IBRACON Structures and Materials Journal
Revista IBRACON de Estruturas e Materiais
ISSN 1983-4195 ismj.org

ORIGINAL ARTICLE

Bridge Information Modeling (BrIM) used in the operation and maintenance of Civil Engineering Structures (CESs)

Bridge Information Modeling (BrIM) aplicado na operação e manutenção de Obras de Arte Especiais (OAEs)

Thalyta de Miranda Lanna Rios[a]
Luiz Reynaldo de Azevedo Cardoso[a]
Beatriz Montelato[b]
Tiely Zurlo Mognhol[b]

[a]Universidade de São Paulo – USP, Escola Politécnica, Departamento de Engenharia de Construção Civil, São Paulo, SP, Brasil
[b]Universidade de São Paulo – USP, Escola Politécnica, São Paulo, SP, Brasil

Received 17 January 2023
Accepted 28 May 2023

Abstract: Studies have shown a worrisome condition as to the conservation of Civil Engineering Structures (CESs) in Brazilian highways. This situation mainly results from the lack of an efficient system for managing such structures, specifically during their operational stage, when periodic maintenance is required. As a solution, the Bridge Information Modeling (BrIM) has proven to be an efficient system for managing CESs, integrating different technologies into this process. The purpose of this paper is to assess how BrIM can contribute to improve the management procedures of these structures. The research methodology has been divided into two stages. The first one is the literature review detailing the management scenario of CESs in the country, as well as the analysis of the BrIM used as a tool to manage such structures in a general context. The second stage is a case study addressing the operational and maintenance process of CESs used by a highway concessionaire in an important Brazilian state. The analysis concluded that, although recent, the adoption of BrIM has been growing in several countries, and it can substantially contribute to improving the operational and maintenance stages of CESs.

Keywords: BIM, BrIM, bridges, management, life cycle.

Resumo: Estudos apresentam um quadro preocupante no que se refere à conservação das Obras de Arte Especiais (OAEs) presentes nas rodovias brasileiras. Esse problema deve-se, em grande parte, à falta de um sistema eficiente para o gerenciamento das OAEs, especialmente na etapa de operação das estruturas, quando há necessidade de manutenções periódicas. Como solução, o Bridge Information Modeling (BrIM) tem se mostrado um sistema eficiente para o gerenciamento de OAEs, integrando diferentes tecnologias nesse processo. O objetivo desse trabalho é avaliar como o BrIM pode contribuir para o aperfeiçoamento dos procedimentos de gerenciamento das OAEs adotados no Brasil. A metodologia de pesquisa foi dividida em duas etapas. A primeira refere-se à revisão bibliográfica que apresenta o cenário do gerenciamento das OAEs no país, bem como à análise do uso do BrIM como uma ferramenta de gerenciamento de OAEs em um contexto geral. A segunda etapa apresenta um estudo de caso que aborda o processo de operação e manutenção de OAEs por uma concessionária de rodovias de um importante estado brasileiro. A análise permitiu concluir que, apesar da utilização do BrIM ser relativamente recente, sua adoção está em crescimento em vários países e pode contribuir substancialmente para o aperfeiçoamento da etapa de operação e manutenção de OAEs.

Palavras-chave: BIM, BrIM, pontes, gerenciamento, ciclo de vida.

How to cite: T. M. L. Rios, L. R. A. Cardoso, B. Montelato, and T. Z. Mognhol, "Bridge Information Modeling (BrIM) used in the operation and maintenance of Civil Engineering Structures (CESs)," *Rev. IBRACON Estrut. Mater.*, vol. 17, no. 3, e17304, 2024, https://doi.org/10.1590/S1983-41952024000300004

Corresponding author: Thalyta de Miranda Lanna Rios. E-mail: thalyta.rios@usp.br
Financial support: None.
Conflict of interest: Nothing to declare.
Data Availability: All data that support the findings of this study are already available in the article. Additional information is available from the corresponding author, [T. M. L. Rios], upon reasonable request.

1 INTRODUCTION

Most federal, state, and municipal agencies responsible for the highways that make up the Brazilian highway network do not have specific and efficient systems for managing Civil Engineering Structures (CESs) – bridges, tunnels, viaducts, footbridge, and containment structures (DNIT [1]) - or even systematically conduct the inspection and maintenance procedures of these structures. Corroborating this statement, Vitório [2] points out that the lack of maintenance "has resulted in a worrisome condition as the deterioration processes of these bridges, which have been evolving over the years, are observed, being the situation, in some cases, close to structural ruin" [2, p. 13].

A study by Vitório and Barros [3] presented the analysis of inspections conducted on 100 bridges on eight Brazilian federal highways and concluded that none of them reached the maximum score, which corresponds to a trouble-free engineering work. On the contrary, this study pointed out that 38% of the CESs analyzed were classified as potentially problematic, 35% as poor engineering works, 24% as engineering works without major problems, and 3% at risk of collapsing. According to Jeong et al. [4], in most cases, the bridge management practice interacts with distinct types of information, uses single systems, and operates with limited use of data. These authors add that information sharing and integration tend to significantly improve the management of these structures.

In this context, the Building Information Modeling (BIM) emerges as a viable technological option to systematize and integrate all the processes required for the management of CESs. BIM is defined as an innovative approach to developing and managing projects that integrates people, systems, and business structures into a collaborative process with the goal of reducing waste and optimizing efficiency at all stages of the project life cycle (Azhar [5] *apud* Glick and Guggemos). Many countries, such as the United Kingdom, Canada, the United States of America, and Germany, are studying and adopting BIM, both in the feasibility, design, and construction stages, and in the operational stage of CESs, cases in which the model is called Bridge Information Modeling (BrIM).

According to Costin et al. [6], structures such as bridges differ greatly from buildings, especially in the construction and operation stages – besides the unique characteristics of these structures, such as the alignment of the structure with the road, among others and therefore it is necessary to separate BrIM from BIM. Another point that emphasizes the need for this separation is the large investment required in the operation and maintenance stages throughout the life cycle of these structures.

Specifically in the operational stage, which includes the monitoring of structures through procedures such as inspections, rating, and prioritization of interventions, BrIM is used as a system that integrates data from different technological devices, such as unmanned aerial vehicles (drones) equipped with cameras in inspections and laser scanners, which generate point clouds and enable the production of 3D models. Another example consists of a study by McGuire et al. [7], which presents a method that uses Building Information Modeling (BIM) software to link and analyze data from the inspection, assessment, and management of bridges. The results of this study suggest that BIM can effectively facilitate bridge inspection and assessment, leading to an automated practice, and allowing transportation agencies to effectively manage bridge inventories.

In Brazil, the federal administration supports initiatives for the diffusion of innovations in the construction sector, one of these being the publication of Decree nr. 9,983 of August 22, 2019 [8], which provides for the National Strategy for the dissemination of BIM, called BIM BR Strategy (Estratégia BIM BR), with the purpose of promoting a suitable environment for investment in the methodology and its diffusion in the country. Along the same lines of encouraging the dissemination of BIM use, the federal administration published on April 2, 2020, Decree nr. 10,306 [9], which establishes the use of BIM in the direct or indirect execution of engineering works and services performed by agencies and entities of the federal public administration, under the BIM BR Strategy. Also noteworthy is the Structure Maintenance and Rehabilitation Program (PROARTE - Programa de Manutenção e Reabilitação de Estruturas), a pilot project that aims to implement BIM in the maintenance, recovery and rehabilitation stages of the CESs distributed along the network of federal highways administered by the National Department of Transport Infrastructure (DNIT - Departamento Nacional de Infraestrutura de Transportes [1]).

Considering the above and in view of the urgent demand for the adoption of more efficient and technological methods for the management of CESs in Brazil, this study aims to assess how the Bridge Information Modeling (BrIM) can contribute to the systematization of the necessary procedures to ensure the operation, maintenance, safety adequacy, and functionality required throughout the life cycle of these structures.

2 OPERATION AND MAINTENANCE OF CESS IN BRAZIL

Most Civil Engineering Structures, such as bridges and viaducts, as well as other infrastructure works: highways, railways, hydroelectric power plants, transmission lines, among others, were designed and built in the 1940s in Brazil, when the construction of the major highway works (Dutra and Anchieta highways), steel mills (CSN), hydroelectric power plants (Henry Borden, from the 1930s, and Ilha Solteira, from the late 1960s) began, as reported in a study conducted in 2005 by the National Association of Architectural and Consulting Engineering Companies (SINAENCO - Sindicato Nacional das Empresas de Arquitetura e Engenharia Consultiva). According to this study, the situation is even worse in the states and municipalities, since much of the urban infrastructure in major metropolises was built in the early 20th century and, thus, has been on its expiration date for a few years now. Therefore, the consequences are beginning to be seen with greater intensity in the central – and older – areas of capital cities such as São Paulo, Rio de Janeiro, Salvador, Recife, among others. [10].

According to Vitório [2], a large part of CESs in the federal, state, and municipal highway networks present pathological problems resulting from lack of maintenance.

As examples, it is worth mentioning the cases of the Marginal Pinheiros viaduct (Figure 1A), and the General Olímpio da Silveira viaduct (Figure 1B), both located in the city of São Paulo. On November 15, 2018, part of the structure of the Marginal Pinheiros viaduct gave way by approximately two meters. The risk of a major accident was high, given that Marginal Pinheiros is a road with a large flow of vehicles and has an interface with the railroad of the São Paulo Metropolitan Trains Company (CPTM - Companhia Paulista de Trens Metropolitanos), a railway modal used for passenger transportation. The reinforcement of the General Olímpio da Silveira viaduct is exposed under the deck, a frequent problem in CESs in Brazil. Other problems, such as deteriorated expansion joints, beams with damage caused by vehicle collisions, and wear of the support devices between the precast elements, are also common due to the lack of monitoring and maintenance processes.

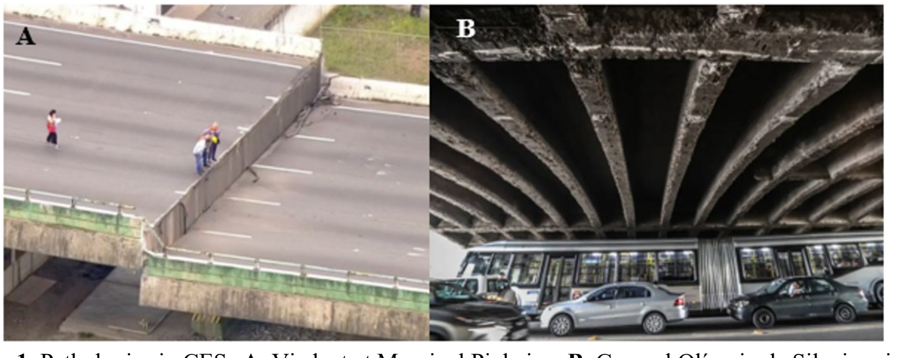


Figure 1. Pathologies in CESs **A.** Viaduct at Marginal Pinheiros **B.** General Olímpio da Silveira viaduct

The situation is complex since the routine of inspections and maintenance is not conducted regularly and, therefore, the possibility of structure collapse is not evaluated. Agencies such as DNIT and the Department of Highways (DER - Departamento de Estradas de Rodagem), responsible for the operation and maintenance of highways, and consequently of CESs, at the federal and state levels, respectively, as well as the municipalities - responsible for CESs at the municipal level - and highway concessions, which are responsible for the operation and maintenance of CESs along the stretches under concession, base their inspection procedures on the Brazilian Standard ABNT NBR 9452 (Associação Brasileira de Normas Técnicas - Norma Brasileira) [11].

This standard, revised in 2019, specifies the requirements for conducting and presenting the results of inspections of concrete bridges, viaducts, and footbridges, and aims to standardize the identification and assessment of the constituent elements of CESs, the provision of parameters for rating their conservation status, and also the offer of subsidies for prioritizing actions for maintenance and intervention of the engineering works according to the severity of the problems observed.

This way, ABNT NBR 9452 [11] establishes four types of inspections, as well as their regularity: 1) registration inspection; 2) routine inspection; 3) special inspection; and 4) extraordinary inspection.

During inspections, the CESs are classified according to the following parameters: i) structural - related to the structural safety of the Civil Engineering Structure (stability and bearing capacity); ii) functional - evaluating aspects of the Civil Engineering Structure directly related to the purposes for which it is intended (visibility, adequate vertical and horizontal clearances, etc.), in addition to comfort and safety of users (intact guardrails, absence of depressions and/or holes in the roadway, and adequate signaling); and iii) durability - evaluating the characteristics of the Civil Engineering Structure directly associated with the roadway.), besides the comfort and safety of users (intact guardrails, absence of depressions and/or holes in the roadway, and proper signaling); and iii) durability - assessing the characteristics of the Civil Engineering Structure directly associated with its life cycle, i.e., the estimated time the structure should fulfill its service functions. Examples of anomalies associated with durability are the lack of reinforcement cover, corrosion, cracks that allow infiltration, erosion on junction slopes, among others.

ABNT NBR 9452 [11] establishes the criteria for rating CESs based on grades, consisting in the attribution of the assessment of their condition, which can be excellent, good, regular, poor, or critical, associating grades to the structural, functional, and durability parameters. The assessment grades range from 1 to 5, reflecting greater severity (1) or lesser severity (5) for the problems detected. Although there are procedures that aim to guarantee the maintenance regularity of CESs in Brazil, it is important to highlight some aspects, identified according to the authors´ experience and knowledge, that hinder the implementation of such procedures and can be solved with the adoption of new technologies:

- Large amount of CESs with no *as built* drawings;
- Inspection reports delivered in printed or digital media, but which are not organized. This makes it difficult to consult the documents, especially to monitor the evolution of pathologies and the general stage of each structure;
- Changes in the management teams of CESs, combined with the lack of an integrated system for filing the inspection reports, which implies data loss, considering the long life cycle of CESs;
- Absence of a system with alerts for the inspection due dates, which requires the management team to be extremely responsible for this control; among others.

3 RESEARCH METHODOLOGY

The research was conducted in two stages. The first corresponds to a literature review using the main databases to outline an overview of the use of BIM integrated technologies in the operational and maintenance stages of CESs, as detailed in chapter 4. On the other hand, the second stage, detailed in chapter 5, shows, in a case study, the management processes of CESs adopted in a company of the highway concessions segment in Brazil, highlighting as an advantage the inclusion of tools and technologies to optimize these processes. In addition, the benefits already achieved with the use of such technologies and the opportunities for improvement will be shown, considering the possibility of integrating the into BrIM. The criteria to select the case were the researchers´ access to key stakeholders and documentation on the management processes of CESs.

4 LITERATURE REVIEW

To analyze the implementation of BrIM in the operation and maintenance stage of CESs, a literature review was conducted by searching for publications indexed in the Scopus and Web of Science databases, using the keywords "building information model*" and "bridge" as search parameters, selecting only scientific articles and reviews, delimiting the period from 2016 to 2023. The first results showed 254 publications. From this sample, a duplicity analysis was conducted, comparing the two databases used and excluding repeated articles, resulting in 184 publications. Then, the titles were analyzed, resulting in a sample of 98 publications specific to the application of the BIM process in CESs.

Next, content was analyzed, identifying as the dominant theme the use of BrIM in the design, construction, operation, and maintenance phases, including monitoring, inspection, and management of CESs, as well as publications focused on sustainability or information technology. From this analysis, 78 articles were excluded for not reflecting the scope of the research, resulting in a final sample of 20 articles more relevant and specific to the use of BrIM in the Operation and Maintenance phase of CESs. The content analysis of these articles will be detailed in the following subsections.

4.1 Inspection Technologies

Paper-based data acquisition and manual transfer between software or incompatible data formats during bridge inspections, as currently conducted, are time-consuming, error-prone, complicated, and lead to loss of information according to Artus et al. [12], what limits the ability to transfer knowledge throughout the life cycle of the structure.

Samuel et al. [13] conducted a survey of bridge inspectors, which pointed out that visual inspection techniques are the prominent inspection method, but result in inaccuracy and ambiguity due to large variations between inspectors' analyses.

According to Morgenthal et al. [14], the interpretation and judgments of inspections based on human vision are subjective. The manual process is expensive and time-consuming, in addition to posing safety risks, as well as requiring skilled, experienced, and highly trained professionals. Chan et al. [15] report that inspections require systematic investment strategies with intelligent and accurate condition assessment paradigms.

With the scarce number of engineers and extensive work to conduct the inspections, technologies can assist, for example, with the use of equipment that generates point clouds (Figure 2), from which 3D models can be derived. However, as mentioned by Sacks et al. [16], there are still two challenges to be overcome: semantic enrichment and automatic recognition of the elements.

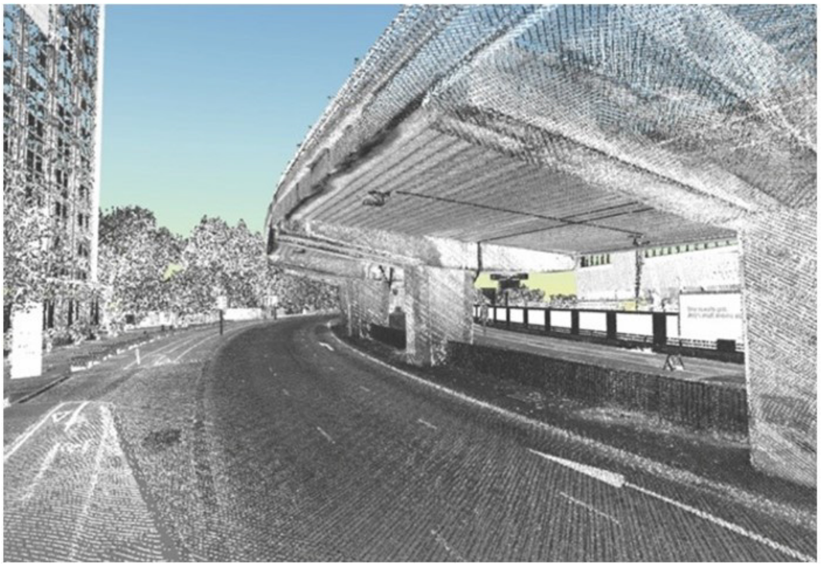


Figure 2. Point clouds of the M4 Flyover in West London

The implementation of BrIM for collecting field data, through the integration between technologies assists the gathering of georeferenced data, and archives information about the history of inspections and interventions in structures throughout the life cycle, being possible to integrate information related to their condition and deterioration. According to Chan et al. [15], BIM, together with the advances in computing and imaging technologies, allows the detection of defects such as fissures, cracks, and corrosion through texture recognition.

The as built of structures can be drawn from information (point clouds) provided by a laser scanner. According to Chan et al. [15], laser scanning technology can improve efficiency and save resources over the traditional large-scale structure survey method. These advantages arise from the fact that traditional measurement is conducted from theodolites, requiring leveling and alignment during use, as well as coordinate registration, being susceptible to accumulating distinct types of errors.

However, the location of the laser scanner can interfere with data quality and result in occlusions (dark areas/shadow areas). Therefore, depending on local conditions, it may be difficult to place the laser scanner in all desired locations. One of the solutions is to use this equipment in the air, on drones. However, as cited by McKenna et al. [17], airborne laser scanning significantly reduces geometric accuracy, as the technology still needs advances in accuracy (Wang et al. [18]).

In addition to the laser, the inspection can be conducted from drones equipped with cameras, enabling the inspectors to analyze them afterwards. Drones are mainly used in hard-to-reach locations. Jensen [19] mentions that, with video images, it is hard to locate each observation due to the comprehensive size of the structure and presence of very similar surfaces. Another form of inspection can be conducted from photos or videogrammetry, equipped on a drone, with the digital generation of high-resolution image data of the structural surface, enabling the estimation of motion and constant imaging properties from a single camera, from the identification of image points, calculation of initial image geometry and 3D point clouds geometry.

Anomaly detection can be conducted from a 3D model imported along with the imagery as presented by Jensen [19] in Figure 3, or by applying using the imagery from photogrammetry (Morgenthal et al. [14]), shown in Figure 4.

Figure 3. Image overlapping on the 3D model

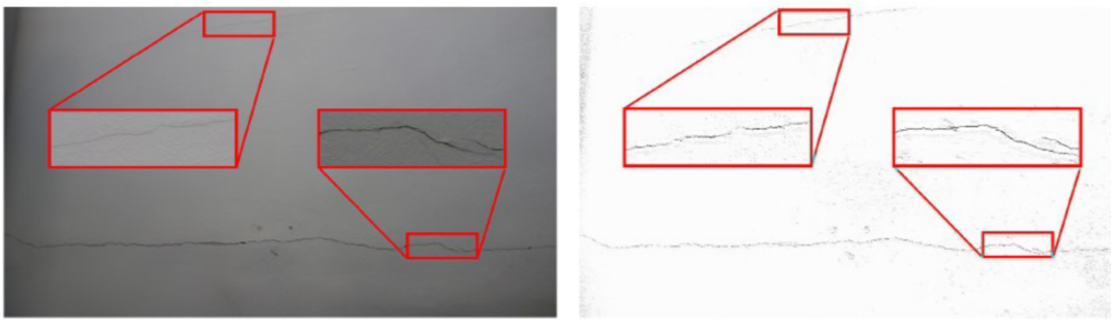


Figure 4. Surface without fissure (left) and surface with fissure (right)

According to Jensen [19], COWI, an international consulting group specializing in engineering, environmental science, and economics, has developed a web-based tool called COWI Virtual Inspection (CVI). With this tool, the 3D surface model of the structure is imported along with images, both generated from the inspection conducted by the drone, and all the data collected during the inspection is inserted into its respective geographical location. In addition, the data obtained in the field can be recorded in the system. Morgenthal et al. [14] proposed an image processing sequence such as enhancement, segmentation, and feature extraction to identify and group the crack pixels in images. In the future, additional data such as thermography may assist detections.

As presented by Chan et al. [15], the random and irregular shapes of cracks and fissures can be confused with the various surfaces of objects, resulting in false detections, indicating the need for technological advances, and not excluding the analysis of inspectors.

According to Sacks et al. [20], SeeBridge (Semantic Enrichment Engine for Bridges) was developed by the European Union, together with partners from the United States of America, the United Kingdom, Germany, and Israel. The tool aids in inspection as it scans the point clouds as well as semantic enrichment with the encoding of the bridge components. In the process, high-resolution images of the pathologies are mapped onto the surfaces of the model objects, and the damage associated with the identified defects is measured.

In addition to BrIM´s assistance in reproducing the as built and identifying anomalies in structures, the process contributes to the quantification of anomalies. According to McGuire et al. (2016) [7], the Bridge Information Modeling for Inspection and Evaluation (BIEM) was created using a plug-in developed in Revit, a BIM software, called Damage Location Tool (DLT) with which it is possible to model the pathology in the structure from a parametric parallelepiped used to represent the volume and severity of the anomaly, also providing a graphical visualization of the damaged areas of the structure.

Mohammadi et al. [21] presents a real case study that integrated BrIM with a Decision Support System (DSS) for the digital twinning and management of Werrington Bridge, a cable-stayed bridge in New South Wales, Australia. Figure 5 shows the detection of a vertical deformation in the concrete deck of the bridge, illustrated by color counters. The deviation of the 3D CAD model and the point clouds, generated by Terrestrial Laser Scanning (TLS), were analyzed using an interference detection algorithm integrated into 3D CAD modeling software called Tekla Structures. The conflict detection and progress tracking algorithms allow engineers to discover changes in the bridge model or TLS data over time, and the results can be a reliable source of information for bridge evaluation at distinct levels of inspection.

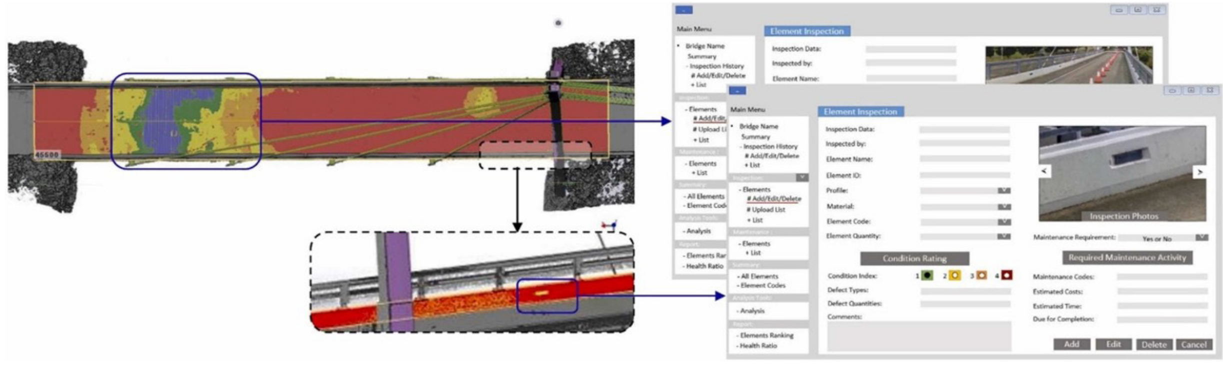


Figure 5. Clash detection and data assignment into BrIM-oriented BMS plugin

4.2 Monitoring Technologies

Monitoring techniques provide important data for maintaining the integrity of structures, contributing to avoid unexpected disruptions in CESs with significant importance. According to Delgado et al. [22], BIM transforms structural monitoring into a more dynamic process. This is because the automatic generation of parametric BIM models from structural monitoring systems, which include time-series sensor data, allows for dynamic, data-driven organization and visualization in an interactive 3D environment as a way of mitigating disasters from long-term monitoring data (Boddupalli et al. [23] and Delgado et al. [22]). Applications of integrated Structural Health Monitoring (SHM) systems using BrIM were studied in the United Kingdom on a bridge near Stafford (Delgado et al. [22]), as well as in the United States of America on a bridge located in Monroe, Michigan (Jeong et al. [4]), and in Canada on a bridge in Thunder Bay, Ontario (Boddupalli et al. [23]).

As presented by Delgado et al. [22], the use of BIM allows the visualization of key structural performance parameters, as well as long-term continuous updating and data management, facilitated by interoperability and use of Industry Foundation Classes (IFC). In addition, it helps decision making, evaluating whether an asset is operating at sufficient safety levels and whether further inspection or immediate intervention is required. From the development of an IFC-compatible data model for structural monitoring systems, Delgado et al. [22] validated the use of BIM for monitoring from the use on a real structure. Fiber optic-based strain sensor systems were integrated with a BIM environment capable of importing, visualizing, and managing monitoring data over time.

Boddupalli et al. [23] presented a study conducted on a bridge in Canada on the use of BIM for a better understanding of structural damage evolution in a federated model of the structure by comparing expected results, calculated from structural analysis software, with those obtained experimentally through sensors.

Applications have shown that BrIM assists in interpreting data through a simple interface to communicate with various stakeholders, allowing the identification of malfunctioning sensors, contributing to assess the durability of the monitoring system, to which it can be integrated with a powerful asset management tool.

4.3 Priority Management and Planning

Those responsible for the asset management need solutions to maximize the effectiveness and reliability of structures, and minimize the costs and environmental impacts, and end of life cycle probability of the structure. Thus, it is important to consider both the history of operation and maintenance, as well as new ways of working with the innovation of technologies (Jensen [19]). Preventive maintenance is much better than corrective maintenance. For this to occur, management throughout the entire life cycle of the structure is crucial, and a process of prioritizing maintenance and monitoring is indispensable.

According to Hendy et al. [24], BrIM can assist by visually representing the maintenance strategy, thus allowing visualization of the evolution of deterioration over time and making it possible to decide when intervention is required by providing an interactive and intuitive logging system. The priorities are not only for the need of structural reinforcement, but also for monitoring and maintenance of the structures. BrIM can be adopted for both new and existing developments.

According to McGuire et al. [7], in addition to the DLT plugin (used in inspections), BIEM features the Damage Evaluation Tool (DET) plugin, from which inspection results, such as geometry and damage location, are used in the evaluation for decision making, including structural performance and resistance load rating, proposing maintenance and recommendations for the selected elements, thus improving the accuracy of repair and maintenance projects, as well as budgeting and contract drafting. Using Navisworks, a BIM software, data can be visualized numerically or by color scale (Figure 6), along with the evolution of deterioration, allowing predictions of the structure´s condition for prioritizing interventions.

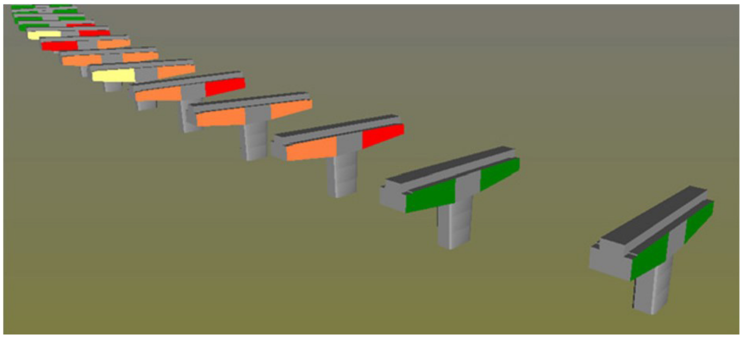


Figure 6. Variation of chloride levels in the crossbeams (Navisworks)

According to Jensen [19], the wider application of recent technologies in bridge operation and maintenance will occur when they become more technically and financially feasible.

With the recent development of the Internet of Things (IoT), Digital Twin (DT) related technologies have been developing for applications in the management of structures, such as bridges, throughout their life cycle. DT is based on connecting a physical artifact and its digital counterpart, and by integrating technologies such as IoT, GIS, laser scanning, and photogrammetry, it is possible to monitor geometric and non-geometric information and control the physical parts of structures in order to perform asset management comprehensively, which includes disaster prevention and mitigation (Jiang et al. [25]).

Jiang et al. [25] highlights that, although both BIM and DT require a virtual model, these technologies are quite distinct as a BIM model is a digital representation of the physical and functional characteristics of something that may not yet exist, whereas a DT must necessarily reflect the existing condition of a physical counterpart in a timely manner.

5 PROCEDURES FOR MANAGING CESS ADOPTED IN A HIGHWAY CONCESSION IN BRAZIL

The Concessionaire that is the subject of this study is responsible for managing a highway network in an important state in Brazil, with approximately 500 kilometers and 200 CESs, including underpasses, overpasses, bridges, and footbridges.

The concession contract provides for the monitoring and management of the CESs during the entire concession period to ensure the retention and adequacy of the required safety and functionality, according to a technical specification called *"Especificação Técnica - Monitoração e Gerenciamento de Obras de Arte Especiais"* (Technical Specification - Monitoring and Management of Special Civil Engineering Structures). This specification includes the requirements for the inspection and structural, functional, and durability assessment of CESs, in accordance with the current standards of ABNT NBR 9452 [11].

In this way, the aforementioned specification defines the procedures for preparing records, field inspections, tests, preliminary and final diagnosis, planning of intervention priorities, monitoring, and recording recoveries, performance evaluation, planning with data updating, and recording during routine and/or special inspections of CESs.

In the concession that is the subject of this study, all management of CESs is conducted according to this specification, including in the routine of the technical team responsible for managing these assets the following procedures: i) preparation of records; ii) field inspections and tests; iii) preliminary and final diagnosis; iv) planning of priorities for interventions; and v) monitoring of interventions and records.

To exemplify the methodology used in the inspections conducted by the Concessionaire, Figure 7 shows an example of a Routine Inspection Form. This inspection was conducted by a specialized company engaged by the Concessionaire, and the procedure adopted for the assessment was the on-site inspection, without the use of special equipment and/or resources, as the viaduct is easily accessible throughout the structure. The pathology assessment was conducted during the inspection, including photographic record for further analysis.

ROUTINE INSPECTION

CIVIL ENGINEERING STRUCTURE: 0XX
INSPECTION DATE: XXXXXX

A – Location and Designation
Highway: *XXX* Direction: *Transverse*
Civil Work: *Upper walkway* km: *XXX+XXX*

B – History of Inspections
Beginning: xxx Last Routine Inspection: *xxx* Special: xxx

C – Description of Interventions Performed or in Progress
Repairs: *No evidence.*
Renovations: *No evidence.*
Reinforcements: *No evidence.*

D1 – Visual Characterization of Structure Conditions
Deck: *Cantilever slab with fissures with efflorescence. Longitudinal beams, on cantilever 2 with disaggregate concrete with exposed armor.*
Expansion Joints: *Annexed joints, with cracks on surface.*
Support Equipment: *Freyssinet articulation, in good condition.*
Supports: *Pillars 2 and 3 and holding beam 2 with segregate concrete with exposed armor.*
Junctions: *Curtain with segregate or disaggregate concrete with exposed armor and void. 1 curtain with efflorescence stains.*

D2 – Visual Characterization of Road on Structure
Surface: *Asphalt, with fissures.*
Roadside: *Asphalt surface, with fissures.*
Drainage: *Puddling water on roadsides.*
Guardrail: *Concrete, in good condition.*
Hard barriers: *Hard barriers with disaggregate concrete with exposed armor.*
Metal fenders:

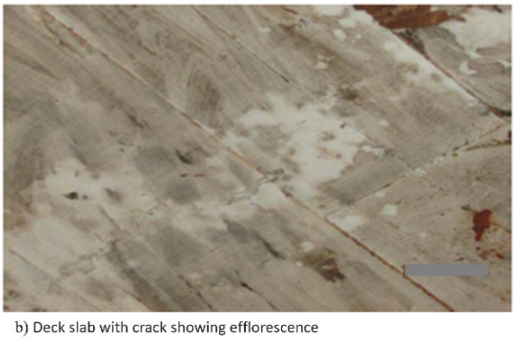
D3 – Visual Characterization of Other Elements
Slopes: *Covered by concrete plates. Cover of North slope with accommodation and South slope with erosion.*
Lighting: -
Signage: *Worn out horizontal signate.*
Clearance: *East/West Road: 5.3m.*
Pillar Protection: *Metal fenders, in good condition.*

D4 – Complementary Information
Flow of vehicles on the upper road in both directions.
Presence of walking area in both sides.

E – Indication of Treatments
1 – Treatment of fissures and efflorescence;
2 – Recovery of areas presenting disaggregate or segregate concrete with exposed armor, surface and slope;
3 – Void filling in junction;
4 – Drainage adequacy on walking areas;
5 – Recovery of junctions, surface, slope, and signage.

F – Updating of Civil Work Rating
Structural: *B2* Functional: *B3* Durability: *B2*

a) Longitudinal beam 3, on overhang 3, with crumbling concrete and exposed reinforcement



b) Deck slab with crack showing efflorescence

Figure 7. Routine Inspection Form

The condition of the Civil Engineering Structure was then written on this form, based on the visual characterization of the elements, photos that prove such condition, and updating the rating of this Civil Engineering Structure.

This procedure fully complies with the specification and ABNT NBR 9452 [11], being adopted in all CESs under the management of the Concessionaire.

An advance adopted in the most recent inspections is the use of drones to perform inspections in very high and long bridges still in operation, difficulty of access and posing risks to inspectors. This occurs because, to perform such inspections, it is necessary to install temporary structures and/or specific equipment, such as articulated lifting platforms, scaffolding, rope climbing, etc., to allow inspectors to access all elements of the structure. Also, because it is a work at height, specific training and protective equipment for inspectors is required. Figures 8, 9 and 10 are examples of photographic records of routine inspections performed with this tool.

Figure 8. Crossbeam 11 with cracks

The use of the drone as a tool for capturing photos, besides the safety factor already mentioned, also brings agility and greater coverage, with the possibility of more distant and closer photos, allowing a better analysis by the inspectors. We also highlight the agility to make new records if the inspectors need more specific photos of some area of the structure.

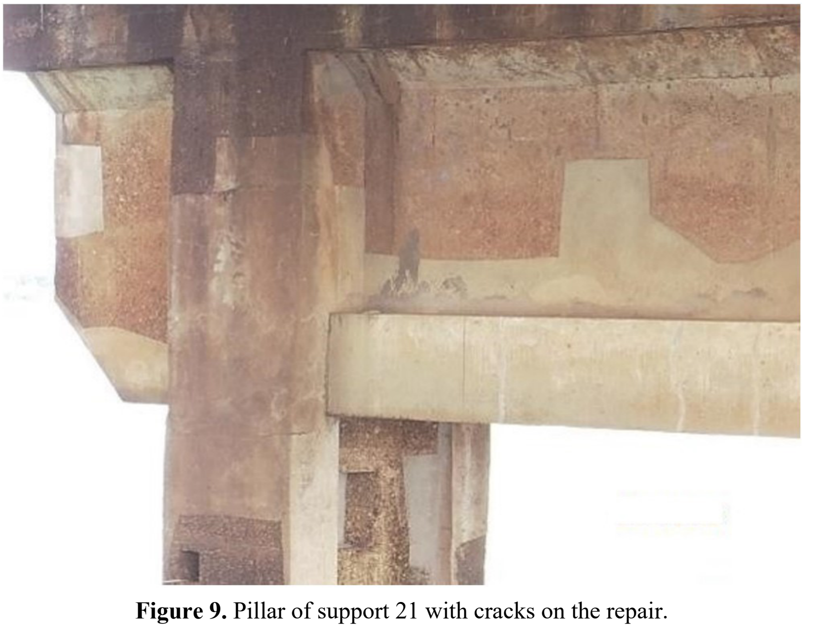


Figure 9. Pillar of support 21 with cracks on the repair.

Figure 10. Span 12 of the longitudinal beam 2, with signs of water infiltration. It was possible to note the absence of an extension tube on the drainpipe.

The technical team responsible for monitoring the CESs controls the frequency of inspections in a systematic way, and directs and monitors the interventions, as defined in the concession contract, recording data, and keeping all the history of each CESs.

For this control, another advance is the use of a website-based system developed specifically for this purpose, in which all the inspection reports are entered, facilitating the retention of this history. Using the system, it is also possible to identify the location of each Civil Engineering Structure along the highway network on a map, where they were schematically inserted just as an icon.

Thus, information about the history of inspections of the CESs is displayed when clicking on each icon on the map.

In addition, the system generates graphs with the rating history of the CESs over the years in which inspections were conducted for structural, functional, and durability parameters. Although not a BIM model, this system shows a relevant advance in the storage and maintenance of information and history of CESs inspections.

More recently, a new tool was implemented in the CESs, with the objective of allowing access to the data of each one of them registered in the aforementioned system, by reading a QR Code fixed on the structure, with the help of a mobile device (cell phone or tablet).

By reading the QR Code, professionals can access in loco all the information of the structure, included in the system, such as data from previous inspections, with no need to print these reports previously, reducing the use of paper. Figure 11 illustrates the reading of the QR Code implemented in one of the CESs with the use of a cell phone. It is noteworthy that the installation location of the QR Code has been standardized, usually at the lower and inside part the structures, to facilitate access by inspectors and also to prevent vandalism.

The technologies shown can be used as tools integrated to BrIM, to add inspection data in the model and promote better information management during the life cycle of the structures.

It is important to emphasize that the entire process described, which includes the regularity of the inspections, rating of CESs, and retention of the history of inspections and interventions in a system, and also the use of tools such as drones and QR Codes, is practiced by the Concessionaire that is the subject of this study and may not reflect the reality of the operation and maintenance situation of most of the CESs in other highways in Brazil.

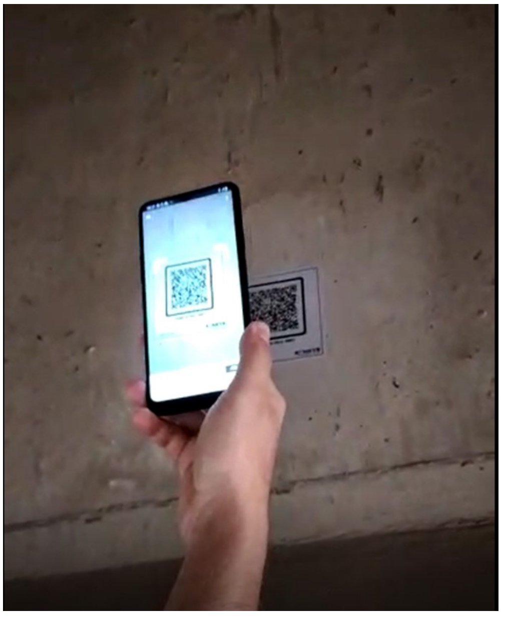


Figure 11. Access to the system and CES information using QR Code.

The procedures and the technologies shown are in place and in full use under the effective management of the Concessionaire´s technical team. However, some aspects can be highlighted such as gaps and/or improvement opportunities:

1. The need for great commitment of the team to keep the system organized and up to date, since the information about the inspections needs to be entered into the system separately for each Civil Engineering Structure, and the quality of this organization, which will allow the easy tracking of the information, totally depends on the technical team that does it;
2. The subjective nature of the inspection, since it depends on the experience and training of the inspector/engineer, and, therefore, the perception about the condition of the pathology may vary;
3. The system does not issue alerts regarding the expiration of inspection deadlines, especially the routine ones, which should occur annually, being such inspections conducted by "campaigns" (every year, the inspections are started in a certain month);
4. The pathologies are not georeferenced, and the analysis of the photos from the previous inspection is not always sufficient to locate and interpret if it is a new pathology or to evaluate if the pathology previously registered evolved; and
5. The quantitative survey and analysis of the services needed for maintenance based on the photos, or the need to conduct new field inspections, in the case of engaging a company to perform the maintenance services.

Such improvements can be achieved by adopting BrIM and its integrated technologies, as explained in the next section.

6 RESULTS AND DISCUSSIONS

The use of BrIM-associated technologies can bring many benefits to the management processes of CESs throughout the entire life cycle, for example as the ones mentioned in the studies of the literature review. The main advances and gains resulting from the use of the BrIM system and integrated technologies are listed next.

The absence and the lack of the habit of preparing as built drawings for CESs can be related to the advanced age of the structures, and many drawings are still on paper (when found), in addition to the slow and inaccurate traditional survey methodology. Usually, the as built, when inexistent, is drawn only in cases that intervention, enlargement, reinforcement, or alteration of loads on the structures are required. Recent technologies such as laser scanner, photo, or videogrammetry, along with BrIM, help the fast and accurate survey of the structure, and can also transform data into 3D models through semantic enrichment including information for operation and maintenance, eliminating paper drawings.

The large volume of printed drawings and inspection reports makes it difficult to analyze and retrieve the history of the structures, as well as to systematically control inspections throughout their life cycle. From the insertion of the information in the BrIM model, with the CESs mapped and georeferenced, the asset management can be digitally conducted throughout their life cycle, being possible to integrate a schedule control of the inspections into the system, creating alerts, according to the periodicity of the pre-defined inspections. At this point, BrIM shows relevant advances when compared to the system described in the case study, since in the latter the structures are not georeferenced and there is no associated inspection schedule, making alerts impossible. Therefore, BrIM is the solution to the gap highlighted in item 3 of the previous chapter.

According to the studies and item 2 of the case study, one of the problems highlighted is the subjective nature of inspections, as the analysis of the structure condition depends on the experience and training of the inspector or engineer. With the possibility of obtaining high-resolution and georeferenced images of the pathologies, it will be possible to enable remote analysis by more expert professionals. In this context, technologies involving intelligent algorithms to identify pathologies and their probable causes are being developed to assist in the analysis and ratings of the condition of structures.

Given BrIM´s ability to store all the specific information collected during the construction, inspection, and maintenance phases, integrating georeferenced pathology information with the 3D model of the structure, it is possible to easily access the relevant information during the entire life cycle of the asset, allowing engineers and inspectors to analyze the evolution of such pathologies – which would be a solution to the gap listed in item 4 of the case study.

The use of the QR Code implemented in the CESs, which can be read using smartphones and tablets, as mentioned in the case study, is an efficient tool for accessing the reports of the previous inspections of these structures in loco, eliminating the need for paper, making it possible to quickly access and analyze the evolution of pathologies.

The lack of agility and assertiveness in the preparation of the terms of reference for engaging maintenance services, such as the quantitative survey of the pathologies through the analysis of paper reports - a gap identified in item 5 of the case study - can be solved with BrIM by automatically obtaining a quantitative list with the pathologies, enabling the dimensioning of services and assertiveness for future service engagement.

The difficulties to access the inspected regions, the risks for inspectors, and the difficulty in mapping the pathologies can be solved using unmanned aerial vehicles (drones), as the example mentioned in the case study. In addition, the studies showed advances in which drones can be electronically and computationally controlled at a distance, with the capacity to send the georeferenced information about the pathologies directly to the BrIM model.

The possibility of associating the information collected in the inspections directly to the BrIM model, by means of the different technologies highlighted in the literature review, is the solution to the gap identified in item 1 of the case study.

Other advances and benefits of BrIM are:

- The CESs monitoring systems are developed to ensure the integrity of structures. Through the interoperability of BrIM models, and the possibility of entering information to the elements, monitoring through sensors is integrated into the model, enabling early identification of damage, and prevention of catastrophic failures;
- The system of the current process is precarious for identifying priority interventions and risk management. With the use of BrIM, it is possible to rate the elements according to their structural importance, enabling the rating of the structure and, consequently, the prioritization of service orders;
- The monitoring of maintenance services and the update of as built drawings can be automatic, associating to the model a schedule (BIM 4D) that also allows the inclusion of resources (labor, equipment, and materials), and the monitoring of physical progress by all stakeholders.

7 CONCLUSION

The literature review showed that the application of BrIM in CESs is recent and has developed over the last years with the progressive incorporation of technologies to the system.

The current operation and monitoring processes of CESs are mostly based on physical documentation, with scattered information, which causes inefficiency to the system. Despite this, the case study showed important advances obtained with the use of technologies, such as: the use of drones to inspect CESs, especially those difficult to access, bringing agility in the process to register the conditions of the structure and greater safety for inspectors; the adoption of a system to record the information on each of the structure, which facilitates data access in an organized way and the filing of inspection history; and the implementation of QR Codes in CESs, eliminating the need to use paper in the field, facilitating the access to such information remotely, by using tablets and smartphones. Such tools can be integrated to BrIM, with great potential to further optimize all inspection, operation and maintenance processes of CESs.

Studies to implement BrIM in inspection, monitoring, and management of CESs showed that the system contributes effectively to the agility, quality, and integration of information and assessment of the history of CESs, directing the decision making, savings in asset management, and process control with risk reduction, especially the collapse of structures.

The implementation of BrIM in the bridge operation and maintenance process can be used in both new and existing developments.

The literature review showed that there are still major challenges related to information technology and professional training for the use of BIM software. Nevertheless, there is great expectation on the part of the authors for the development of technologies to solve such challenges and consolidate the use and dissemination of the system.

REFERENCES

[1] Departamento Nacional de Infraestrutura de Transportes, *Boletim Administrativo Instrução Normativa*, DNIT Nº 27, 2021.

[2] J. A. P. Vitório, "Vistorias, conservação e gestão de pontes e viadutos de concreto", in: *Anais do 48° Congresso Brasileiro do Concreto (IBRACON)*, 2006, pp. 1–16.

[3] J. A. P. Vitório and R. M. M. C. Barros, "Análise dos danos estruturais e das condições de estabilidade de 100 pontes rodoviárias no Brasil," in *Congresso Nacional Sobre Segurança e Conservação de Pontes*, 2013, pp. 62–70.

[4] S. Jeong, R. Hou, J. P. Lynch, H. Sohn, and K. H. Law, "An information modeling framework for bridge monitoring," *Adv. Eng. Softw.*, vol. 114, pp. 11–31, 2017, http://dx.doi.org/10.1016/j.advengsoft.2017.05.009.

[5] S. Azhar, "Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry," *Leadership Manage. Eng.*, vol. 11, no. 3, pp. 241–252, 2011, http://dx.doi.org/10.1061/(ASCE)LM.1943-5630.0000127.

[6] A. Costin, A. Adibfar, H. Hu, and S. S. Chen, "Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations," *Autom. Construct.*, vol. 94, no. June, pp. 257–281, 2018, http://dx.doi.org/10.1016/j.autcon.2018.07.001.

[7] B. McGuire, R. Atadero, C. Clevenger, and M. Ozbek, "Bridge information modeling for inspection and evaluation," *J. Bridge Eng.*, vol. 21, no. 4, pp. 04015076, 2016, http://dx.doi.org/10.1061/(asce)be.1943-5592.0000850.

[8] Brasil, "Decreto nº 9.983, de 22 de agosto de 2019," *DOU*, Aug. 22, 2019. https://www.planalto.gov.br/ccivil_03/_ato2019-2022/2019/decreto/d9983.htm (accessed Mar. 15, 2023).

[9] Brasil, "Decreto nº 10.306, de 2 de abril de 2020," *DOU*, Apr. 2, 2020. https://www.planalto.gov.br/ccivil_03/_ato2019-2022/2019/decreto/d9983.htm (accessed Mar. 15, 2023).

[10] Sindicato Nacional das Empresas de Arquitetura e Engenharia Consultiva. *Infraestrutura da Cidade de São Paulo: Prazo de Validade Vencido*. São Paulo, Brazil: SINAENCO, 2005.

[11] Associação Brasileira de Normas Técnicas, *Inspeção de Pontes, Viadutos e Passarelas de Concreto – Procedimentos*, NBR 9452, 2019.

[12] M. Artus, M. S. H. Alabassy, and C. Koch, "A BIM based framework for damage segmentation, modeling, and visualization using IFC," *Appl. Sci. (Basel)*, vol. 12, pp. 2772, 2022, http://dx.doi.org/10.3390/app12062772.

[13] J. I. Samuel, O. Salem, and S. He, "Defect-oriented supportive bridge inspection system featuring building information modeling and augmented reality," *Innov. Infrastruct. Solut.*, vol. 7, pp. 247, 2022, http://dx.doi.org/10.1007/s41062-022-00847-3.

[14] G. Morgenthal et al., "Framework for automated UAS-based structural condition assessment of bridges," *Autom. Construct.*, vol. 97, pp. 77–95, 2019, http://dx.doi.org/10.1016/j.autcon.2018.10.006.

[15] B. Chan, H. Guan, L. Hou, J. Jo, M. Blumenstein, and J. Wang, "Defining a conceptual framework for the integration of modelling and advanced imaging for improving the reliability and efficiency of bridge assessments," *J. Civ. Struct. Health Monit.*, vol. 6, no. 4, pp. 703–714, 2016, http://dx.doi.org/10.1007/s13349-016-0191-6.

[16] R. Sacks, L. Ma, R. Yosef, A. Borrmann, S. Daum, and U. Kattel, "Semantic enrichment for building information modeling: Procedure for compiling inference rules and operators for complex geometry," *J. Comput. Civ. Eng.*, vol. 31, no. 6, pp. 04017062, 2017, http://dx.doi.org/10.1061/(asce)cp.1943-5487.0000705.

[17] T. McKenna, M. Minehane, B. O'Keeffe, G. O'Sullivan, and K. Ruane, "Bridge Information Modelling (BrIM) for a listed viaduct," *Proc. Inst. Civ. Eng. Bridge Eng.*, vol. 170, no. 3, pp. 192–203, 2017, http://dx.doi.org/10.1680/jbren.16.00007.

[18] Q. Wang, H. Sohn, and J. C. P. Cheng, "Automatic as-built BIM creation of precast concrete bridge deck panels using laser scan data," *J. Comput. Civ. Eng.*, vol. 32, no. 3, pp. 04018011, 2018, http://dx.doi.org/10.1061/(asce)cp.1943-5487.0000754.

[19] J. S. Jensen, "Innovative and sustainable operation and maintenance of bridges," *Struct. Infrastruct. Eng.*, vol. 0, no. 0, pp. 1–12, 2019, http://dx.doi.org/10.1080/15732479.2019.1604772.

[20] R. Sacks et al., "SeeBridge as next generation bridge inspection: overview, information delivery manual and model view definition," *Autom. Construct.*, vol. 90, no. February, pp. 134–145, 2018, http://dx.doi.org/10.1016/j.autcon.2018.02.033.

[21] M. Mohammadi, M. Rashidi, Y. Yu, and B. Samali, "Integration of TLS-derived Bridge Information Modeling (BrIM) with a Decision Support System (DSS) for digital twinning and asset management of bridge infrastructures," *Comput. Ind.*, vol. 147, pp. 103881, 2023, http://dx.doi.org/10.1016/j.compind.2023.103881.

[22] J. M. D. Delgado, L. J. Butler, I. Brilakis, M. Z. E. B. Elshafie, and C. R. Middleton, "Structural performance monitoring using a dynamic data-driven BIM environment," *J. Comput. Civ. Eng.*, vol. 32, no. 3, pp. 04018009, 2018, http://dx.doi.org/10.1061/(asce)cp.1943-5487.0000749.

[23] C. Boddupalli, A. Sadhu, E. R. Azar, and S. Pattyson, “Improved visualization of infrastructure monitoring data using building information modeling,” *Struct. Infrastruct. Eng.*, vol. 15, no. 9, pp. 1247–1263, 2019, http://dx.doi.org/10.1080/15732479.2019.1602150.

[24] C. Hendy, C. Brock, and T. Nicholls, “Management of the M4 Elevated Section Substructures,” *Inst. Civ. Eng. Bridge Eng.*, vol. 170, no. 3, pp. 159–167, 2017.

[25] F. Jiang, L. Ma, T. Broyd, and K. Chen, “Digital twin and its implementations in the civil engineering sector,” *Autom. Construct.*, vol. 130, no. February, pp. 103838, 2021, http://dx.doi.org/10.1016/j.autcon.2021.103838.

Author contributions: TMLR: conceptualization, supervision, literature review, data, writing; LRAC: conceptualization, supervision; BM: conceptualization, literature review, writing; TZM: literature review.

Editors: Sergio Hampshire C. Santos, Guilherme Aris Parsekian.