinations), four (five combinations), or five (one combination) groups of strings. The string search was applied to the title, keywords, and abstract of each paper. The combinations and the number of results obtained for each one are shown in Figure 1.

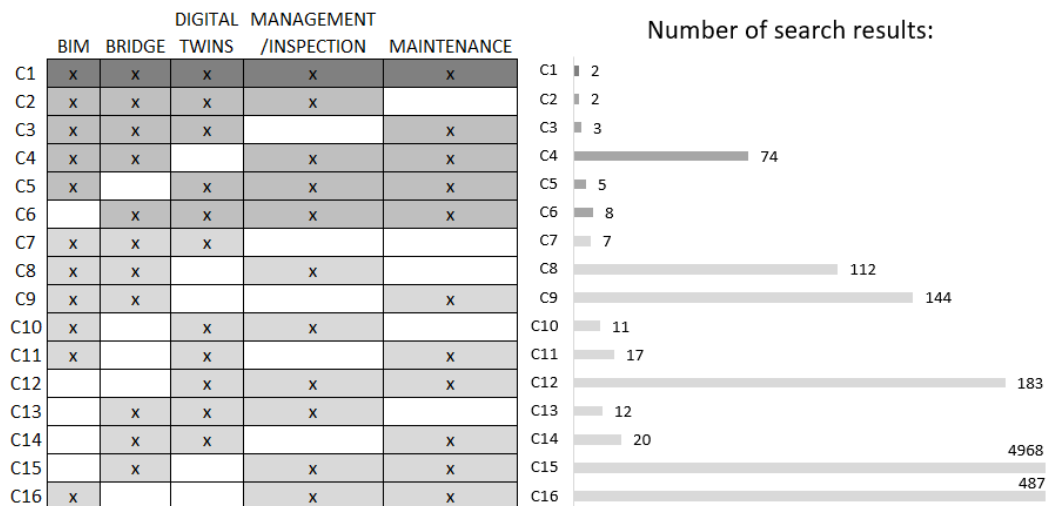


Figure 1 - String combinations (left) and the number of search results obtained for each one (right)

Two of the 16 combinations (C15 and C16) were eliminated for being too broad; the remaining 14 combinations (C1-C14) collectively provided 600 results in Scopus [10]. Some of the papers retrieved in this way were eliminated before assessment because the article had already been assessed while reviewing the results of an earlier string combination, was written in a language other than English, was conference review paper, or dealt with an unrelated area of research (medicine, psychology, etc.).

Each article was then evaluated using three sequential filtration steps; the first focused on the title, abstract and keywords, the second on the introduction and conclusion, and the third on the entire paper. Articles that passed all three steps were included in the review. The main reason for exclusion in all three filters was low relevance of the subject of the paper to the topic of the review;

other reasons for rejection included lack of access to the full paper or low overall quality. An iterative process was applied: all publications cited in the papers that passed all three filtration steps were filtered in the same way and included in the review if they also passed all three filters.

As shown in Figure 1, there were far more search results pertaining to bridge inspection and BIM than to DTs, which is a newer area of research. The five combinations that did not include the search string "digital twins" (C4, C8, C9, C15, C16) collectively yielded 5 785 results, with an average of 1 157 results per combination, whereas the eleven combinations including "digital twins" (C1-C3, C5-C7, C10-C14) only provided 270 results, with an average of 25 results per combination. It is also noteworthy that many of the papers that did include the term "digital twins" in their keywords or text did not actually discuss the creation of DT models. They either used the expression "digital twin" as a synonym for a 3D BIM or stated that the research could support the creation of a digital twin in the future but did not actively contribute to the existing knowledge on digital twins.

The distribution of the selected papers based on their year of publication is indicative of the recent emergence of DTs as a field of study: 50% of the included papers were published between 2010 and 2018, and the remaining 50% were published in 2019 or 2020. The articles selected using the methodology described above are reviewed in the following sections.

3. BRIDGE INSPECTION

The proliferation of road traffic has increased the loads faced by bridges on public roads. Environmental and mechanical damage, besides natural aging, result in decreasing structural performance of the bridges. Regular structural health assessments and maintenance interventions are therefore needed to ensure that the bridges continue to operate safely throughout their intended design life and beyond [11]. The first step in determining the current health of a bridge and planning for maintenance is performing inspections. Routine inspections are periodic quality assessment procedures that are usually scheduled during a bridge's service life to evaluate its health [11, 13]. The frequency at which inspections are scheduled can vary within a country's BMS. Usually there is one principal and more detailed inspection every 3-6 years, one annual or semi-annual follow-up inspection, and more regular superficial routine inspections.

Although the implementation of inspection procedures varies between countries, there are some common basic principles [13]. Current bridge inspection procedures are mostly based on intensive visual investigations and field measurements performed manually by bridge inspectors [14]. During an inspection, the inspector examines each element of the bridge, searching for visible damage. Some non-destructive testing may also be performed to complement the visual inspection. Concrete spalling, cracks, and reinforcement corrosion are the most frequently identified types of damage in reinforced concrete bridges, aside from equipment-related defects (e.g., defects in bearings or expansion joints) [13]. The measurements and observations obtained during the inspection are then documented in the form of field inspection notes, freehand sketches, and photographs [11, 14].

Unfortunately, these procedures present several challenges that make manual inspections time-consuming and inefficient. These challenges may include difficulty in accessing the bridge (due to its large dimensions and/or environmental and traffic conditions), dependence on individual

inspectors' knowledge of the bridge's structural behaviour, and transferring information between inspection periods. Consequently, there is a need for new infrastructure inspection and monitoring techniques that reduce disruption while increasing the efficiency of data gathering and the reliability of the acquired data [14].

Approaches based on substituting human visual inspections with automated and systematic 3D point cloud assessments are currently being studied intensively [13]. Much recent research has focused on combining image acquisition techniques with damage detection and feature extraction methods to create automated bridge inspection systems [13]. Figure 2 shows some of the various technologies that have been used for this purpose, which are discussed in more detail below.

BRIDGE MONITORING AND INSPECTION TECHNOLOGY

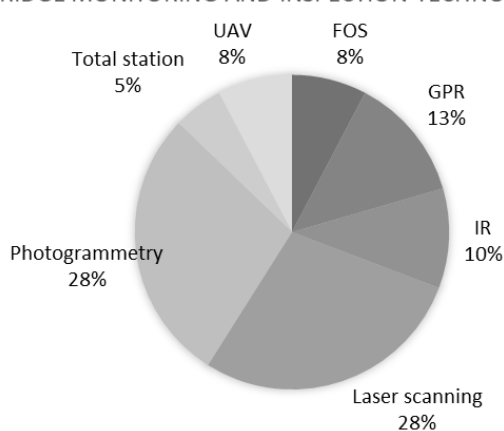


Figure 2 - Technologies used to enhance bridge monitoring and inspections in recently published studies (FOS: Fibre Optic Sensors; GPR: Ground Penetrating Radar; IR: Infrared; UAV: Unmanned Aircraft Vehicle) [11-30].

The evolution of monitoring technology has significantly improved the efficiency of structural health assessment of bridges. Inspections and data collection processes have been automated, leading to significant increases in the accuracy and quality of the inspection data. Technologies used in these automated processes include fibre optic sensors [15, 16], UAV [11, 17, 18], laser scanning [14, 18, 19, 20, 21, 22, 23, 24, 25], photogrammetry [11, 13, 14, 19, 20, 21, 23, 26, 27], and ground penetrating radar [27, 28, 29, 30]. Notable publications in this area are summarized below.

Popescu et al. [14] and Riveiro et al. [19] compared the performance of photogrammetry and laser scanning for bridge inspections; Popescu et al. [14] also included infrared (IR) scanning in their comparison. Their results showed that the two methods achieved similar final accuracies and have great potential to facilitate the 3D reconstruction of bridges. However, laser scanning was found to be more efficient because of its higher data acquisition rate and automated post-processing. The authors found that the main advantage of the photogrammetry technique stemmed from its lower equipment cost.

Riveiro et al. [19] developed an algorithm using MATLAB [31] to automate the measurement of minimum vertical under-clearance during bridge inspections. McGuire et al. [32] developed a method to link and analyse data related to bridge inspection, evaluation, and management using a custom Microsoft Excel [33] tool. Huthwohl et al. [34] used Industry Foundation Classes (IFC)

to categorize inspection information on reinforced concrete bridges and to standardize its storage in a format suitable for sharing and comparison by different users. Abu Dabous et al. [28] used cloud-based solutions to sync BIM of bridges so that they could be accessed from tablet computers on-site. Omer et al. [12] used Light Detection and Ranging (LiDAR) to digitize bridges so that they could later be inspected in a virtual reality (VR) environment.

Morgenthal et al. [11] and Xu & Turkan [17] proposed bridge inspection methodologies based on camera-equipped Unmanned Aerial Vehicles/Systems (UAV/UAS). Morgenthal et al. [11] generated flight paths automatically from a basic 3D model and used photogrammetry- and machine learning-based methods to compute automatically geometries and typical damage patterns. Xu & Turkan [17] used computer vision algorithms to collect and process inspection data, storing and managing all of the related inspection information in a Bridge Information Model (BrIM).

Sacks et al. [20] proposed an integrated bridge inspection system called SeeBridge to upgrade the traditional bridge inspection process by producing semantically rich BIM of the inspected bridges. The system uses remote sensing techniques for data collection, software for automated compilation of the remote sensing data, a semantic enrichment engine for converting the 3D model into a semantically rich BIM, and a damage detection tool. Within the system, IFC are used to represent bridge elements, their properties, and the relationships between them.

4. BrIM

Building Information Modelling (BIM) for bridges is commonly referred to as Bridge Information Modelling, or BrIM. BrIM is a novel approach that can be used to manage the whole life cycle of a bridge including its fabrication, construction, operation, inspection, and maintenance [23]. Data gathered using the inspection technologies discussed in the preceding section can be used to generate accurate digital models of bridges using BIM [13, 17, 20, 28, 32, 34]. These BIM can then be used for predictive purposes, for example to predict the future decay of the structure using Finite Element (FE) methods [29]. This is essential for the creation of smart BMS because accurate modelling of the current situation and prediction of future problems are key elements in a digital twin model.

In the case of new bridge structures, the BrIM can be created during bridge's design phase, before its construction. This allows full exploitation of the potential benefits of life-cycle management. If the model is coupled to a structural health monitoring (SHM) system, the sensor data for the bridge can be analysed directly with the model, improving visualization and creating a shared environment that facilitates long-term management [15, 21, 35].

However, because bridges have long life spans, BrIM is often applied to historical bridges [23] [18, 24, 25, 27]. BIM for heritage or historical structures is often referred to as H-BIM. The aim when modelling such a bridge is to create a digital model for recording information that will allow the bridge's cultural significance to be preserved while ensuring its safe operation and providing a virtual tool that can be used to help define effective restoration strategies [18]. The main difficulty in this reverse engineering process is that these heritage bridges often have overly complex geometries and lack detailed formal design documents, which causes challenges when modelling or capturing geometric data on such structures [18].

It should be noted that the modelling of new bridges is also often challenging. A characteristic problem presented by new bridges is that they often have variable curvature and complex cross sections [23]. While commercial BIM software is capable of creating 3D bridge models with highly accurate geometry, there are only a few families of dedicated libraries for the modelling of complex civil structures such as bridges [13, 23, 25]. The lack of existing object libraries may thus necessitate the development of new algorithms and specific families to represent properly the different structural elements of the bridge [23].

Several solutions have been proposed in the literature to tackle the challenges of accurate representation within BIM and interoperability between platforms. In most of the studies included in this review, the commercial software package Autodesk Revit [36] was the tool of choice for generating BIM [18, 23, 24, 25] because it can be tailored and enhanced using its application programming interface (API) [32]. It also offers an inter-operable IFC platform that enables the exchange of data between non-native file types [32]. IFC is a neutral format for exchanging digital building models, and it is hoped that the use of IFC as a standard BIM file format will eliminate or greatly reduce interoperability issues [13]. In addition to IFC, MATLAB [31] and other programming languages have been used to create tailored interoperability solutions [37].

5. DIGITAL TWINS

The first definition of the concept now known as the Digital Twin was proposed by Michael Grieves in a presentation in 2002 [7,38]. Although the context was related to product life-cycle management, it contained all the elements of the Digital Twin concept: a real space, a virtual space, and a link supporting data flow between the two [7]. The premise underpinning the model was that each system consisted of a physical system, a virtual system containing all available information on the physical system, and a mechanism for mirroring (or twinning) changes in the real and virtual spaces [7]. It also implied that the virtual and real systems should be linked throughout the life cycle of the physical system, from its creation and production (manufacture) through to its operation (sustainment/support) and disposal [7]. The Digital Twin concept was first used heavily in the aerospace sector; it was initially used by the National Aeronautics and Space Administration of the U.S.A. (NASA) to replicate the life of air vehicles [8, 39]. At that time, the concept was given the name DT and it was introduced as such to the aerospace world via NASA's Technology Roadmaps [38].

The basic concept of the DT model is based on the idea that a digital informational model about a physical system can be created as an entity in its own right [7]. This digital model then functions as a “twin” of the information embedded within the physical system itself and is linked with that physical system throughout its life cycle [7].

Although much has been published on the topic, there is still little or no consensus among researchers and practitioners regarding the features and scopes of a digital twin [40]. Negri et al. [39] defined a digital twin as a virtual representation of a system that can be used in multiple different kinds of simulations and that is characterized by synchronization between the virtual and real systems based on sensed data and connected smart devices, mathematical models, and real time data elaboration. Kritzinger et al. [38] proposed definitions of Digital Models, Digital Shadows, and Digital Twins that are illustrated in Figure 3 and summarized below:

- Digital Model: A digital representation of an existing physical object that lacks any form of automated data exchange with the physical object.
- Digital Shadow: A digital representation of a physical object with an automated one-way data pathway allowing information on the physical object’s state to be automatically transferred to the digital object.
- Digital Twin: A digital representation of a physical object together with an automated and fully integrated bidirectional data pathway allowing exchange of data between the two objects.

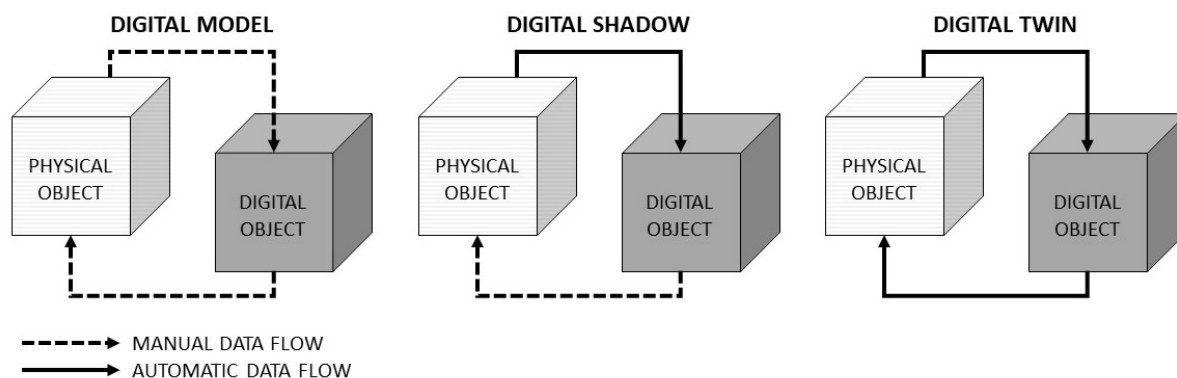


Figure 3 - Data flow in a Digital Model (left), a Digital Shadow (centre), and a Digital Twin (right). Adapted from Kritzinger et al. [38].

Lu et al. [9], Cimino et al. [8] and Khajavi et al. [41] performed literature reviews on digital twins. Lu et al [9]. proposed a framework for achieving smart DT-enabled asset management in the operations and maintenance (O&M) phases. The authors concluded that BIM still has limited adoption within asset management, mostly because in daily O&M management BIM is not enough for complex situations and comprehensive data management [9].

5.1 Digital Twins: bridges

In accordance with the aim of this review, one of the main purposes was to identify studies that propose digital twins for bridge structures. However, only few articles among the ones assessed address digital twins for bridges, namely: Shim et al. [42], Lu & Brilakis [43] and Ye et al. [44]. The following subsections present a discussion on these identified studies.

Shim et al. [42]

Shim et al. [42] proposed a framework for a bridge maintenance system and applied it to a real bridge in a pilot study. The proposed system applies the digital twin concept by creating three models: (1) a physical 3D geometry model (the so-called geometric digital twin, or gDT), (2) a reversed 3D surface model (the reality twin model), and (3) a federated model.

The gDT is based on the as-built documents of the existing bridge; it can be generated using parametric modelling with the aid of an open-source application-programming interface. The reality twin model is created via a 3D scanning procedure and contains information on the current state of the bridge. This model is based on a combination of photo scanning data collected using

an unmanned aerial vehicle (UAV) and laser scanning cloud data. Finally, the federated model is created by merging the gDT and reality twin models, which overlap at points bearing predefined marks that are placed on the real bridge before the 3D scanning procedure.

The initial version of the federated model represents the status of the real bridge at the beginning of a maintenance task and is updated as subsequent maintenance tasks are performed. For automated surface damage detection, inspection data from the scanning procedure are automatically converted into technical damage reports and used directly to update the initial model. The general procedure for maintenance work is a closed loop of interactive processes including inspecting, monitoring, performing appropriate repair or rehabilitation work, and importing the resulting feedback into the database.

Lu & Brilakis [43]

Lu & Brilakis [43] proposed an automated method for generating a gDT of an existing bridge from four types of labelled point clusters. Only geometric representations of the four main components of typical RC slab and beam-slab bridges (the slab, piers, pier caps, and girders) were included in the models. Other semantic information including data on the materials, defects, additional relationships, and so on, were considered beyond the study's scope. Lu & Brilakis [43] argue that all of the geometric and property information associated with the gDT should be stored in a platform-neutral data format (i.e., IFC) to support the use of the gDT in the construction industry. This format allows the categorization of inspection information and standardized storage in a format that facilitates sharing and comparison by different users [34]. The output of this study was an IFC file containing the various IfcObjects (IfcSlab, IfcBeam and IfcColumn) that comprise a bridge gDT. Point clusters of the four component types were created, then ground truth gDTs were manually generated and exported into IFC files using Autodesk Revit [36], which was described as one of the most advanced digital twinning software solutions [43]. In conclusion, Lu & Brilakis [43] reported a gain in time saving, better results in six out of ten bridges modelled and that human assistance is still necessary in some challenging scenarios that the current automated method could not handle [43].

Ye et al. [44]

The digital twin framework developed by Ye et al. [44] combines BIM with bridge sensor data, FE modelling, and statistical monitoring. The framework was applied in a case study on two composite (steel and pre-stressed concrete) railway bridges that were instrumented with discrete and distributed fibre optic sensor (FOS) systems during their construction. The sensor data and associated bridge behaviour were visualized in a BIM environment. The FE model was created to investigate the performance of the bridge during construction and operation; it was validated using sensor data and its predictions were verified by FOS strain measurements. The resulting information could be used to help establish a performance baseline that will support long-term condition monitoring and data-informed asset management as further sensor data are collected throughout the bridge's operating life [44]. The conceptual framework was developed by integrating both physics-based (FE modelling) and data-driven (statistical modelling) approaches.

The framework was applied in a case study on experimentally tested and field monitored railway sleepers, with the goal of predicting their operational performance over time. The authors indicate that future work will include developing a working digital twin and improving the level of confidence in the integrated simulation model and its predictions.

6. BRIDGE MANAGEMENT SYSTEMS (BMS)

6.1 BMS in the world

National road administration authorities generally have their own management systems that are used to manage tunnels, culverts, ferry berths, retaining walls, pavements, and quays as well as bridges [45]. These systems are either developed internally by the managing organization itself (with or without the help of private companies), or bought off-the-shelf and modified to suit their needs [46]. Most such systems are only used within a single country, probably due to the differences in bridge management practices between countries [46]. When systems are bought off-the-shelf and adopted by an agency, they are usually significantly modified, creating a new system with a new name (e.g. Eirspan, which was developed using DANBRO as a starting point) [46].

Helmerich et al. [47] listed the best-known software based digital bridge management systems in Europe: BaTMan (Sweden), BAUT (Austria), DANBRO (Denmark), KUBA (Switzerland), SIB-Bauwerke (Germany), and SMIS (United Kingdom). Additionally, the Federal Highway Administration (FHWA), American Association of State Highway and Transportation Officials (AASHTO), and National Cooperative Highway Research Program (NCHRP) of the United States sponsored a scanning study to determine how highway agencies in Europe, North America and South Africa handle bridge maintenance, management, and preservation [45]. The U.S. delegation met with bridge preservation and maintenance experts from these countries (apart from Austria), and with representatives from Finland (BMS: HiBris, Hanke-Siha), France (BMS: LAGORA), Norway (BMS: Brutus), and South Africa (BMS: STRUMAN) [45]. The investigated management systems evaluate the bridges' condition through rating scales, such as a 1-4 point scale [45]. They also establish frequency of bridge inspection, which usually means one principal inspection every 5 to 6 years, some condition evaluation every 2 to 3 years and routine evaluations of damage [45].

The results from research projects on bridge management that have been conducted in Europe contributed significantly to initiating or enhancing the development of national integrated BMS [47]. For example, BRIME (1998-1999) was conducted with the objective of developing Bridge Management Systems for the European Highway authorities [47]. Likewise, Sustainable Bridges (2003-2007) was a consortium of 32 partners from twelve European countries for improved assessment tools, repair and strengthening methods. Guidelines were set to support the railway infrastructure departments with technical background information in the fields of inspection; condition, load and resistance assessment; monitoring; repair and strengthening of railway bridges (including NDT) [47].

In the United States, the FHWA sponsored the creation of two highway BMS, BRIDGIT and PONTIS, which are used to manage bridges on state and interstate highways [2]. PONTIS is the main bridge management system employed in the USA; it is currently managed by AASHTO and has been renamed BrM in reference to bridge management [2, 48]. Some other BMS currently used around the world are: SAMOA, APTBMS (Italy), FBMS (Finland), GBMS (Germany), Eirspan (Ireland), DISK (Netherlands), SMOK/SZOK (Poland), SGP (Spain), OBMS, QBMS, EBMS, PEI BMS, GNWT (Canada), Bridge-ASYST, MRWA and NSW (Australia), MICHI,

RPIBMS (Japan), KRMBMS (Korea) [46, 49]; GOA (Portugal) [50]; SGO (Brazil) [51]; T-BMS (Taiwan) [52].

6.2 Modules of a BMS

Each of the systems discussed in the preceding section can be used by the corresponding national road administration to perform a different set of management activities. The tasks can vary according to the specific needs and resources of each country, they can be more or less thorough and frequent, and prioritize different parts of the BMS scope. However, all of the BMS have similar scopes based primarily on inspection, structural health monitoring, and rehabilitation [3].

Inspection is the first step in the management process. During inspections, the inspectors establish the physical and functional condition of individual structural members and the entire bridge [53]. Along with the inspectors' experience, the condition is assessed using measurement equipment and well-developed tools and techniques [53]. Rating criteria are then applied to determine the bridge's condition, and rehabilitation procedures are implemented [3].

The management tasks are usually divided into different modules in the systems. For a BMS to function efficiently, the system modules must be integrated internally to minimize duplication and user inputs and thus achieve optimal performance [4]. The modules are usually related to inventory, inspection, condition analysis, and maintenance planning. The main module is the inventory module, which is considered the foundation from which the rest of the BMS operates [4]. According to Woodward et al. [1], a bridge management system capable of fulfilling the various objectives of the managers must be modular and incorporate modules for performing at least the following key tasks:

1. Taking inventory of the stock;
2. Compiling knowledge of bridge and element condition and its variation with age;
3. Evaluating the risks incurred by users (including assessment of load carrying capacity);
4. Managing operational restrictions and the routing of exceptional convoys;
5. Evaluating the costs of the various maintenance strategies;
6. Forecasting the deterioration of condition and the costs of various maintenance strategies;
7. Assessing the socioeconomic importance of the bridge (evaluation of indirect costs);
8. Performing optimization under budgetary constraints;
9. Establishing maintenance priorities;
10. Performing short- and long-term budgetary monitoring.

6.3 Current practices in bridge management

To handle the amount of information required to achieve optimal management of infrastructure, managing agents are using increasingly sophisticated computerized management systems to support their decision-making process [54]. Mirzaei et al. [54] conducted a survey of 25 bridge management systems that are used to manage approximately 1 million (bridges, culverts, tunnels, retaining structures and other objects) in 18 countries. The main results of this survey are presented in Table 1. The results include information on each system's data entry and information access capabilities, stored information, handling of structural information, handling of cost

information, predictive capabilities, use of predictions and the systems' contributions to the education and qualifications of their users.

Table 1 - Current practices in BMS [54]

| N° (%) | Item |
|---|--|
| <i>Data entry and information access</i> | |
| 11 | allow data entry through mobile computers |
| 12 | allow access to information in the system over the internet. |
| <i>Stored information</i> | |
| 7 | allow basic construction information to be archived in the system (the majority of systems allow the information to be either stored in some way or referenced). |
| 24 | allow archiving of inspection information. |
| 23 | allow archiving of intervention history. |
| <i>Information handled on the structure level</i> | |
| 24 | handle condition information from inspections. |
| 20 | handle information on load carrying capacity. |
| 19 | handle information from inspections concerning safety. |
| 18 | handle information from inspections concerning risk. |
| <i>Cost information</i> | |
| 24 | can handle intervention cost information. |
| 6 | handle inspection costs. |
| 11 | handle traffic delay costs. |
| 7 | handle accident costs. |
| 8 | consider environmental costs. |
| <i>Predictive capabilities</i> | |
| 19 | can predict deterioration; 12 systems use probabilistic methods. |
| 18 | can predict the improvement due to future interventions; 9 use probabilistic methods. |
| 19 | can identify optimal intervention strategies. |
| <i>Use of prediction information</i> | |
| 23 | are used to prepare budgets. |
| 15 | are used to set performance standards. |

7. DISCUSSION

The process of creating a BMS for smart asset management of bridges using Digital Twins can be divided into four steps: (1) Inspection/Data acquisition, (2) BIM creation, (3) Digital Twin creation, and (4) Asset Management. The overview of currently operational BMS presented in Table 1 shows that there is room for improvement in many respects. This section analyses the main findings of the systematic literature review presented above.

Most problems associated with current bridge inspection practices relate to time consumption, the limited accuracy and impracticality of manual sketches, knowledge transfer between inspection periods, and issues with access to certain bridge sites. Several technologies that could enhance the quality of inspection data while also improving the efficiency and automation of the inspection process have been proposed in the literature. For example, a synced BIM of the bridge can be accessed from the site to facilitate inspection [28], UAVs can be used to perform inspections with

automatically generated flight paths [11], damage detection can be automated with computer vision algorithms [17], and the inspections themselves can be performed using virtual reality bridge models [12]. As shown in Figure 2, photogrammetry and laser scanning were the most widely used methods in the various publications on inspection technologies included in this review.

A very complex data flow is required to transfer information generated during bridge inspections to a BIM that can be used to manage all data on the bridge across its life cycle. The flow must support a semantically rich geometry model, assessment of monitoring equipment and treatment of the resulting data, and visualization of the data in the bridge model while also enabling analysis and predictions. This requires interaction and data transfer between different platforms that do not necessarily communicate directly. Enabling such transfers and interactions is a major challenge, as is establishing interactions between the equipment and its digital mirror. In the literature, the main way of overcoming these challenges was to use IFC to categorize the inspection information and standardize its storage in a format suitable for comparison and sharing with different users.

At present, BIM is mainly used for design purposes and is rarely applied in asset management. The main issue reported in the literature when using commercial software to create BrIM stemmed from the complex geometry of the structures, which can generally not be properly represented using standard libraries. It is therefore often necessary to spend considerable amounts of time to design new families for each modelling effort. Autodesk Revit [36] was the commercial BIM software favoured by most authors because of its interoperable IFC platform and the fact that it is readily modified using its application-programming interface. Most studies included in this review combined a structural health management and/or monitoring system with a BIM [13, 14, 15, 20, 21, 26, 28, 32, 34, 35, 37, 55, 56, 57].

Different solutions can be used to tackle these challenges. Among the reviewed studies, the most common strategy for integrating different kinds of data was to use separate layers or models in the digital twin [42, 43, 44, 58]. These layers often included a data acquisition layer, a layer for 3D representation of geometry and visualization of sensor data, and a layer for transmission/integration of data resources. The 3D geometry can be automatically compiled from remote sensing data and coupled with an engine for converting the 3D model into a BIM [20]. In addition to separate layers, IFC [13, 34, 43, 59], MATLAB [19, 37], and machine learning algorithms [11, 26, 41] were also used to facilitate data integration between platforms.

Based on the summary presented in Table 1, some observations about current practices in BMS can be made. First, no existing BMS includes BrIM or geometric representations of bridges of any kind [13, 46]. Traditional paper-based methods of maintaining infrastructure are no longer viable because governments now expect digital tools that leverage information and communication technology [4]. Additionally, fewer than half of the systems allow remote or online access to the BMS; most only allow access through desktop computers, which limits access to information. This should be addressed because many of the technological advances in infrastructure management rely on cloud-based, mobile, and/or portable technology. The BIM can be linked to the BMS using many different methods and tools including Structured Query Language (SQL) statements [60]; C# [60], MATLAB [19, 37] or other programming languages; IFC [13, 34, 43, 61, 62, 63]; or machine learning [11, 26, 41] and artificial intelligence algorithms [64].

Most current systems can manage information on inspections and interventions. However, to enable adequate life cycle management, a BMS should also include budgetary information and data from construction and design plans so that they can be compared to the current condition data obtained from inspections. This enables future deterioration to be predicted more accurately and facilitates the planning of interventions. Many current systems can also predict deterioration – i.e. changes in physical condition or performance indicators [46], mainly using probabilistic methods. However, there have been many advancements in structural analysis using BMS frameworks that could be used to make improvements in this area; examples include the development of automated bridge assessment tools using artificial intelligence algorithms [64] and the combination of BIM with FE models [60, 65] and Geographic Information Systems (GIS) [62]. Figure 4 presents a modular framework of activities that should be supported by a comprehensive BMS based on an evaluation of the data entering a typical BMS [1, 3, 4, 5, 51, 52, 61, 66].

This review identified several papers published over the last decade dealing with the first two processes within the concept presented, i.e. (1) Inspection and (2) BIM creation. Different inspection and monitoring technologies have been tested and compared, and automated inspection methodologies have been developed and linked to BIM. However, the potential uses of BIM and BrIM post-construction remain under-explored.

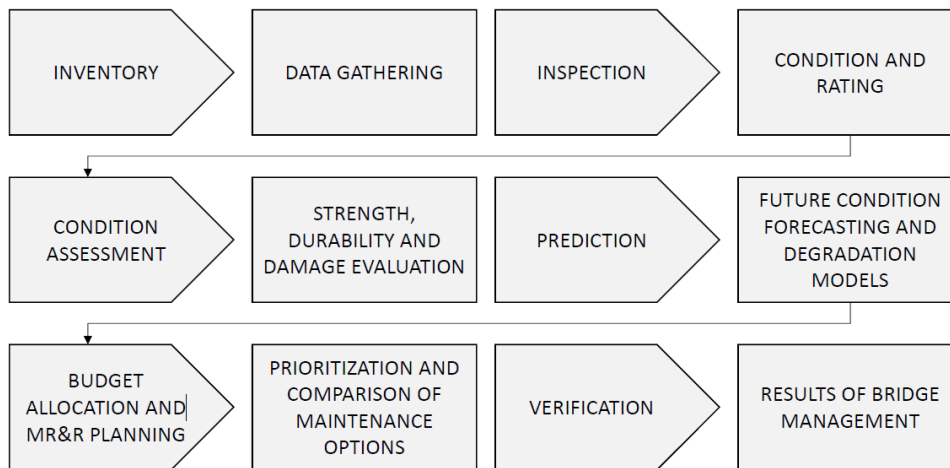


Figure 4 - Management activities within the suggested scope of a BMS.

Research on digital twins in construction is less well established than in other sectors such as aerospace [67], but interest in their application is growing rapidly, as demonstrated by the trends shown in Figure 2. However, there is currently no consensus about what a digital twin model should include and how it should operate. Therefore, the “digital twins” used in many published works would be more accurately described as "digital models" or "digital shadows" (Figure 3) that lack the full capabilities expected of a digital twin. The automation of the two-way data flow between the physical entity and the digital model is a major challenge in the development and post-construction use of digital twins. While there have been some initial studies in this area, much remains to be done.

8. CONCLUDING REMARKS

The growing stock of bridges and the increasing need to optimize investments in bridge maintenance while ensuring safe operation have created a demand for optimized bridge management systems. In recent years, there have been major advances in technologies for bridge inspection, damage detection, digital modelling, and maintenance. This state-of-the-art literature review of asset management for bridges using BIM and Digital Twins summarizes these advances. To this end, the review examined four processes and tools separately: inspection, BIM, Digital Twins, and Asset Management. Each has been addressed in the literature using methods that combine different sets of solutions and technologies. Despite the rapid increase in research on digital twins and the large body of existing research on BIM and bridge inspection, several gaps remain to be addressed:

- The potential uses of BIM and BrIM post-construction are still under-explored;
- There is no consensus concerning the definition of digital twins, which has caused digital models and digital shadows to be wrongly categorized as digital twins;
- The development of functional digital twins requires a very complex automated data flow, which has hindered the exploitation of their full potential.
- There has been little work on the development of asset management and structural health systems using digital twins for bridge structures.

The analysis in this review also revealed some points of improvement in current BMS for asset management of bridges:

- Geometric representations of the bridges under management (e.g. BIM) should be integrated into existing BMS;
- Remote or online access to existing BMS should be made possible;
- Automated inspection procedures (e.g. automated damage detection processes) should be introduced and linked to the BMS, preferably directly to a BIM;
- Life cycle analysis should be incorporated into the systems. This would require better integration of construction information to enable comparisons to inspection data on the structure's current condition, as well as predictions of deterioration generated using structural analysis tools such as FE modelling to enable better planning of interventions.
- Structural analysis and deterioration predictions should be improved; such improvements could have direct impacts on subsequent budgetary analyses.
- Budget analysis throughout the bridge's life cycle should be integrated into the system and should include peripheral costs such as those due to traffic delays, accidents, environmental costs, and inspection and maintenance costs.

This literature review is a part of a project aiming to develop a BMS for asset management of bridges using digital twins. Future work should include studies on the use of IFC with SHM systems, automated damage detection during bridge inspections, and machine learning algorithms to improve the links between the system's modules.

ACKNOWLEDGEMENTS

This work was carried out within the strategic innovation program InfraSweden2030, a joint venture by Vinnova, Formas and The Swedish Energy Agency. The work is also funded by SBUF

(construction industry's organization for research and development in Sweden) and Skanska Sweden.

REFERENCES

1. Woodward R, Cullington D W, Daly A F, Vassie P R, Haardt P, Kashner R, Astudillo R, Velando C, Godart B & Cremona C: “Bridge management in Europe (BRIME) -Deliverable D14”. *Final Report*, 2001.
2. Hurt M & Schrock S: “Highway Bridge Maintenance Planning and Scheduling”. Chapter 1, “Introduction”, 2016, pp. 1–30.
3. Khan M A: “Accelerated Bridge Construction”, Butterworth-Heinemann, Boston, USA, 2015, pp. 53–102.
4. Powers N, Frangopol D M, Al-Mahaidi R & Caprani C: “Maintenance, safety, risk, management and life-cycle performance of bridges”, CRC Press, London, UK, 2018, p. 219–225.
5. Darbani B M & Hammad A: “Critical review of new directions in bridge management systems”. *Computing in Civil Engineering*, 2007, pp. 330–337.
6. Boje C, Guerriero A, Kubicki S & Rezguy Y: “Towards a semantic Construction Digital Twin: Directions for future”. *Automation in Construction*, Vol. 114, No. 103179, 2020.
7. Grieves M & Vickers J: “Digital Twin: mitigating unpredictable, undesirable emergent behavior in complex systems”, *Transdisciplinary Perspectives on Complex Systems*, Springer, Cham, 2017, pp. 85–113.
8. Cimino C, Negri E & Fumagalli L: “Review of digital twin applications in manufacturing”. *Computers in Industry*, Vol. 113, No. 103130, 2019.
9. Lu Q, Parlikad A K, Woodall P, Don Ranasinghe G, Xie X, Liang Z, Konstantinou E, Heaton J & Schooling J: “Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus”. *Journal of Management in Engineering*, Vol. 36, No. 05020004, 2020.
10. ELSEVIER: “Scopus”, ELSEVIER, 2021. [Online]. Available: <https://www.scopus.com/>. [Accessed 2021].
11. Morgenthal G, Hallermann N, Kersten J, Taraben J, Debus P, Helmrich M & Rodehorst V: “Framework for automated UAS-based structural condition assessment of bridges”. *Automation in Construction*, Vol. 97, pp. 77–95, 2019.
12. Omer M, Margetts L, Hadi Mosleh M, Hewitt S & Parwaiz M: “Use of gaming technology to bring bridge inspection to the office”. *Structure and Infrastructure Engineering*, Vol. 15, No. 10, 2019, pp. 1292–1307.
13. Isailovic D, Stojanovic V, Trapp M, Richter R, Hajdin R & Döllner J: “Bridge damage: Detection, IFC-based semantic enrichment and visualization”. *Automation in Construction*, Vol. 112, No. 103088, 2020.
14. Popescu C, Täljsten B, Blanksvärd T & Elfgren L: “3D reconstruction of existing concrete bridges using optical methods”. *Structure and Infrastructure Engineering*, Vol. 15, No. 7, 2019, pp. 912-924.
15. Delgado J M D, Butler L J, Gibbons N, Brilakis I, Elshafie M Z E B & Middleton C: “Management of structural monitoring data of bridges using BIM”. *Bridge Engineering*, Vol. 170, 2017, pp. 204-218.
16. Butler L J, Elshafie M Z E B & Middleton C R: “Pervasive Fibre-optic sensor networks in bridges: a UK case study”. Proceedings, 9th International Conference on Bridge

- Maintenance, Safety and Management, IABMAS, Melbourne, Australia, 2018, pp.1738-1745.
17. Xu Y & Turkan I: “BrIM and UAS for bridge inspections and management”. *Engineering, Construction and Architectural Management*, Vol. 27, No. 3, 2019, pp. 785-807.
 18. Donato V, Biagini C, Bertini G & Marsugli F: “Challenges and opportunities for the implementation of H-BIM with regards to historical infrastructures: a case study of the Ponte Giorgini in Castiglione della Pescaia (Grosseto - Italy)”. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XLII-5/W1, 2017, pp.253-260.
 19. Riveiro B, Jauregui D V, Arias P, Armesto J & Jiang R: “An innovative method for remote measurement of minimum vertical underclearance in routine bridge inspection”. *Automation in Construction*, Vol. 25, 2012, pp. 34–40.
 20. Sacks R, Kedar A, Borrmann A, Ma L, Brilakis I, Hüthwohl P, Daum S, Kattel U, Yosef R, Liebich I, Barutcu B E & Muhic S: “SeeBridge as next generation bridge inspection: Overview, information delivery manual and model view definition”. *Automation in Construction*, Vol. 90, 2018, pp. 134–145.
 21. Banfi F, Barazzetti L, Previtali M & Roncoroni F: “Historic BIM: a new repository for structural health monitoring”. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XLII-5/W1, 2017.
 22. Cha G, Park S & Oh T: “A Terrestrial LiDAR-Based Detection of Shape Deformation for Maintenance of Bridge Structures”. *Journal of Construction Engineering and Management*, Vol. 145(12), No. 04019075, 2019.
 23. Barazzetti L, Banfi F, Brumana R, Previtali M & Roncoroni F: “BIM from laser scans... not just for buildings: NURBS-based parametric modeling of a medieval bridge”. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. III-5, 2016, pp. 51-56.
 24. McKenna T, Minehane M, O'Keefe B, O'Sullivan G & Ruane K: “Bridge information modelling (BrIM) for a listed viaduct”. *Proceedings of the Institution of Civil Engineers - Bridge Engineering*, Vol. 170, 2017, pp.1-12.
 25. León-Robles C A, Reinoso-Gordo J F & González-Quiñones J J: “Heritage building information modeling (H-BIM) applied to a stone bridge”. *International Journal of Geo-Information*, Vol. 8, No. 121, 2019.
 26. Borin P & Cavazzini F: “Condition assessment of RC bridges. Integrating machine learning, photogrammetry and BIM”, *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XLII-2/W15, 2019, pp.201-208.
 27. Stavroulaki M E, Riveiro B, Drosopoulos G A, Solla M, Koutsianitis P & Stavroulakis G E: “Modelling and strength evaluation of masonry bridges using terrestrial photogrammetry and finite elements”. *Advances in Engineering Software*, Vol. 101, 2016, pp. 136-148.
 28. Abu Dabous S, Yaghi S, Alkass S & Moselhi O: “Concrete bridge deck condition assessment using IR Thermography and Ground Penetrating Radar technologies”. *Automation in Construction*, Vol. 81, 2017, pp. 340-354.
 29. Alani A M, Aboutalebi M & Kilic G: “Integrated health assessment strategy using NDT for reinforced concrete bridges”. *NDT&E International*, Vol. 61, 2014, pp. 80-94.
 30. Conde B, Ramos L F, Oliveira D V, Riveiro B & Solla M: “Structural assessment of masonry arch bridges by combination of non-destructive testing techniques and three-dimensional numerical modelling: Application to Vilanova bridge”. *Engineering Structures*, Vol. 148, 2017, pp. 621-638.

31. Mathworks: “MATLAB”. MathWorks, 2021. [Online]. Available: <https://www.mathworks.com/products/matlab.html>. [Accessed 2021].
32. McGuire B, Atadero R, Clevenger C & Ozbek M: “Bridge information modeling for inspection and evaluation”. *Journal of Bridge Engineering*, Vol. 21(4), No. 04015076, 2016.
33. Microsoft: “Excel”, Microsoft, 2021. [Online]. Available: <https://www.microsoft.com/sv-se/microsoft-365/excel>. [Accessed 2021].
34. Huthwohl P, Brilakis I, Borrmann A & Sacks R: “Integrating RC bridge defect information into BIM models”. *Journal of Computing in Civil Engineering*, Vol. 32(3), No. 04018013, 2018, pp. 1–14.
35. Jeonga S, Hou R, Lynch J P, Sohn H & Law K H: “An information modeling framework for bridge monitoring”. *Advances in Engineering Software*, Vol. 114, 2017, pp. 11-31.
36. AUTODESK: “Revit”, AUTODESK, 2021. [Online]. Available: <https://www.autodesk.com/products/revit/overview>. [Accessed 2021].
37. Boddupalli C, Sadhu A, Rezazadeh Azar E & Pattysen S: “Improved visualization of infrastructure monitoring data using Building Information Modeling”. *Structure and Infrastructure Engineering*, Vol. 15, No. 9, 2019, pp. 1247-1263.
38. Kritzinger W, Karner M, Traar G, Henjes J & Sihm W: “Digital Twin in manufacturing: a categorical literature review and classification”. *IFAC PapersOnLine*, Vol. 51, No. 11, 2018, pp. 1016-1022.
39. Negri E, Fumagalli L & Macchi M: “A review of the roles of Digital Twin in CPS-based production systems”. *Procedia Manufacturing*, Vol. 11, 2017, pp. 939-948.
40. Sacks R, Brilakis I, Pikas E, Xie H & Girolami M: “Construction with digital twin information systems”. *Data-Centric Engineering*, Vol. 1, No. E14, 2020.
41. Khajavi S H, Motlagh N H, Jaribion A, Werner L C & Holmstrom J: “Digital Twin: Vision, benefits, boundaries, and creation for buildings”. *IEEE Access*, Vol. 7, 2019, pp. 147406-147419.
42. Shim C S, Dang N S, Lon S & Jeon C H: “Development of a bridge maintenance system for prestressed concrete bridges using 3D digital twin model”. *Structure and Infrastructure Engineering*, Vol. 15, No. 10, 2019, pp. 1319-1332.
43. Lu R & Brilakis I: “Digital twinning of existing reinforced concrete bridges from labelled point clusters”. *Automation in Construction*, Vol. 105, No. 102837, 2019.
44. Ye C, Butler L, Calka B, Iangurazov M, Lu Q, Gregory A, Girolami M & Middleton C: “A digital twin of bridges for structural health monitoring”, Proceedings, 12th International Workshop on Structural Health Monitoring - IWSHM, Stanford, USA, 2019.
45. FHWA: “Bridge Preservation and Maintenance in Europe and South Africa”, Washington D.C., USA, 2005.
46. Mirzaei Z, Adey B T, Klatter L & Thompson P: “The IABMAS Bridge Management Committee Overview of Existing Bridge Management Systems”, International Association for Bridge Maintenance and Safety (IABMAS), Sapporo, Japan, 2014.
47. Helmerich R, Niederleithinger E, Algernon D, Streicher D & Wiggerhauser H: “Bridge inspection and condition assessment in Europe”. *Transportation Research Record*, Vol. 2044, 2008, pp. 31–38.
48. Thompson P D, Small E P, Johnson M & Marshall A R: “The Pontis Bridge Management System”. *Structural Engineering International*, Vol. 8(4), 1998, pp. 303–308.
49. Gholami M, Sam A R M & Jamaludin M Y: “Assessment of Bridge Management System in Iran”. *Procedia Engineering*, Vol. 54, 2013, pp. 573-583.

50. Mendonça T, Brito V & Milhazes F: “Aplicação de gestão de obras de arte - GOA - nova geração” (*Bridge management application – GOA – new generation*). BETAR Consultores Ltda., Lisbon, 2010 (in Portuguese).
51. Mocosó Y F M: “Modelos de Degradação para Aplicação em Sistemas de Obras de Arte Especiais – OAEs” (*Degradation models for bridge application systems*) (PhD Thesis), University of Brasília, Brasília, Brazil, 2017 (in Portuguese).
52. Liao H K & Yau N J: “Development of Various Bridge Condition Indices for Taiwan Bridge Management System”, Proceedings, 28th International Symposium on Automation and Robotics in Construction, Seoul, Korea, 2011, pp.911-916.
53. Safi M, Sundquist H, Karoumi R & Racutanu G: “Development of the Swedish bridge management system by upgrading and expanding the use of LCC”. *Structure and Infrastructure Engineering*, Vol. 9(12), 2013, pp. 1240-1250.
54. Mirzaei Z, Adey B T, Klatter L & Thompson P: “The IABMAS bridge management committee overview of existing bridge management systems”, International Association for Bridge Maintenance and Safety (IABMAS), Sapporo, Japan, 2014.
55. Chan B, Guan H, Hou L, Jo J, Blumenstein M & Wang J: “Defining a conceptual framework for the integration of modelling and advanced imaging for improving the reliability and efficiency of bridge assessments”. *Journal of Civil Structural Health Monitoring*, Vol. 6, 2016, pp. 703-714.
56. Hendy C, Brock C & Nicholls T: “Management of the M4 Elevated Section substructures”. *Proceedings of the Institution of Civil Engineers: Bridge Engineering*, No. 1600006, 2017.
57. Previtali M, Barazzetti L, Banfi F & Roncoroni F: “Informative content models for infrastructure load testing management: The Azzone Visconti bridge in Lecco”. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XLII-2/W11, 2019, pp. 995-1001.
58. Tao F, Zhang M, Liu Y & Nee A Y C: “Digital twin driven prognostics and health management for complex equipment”. *CIRP Annals*, Vol. 67, 2018, pp. 169-172.
59. Brilakis I & Ariyachandra M: “Application of Railway Topology for the Automated Generation of Geometric Digital Twins of Railway Masts”. *ECPPM 2021 – eWork and eBusiness in Architecture, Engineering and Construction*, 2021, pp. 373-380.
60. Dibbernardo S: “Integrated modelling systems for bridge asset management - case study”, Structures Congress, Reston, USA, 2012, pp. 483-493.
61. Brady K C, O’Reilly M, Bevc L, Znidaric A, O’Brien E & Jordan R: “Cost 345 - Procedures required for the assessment of highway structures - Final report”. European Co-operation in the Field of Scientific and Technical Research, Brussels, Belgium, 2009.
62. Zhao Z, Gao Y, Hu X, Zhou Y, Zhao L, Qin G, Guo J, Liu Y, Yu C & Han D: “Integrating BIM and IoT for smart bridge management”, Proceedings, IOP Conference Series: Earth and Environmental Science, Vol. 371, No. 022034, 2019.
63. Zhu J, Tan Y, Wang X & Wu P: “BIM/GIS integration for web GIS-based bridge management”. *Annals of GIS*, Vol. 27(1), 2020, pp. 99-109.
64. Marzouk M M & Hisham M: “Bridge information modelling in sustainable bridge management”. Proceedings, International Conference on Sustainable Design and Construction - ICSDC, Kansas City, USA, 2011, pp. 457-466.
65. Wan C, Zhou Z, Li S, Ding Y, Xu Z, Yang Z, Xia Y & Yin F: “Development of a bridge management system based on the building information modelling technology”. *Sustainability*, Vol. 11, No. 4583, 2019.
66. Hallberg D & Racutanu G: “Development of the Swedish bridge management system by introducing a LMS concept”. *Materials and Structures*, Vol. 40, 2007, pp. 627-639.

67. Shafto M, Conroy M, Doyle R, Glaessgen E, Kemp C, LeMoigne J & Wang L: “DRAFT Modeling, Simulation, Information Technology & Processing Roadmap”, *Technology Area 11*, 2010.