UNIVERSIDADE FEDERAL DE VIÇOSA

Quantification and budgeting in bridge maintenance: parametric modeling, Building Information Modeling, and machine learning applications

Fernando Gussão Bellon
Doctor Scientiae

VIÇOSA - MINAS GERAIS
2025

FERNANDO GUSSÃO BELLON

Quantification and budgeting in bridge maintenance: parametric modeling, Building Information Modeling, and machine learning applications

Thesis submitted to the Civil Engineering Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

Adviser: Jose M. Franco de Carvalho

Co-advisers: Kleos M. L. C. Junior
Jose C. Lopes Ribeiro
Maria C. S. Alvarenga

VIÇOSA - MINAS GERAIS
2025

Ficha catalográfica elaborada pela Biblioteca Central da Universidade Federal de Viçosa - Campus Viçosa

T

Bellon, Fernando Gussão, 1993-

B447q
2025

Quantification and budgeting in bridge maintenance: parametric modeling, Building Information Modeling, and machine learning applications / Fernando Gussão Bellon. – Viçosa, MG, 2025.

1 tese eletrônica (176 f.): il. (algumas color.).

Texto em inglês.

Orientador: José Maria Franco de Carvalho.

Tese (doutorado) - Universidade Federal de Viçosa, Departamento de Engenharia Civil, 2025.

Inclui bibliografia.

DOI: https://doi.org/10.47328/ufvbbt.2025.618

Modo de acesso: World Wide Web.

1. Pontes - Manutenção e reparos. 2. Modelagem de informação da construção. 3. Aprendizagem do computador. 4. Sensoriamento remoto. I. Carvalho, José Maria Franco de, 1979-. II. Universidade Federal de Viçosa. Departamento de Engenharia Civil. Programa de Pós-Graduação em Engenharia Civil. III. Título.

CDD 22. ed. 624.25

Bibliotecário(a) responsável: Euzébio Luiz Pinto CRB-6/3317

FERNANDO GUSSÃO BELLON

Quantification and budgeting in bridge maintenance: parametric modeling, Building Information Modeling, and machine learning applications

Thesis submitted to the Civil Engineering Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

APPROVED: April 28, 2025.

Assent:

Fernando Gussão Bellon
Author

Jose Maria Franco de Carvalho
Adviser

ACKNOWLEDGMENTS

I am grateful to my family, the foundation of everything I am, for their unconditional support, even in the face of challenges and distance.

To my friends, I am thankful for making this journey more joyful and meaningful. Without you, none of this would have been possible.

I extend my deepest gratitude to my advisor, Prof. José Maria Franco de Carvalho, for his guidance and support, which went far beyond the doctoral journey. To my co-advisors, Prof. José Carlos Lopes Ribeiro, Prof. Kléos Magalhães Lenz César Júnior, and Prof. Maria Cláudia Souza Alvarenga, I am grateful for their invaluable contributions and unwavering support. The trust, respect, and partnership of the entire advisory committee were fundamental throughout this challenging journey.

I sincerely appreciate the external committee members Prof. Alexandre Abrahão Cury, Prof. Daniel Luiz de Mattos Nascimento, and Prof. Lucas Nascimento Ferreira for their availability and valuable contributions, which greatly enriched this work. I am also grateful to Prof. Marcos Henrique Fonseca Ribeiro for his contributions and willingness to share his knowledge.

I am grateful to the Federal University of Viçosa (Universidade Federal de Viçosa UFV) for the academic environment, the resources, and the support throughout these years.

I also sincerely appreciate the National Department of Infrastructure and Transportation (Departamento Nacional de Infraestrutura e Transportes – DNIT) for its partnership, financial support through the Decentralized Execution Term TED 703/2020, and technological resources, which were essential to the development of this research. This work has been sponsored by the following Brazilian research agencies: Coordination for the Improvement of Higher Education Personnel (CAPES; Financing code 001), Minas Gerais State Foundation for Research Aid (FAPEMIG) and National Council of Scientific and Technological Development (CNPq).

Finally, I thank everyone who, in some way, has been part of my journey and who, directly or indirectly, also contributed to this thesis.

ABSTRACT

BELLON, Fernando Gussão, D.Sc., Universidade Federal de Viçosa, April, 2025. **Quantification and budgeting in bridge maintenance: parametric modeling, Building Information Modeling, and machine learning applications**. Adviser: Jose Maria Franco de Carvalho. Co-advisers: Kleos Magalhaes Lenz Cesar Junior, Jose Carlos Lopes Ribeiro and Maria Claudia Sousa Alvarenga.

The management of bridges and viaducts requires continuous monitoring throughout their lifecycle, providing essential data for decision-making in preventive maintenance. With the digitalization of processes and the widespread adoption of sensing technologies, the amount of available data is growing exponentially. However, its efficient application requires structured methodologies. In response to this demand, this study proposes solutions for digitalizing and automating bridge and viaduct maintenance quantification and budgeting. To this end, the following were developed: (i) a literature review on the interaction between BIM and bridge management; (ii) a parametric model for the design and budgeting of maintenance work platforms; (iii) a machine learning application for predicting maintenance quantities based on inspection data; and (iv) an IFC-based framework for representing inspection and maintenance data. The literature review highlighted the need to enhance BIM applications in bridge maintenance, revealing opportunities for new solutions. Parametric and data-driven approaches demonstrated potential for integration with bridge management systems, enabling the automation of currently manual processes. The standardized IFC representation facilitates the structuring and interoperability of inspection and maintenance data, significantly contributing to decision-making in infrastructure management.

Keywords: bridge maintenance management; Building Information Modeling; Industry Foundation Classes; machine learning; parametric modeling; quantification; budgeting

RESUMO

BELLON, Fernando Gussão, D.Sc., Universidade Federal de Viçosa, abril de 2025. **Quantificação e orçamentação em manutenção de pontes: aplicações de modelos paramétricos, *Building Information Modeling* e *machine learning***. Orientador: Jose Maria Franco de Carvalho. Coorientadores: Kleos Magalhaes Lenz Cesar Junior, Jose Carlos Lopes Ribeiro e Maria Claudia Sousa Alvarenga.

A gestão de pontes e viadutos demanda monitoramento contínuo ao longo de seu ciclo de vida, fornecendo dados essenciais para a tomada de decisão na manutenção preventiva. Com a digitalização de processos e a popularização de tecnologias de sensoriamento, a quantidade dados disponível cresce exponencialmente, mas sua aplicação eficaz requer metodologias estruturadas. Em resposta a essa demanda, este propõe soluções para a digitalização e automatização da quantificação e orçamentação da manutenção de pontes e viadutos. Para isso, foram desenvolvidos: (i) uma revisão de literatura sobre a interação entre BIM e a gestão de pontes; (ii) um modelo paramétrico para o dimensionamento e orçamentação de plataformas de trabalho para manutenção; (iii) uma aplicação de *machine learning* para predição de quantitativos de manutenção baseados em dados de inspeção; e (iv) um *framework* baseado no esquema IFC para representação de dados de inspeção e manutenção. A revisão destacou a necessidade de aprimorar a aplicação do BIM na manutenção de pontes, evidenciando oportunidades para novas soluções. As abordagens paramétricas e orientadas à dados demonstraram potencial para integração com sistemas de gerenciamento de pontes, possibilitando a automatização de processos atualmente manuais. A representação padronizada em IFC promove a estruturação e interoperabilidade dos dados de inspeção e manutenção, contribuindo significativamente para a tomada de decisão no gerenciamento de infraestrutura.

Palavras-chave: gestão da manutenção de pontes; *Building Information Modeling*; *Industry Foundation Classes*; *machine learning*; modelagem paramétrica; quantificação; orçamentação

TABLE OF CONTENTS

CHAPTER 1 – GENERAL INTRODUCTION

Abstract

This chapter presents a general introduction to the content of the thesis, with a brief contextualization, objectives, and thesis structure.

1. Introduction

Bridges are essential transport infrastructures whose operation has a direct impact on the lives of local society. In their operating phase, which is generally the most extensive and most costly in the life cycle of structures (CHEN; TANG, 2019; GRUSSING; MARRANO, 2007), periodic monitoring and appropriate maintenance are required to guarantee their functionality and safety in the face of progressive deterioration caused by exposure to environmental conditions and traffic (HU; DAGANZO; MADANAT, 2015). The management of bridges, the processes involved, and the large amount of information generated are, therefore, quite complex, generally requiring the implementation of computer systems (RYALL; HARDING; PARKE, 2013).

In the management of the operation phase, cost evaluations are often necessary to aid decision-making and promote the correct allocation of resources. Traditionally manual (FIRAT et al., 2010; MA; WEI; ZHANG, 2013; SHEN; ISSA, 2010; VITÁSEK; MATĚJKA, 2017), the quantification and budgeting processes have been undergoing transitions towards automation, favoring error reduction, reduced subjectivity and time savings. In the context of bridges, these processes have already been implemented computationally within Bridge Management Systems (BMS) (RYALL; HARDING; PARKE, 2013), but alternatives such as Building Information Modelling (BIM) (CHENG; CHEN, 2013; EASTMAN et al., 2011; ISMAIL et al., 2016; WU et al., 2014) and data-driven approaches using artificial intelligence (AI) and machine learning (ML) (JIANG et al., 2023; YANG et al., 2022) have been the subject of numerous recent research. These new initiatives and developments are not only desirable but also necessary, as advances in monitoring and information acquisition techniques make it impossible to use traditional methods to interpret data. However, there are still many gaps in the quantification and budgeting of bridge maintenance in the different approaches (DAYAN; CHILESHE; HASSANLI, 2022; JIANG et al., 2023; MAHAMADU et al., 2020; WAN et al., 2019; YANG et al., 2022), leading to opportunities for development and innovation.

In this context, the current work aimed to explore and propose solutions to digitalize and automate the quantification and budgeting processes based on parametric modeling, BIM, and ML approaches. The products developed were applied to the Brazilian federal context of bridge maintenance management, although not limited to it. To achieve the objectives proposed it was conducted an extensive literature review focused on the current development of BIM within the context addressed, a proposal for a parametric methodology for dimensioning and quantifying work platforms for bridge maintenance, an application of ML models for predicting maintenance service quantities based on inspection data, and an IFC-based framework for representing inspection and maintenance data.

2. Objectives

The main objective of this research was to explore and propose solutions and methodologies for the quantification and budgeting of bridge maintenance services based on the Brazilian federal context.

From the main focus of the research, the following specific objectives have been proposed:

1. Organization of a literature review focusing on the current development of BIM in bridge maintenance, highlighting the most relevant challenges and critical areas for future research;
2. Proposition of methodologies for the design and quantification of working platforms for bridge maintenance;
3. Development of machine learning models to predict the maintenance services and their quantities based on inspection data;
4. Design of an IFC-based data structure to semantically represent the inspection and maintenance information in an open and interoperable format.

3. Thesis structure

This thesis is a compilation of four distinct scientific articles, submitted in international scientific journals. These are the original manuscripts, presented in this document with the structure and formatting recommended by the journals to which they were submitted. Each article corresponds to a distinct research study developed throughout this work. The articles are organized in a logical sequence, reflecting the progressive development of methodologies and solutions for bridge maintenance management.

Chapter 2 presents the review article “Enhancing bridge management systems with BIM: data integration challenges and opportunities”. It reports a systematic bibliometric analysis covering the scope of bridge maintenance, repair, rehabilitation, and management, followed by a comprehensive contextualization and discussion of the current state of BIM usage in several disciplines of maintenance management, highlighting the most relevant research in each context. The analysis highlighted the main challenges and pointed out actions to address them.

The first attempts to develop parametrical relationships and the demands of the national infrastructure bridge maintenance context originated the study presented in Chapter 3, "Parametric modeling of bridge maintenance working platforms to quantification and budgeting", that deeply analyses the possibility of parameterizing the quantities for working platforms. In the addressed context, these services are recurrent and account for a significant part of the overall cost of the maintenance services, justifying a specific approach. To this end, a simplified data structure sufficient to represent the bridge spans and terrain profile data was proposed alongside a configurable parametric methodology for choosing and sizing the two types of platforms discussed throughout the bridge. Additionally, the methodology was computationally implemented and calibrated for a dataset of bridges located in Brazil, creating a case study to assess its performance.

In the review article presented in Chapter 2, a clear trend towards the use of data-driven approaches and the adaptation of information to this new reality was identified. Concurrently, the difficulty of manually establishing accurate parametric relationships in the face of the diversity of variables involved in the maintenance processes was stated in preliminarly analisys and in the study reported in Chapter 3. These findings led to the research in Chapter 4, assessing the quality of the response to the use of data-driven approaches in data relating to damage and maintenance services.

In Chapter 4, the article entitled "Machine Learning Approach for Quantification and Budgeting of Bridge Maintenance Services Based on Inspection Data" details the stages of data acquisition and pre-processing, the choice and validation of machine learning models, and the analysis of the results of the final models. These models, created individually for each bridge maintenance service, had heterogeneous metrics, with varying performance as the maintenance services frequency diminished. While the approach showed promising results for automatically predicting quantities in the most frequent maintenance services evaluated, it demands further analysis to improve the prediction of less common maintenance interventions.

Chapter 5 presents “IFC framework for inspection and maintenance representation in facility management”. The study proposes a framework based on the IFC schema, aiming to standardize a semantic representation of inspection and maintenance data in an open and interoperable format. Including inspection, damage, maintenance, and maintenance cost data, the framework was validated through an official service and evaluated semantically in two case studies. The framework establishes a standard structuration for inspection and maintenance data exchange, enhancing decision-making in facility management workflows. Moreover, the framework encompasses the data generated in the approaches reported in Chapter 3 and Chapter 4, including the individual studies in the BIM context.

Lastly, Chapter 6 consolidates the thesis conclusions, highlighting its principal contributions and providing recommendations for future research and practical developments.

4. References

CHEN, C.; TANG, L. BIM based integrated management workflow design for schedule and cost planning of building fabric maintenance. Automation in Construction, v. 107, p. 102944, 2019.

CHENG, Y. M.; CHEN, J. Y. Application of BIM on Quantity Estimate for Reinforced Concrete. Applied Mechanics and Materials, v. 357–360, p. 2402–2405, 2013.

DAYAN, V.; CHILESHE, N.; HASSANLI, R. A Scoping Review of Information-Modeling Development in Bridge Management Systems. Journal of Construction Engineering and Management, v. 148, n. 9, set. 2022.

DNIT. Com o PROARTE, DNIT já executou obras em 505 estruturas. Disponível em: <https://www.gov.br/dnit/pt-br/assuntos/noticias/com-o-proarte-dnit-ja-executou-obras-em-505-estruturas#>. Acesso em: 5 jun. 2022.

EASTMAN, C. M. et al. BIM Handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors. 2nd ed ed. Hoboken, NJ: Wiley, 2011.

FIRAT, C. E. et al. Quantity Take-off in Model-based Systems. Proceedings of the CIB W78 2010: 27ª International Conference. Anais...Cairo, Egito.: 2010.

GRUSSING, M. N.; MARRANO, L. R. Building component lifecycle repair/replacement model for institutional facility management. Congress on Computing in Civil Engineering, Proceedings, p. 550–557, 2007.

HU, X.; DAGANZO, C.; MADANAT, S. A reliability-based optimization scheme for maintenance management in large-scale bridge networks. Transportation Research Part C: Emerging Technologies, v. 55, p. 166–178, 2015.

ISMAIL, N. A. A. et al. A Review of BIM Capabilities for Quantity Surveying Practice. MATEC Web of Conferences, v. 66, p. 42, 2016.

JIANG, Y. et al. Knowledge driven approach for smart bridge maintenance using big data mining. Automation in Construction, v. 146, 1 fev. 2023.

MAHAMADU, A.-M. et al. Attributes That Determine the Building Information Modelling Capability Maturity of Quantity Surveying Practice. MATEC Web of Conferences, v. 312, p. 2002, 2020.

MA, Z.; WEI, Z.; ZHANG, X. Semi-automatic and specification-compliant cost estimation for tendering of building projects based on IFC data of design model. Automation in Construction, v. 30, p. 126–135, 2013.

RYALL, M. J.; HARDING, J. E.; PARKE, G. A. R. Bridge Management: Inspection, Maintenance, Assessment and Repair. [s.l.] Springer US, 2013.

SHEN, Z.; ISSA, R. R. A. Quantitative evaluation of the BIM-assisted construction detailed cost estimates. p. 26, 2010.

VITÁSEK, S.; MATĚJKA, P. Utilization of BIM for automation of quantity takeoffs and cost estimation in transport infrastructure construction projects in the Czech Republic. IOP Conference Series: Materials Science and Engineering, v. 236, p. 12110, 2017.

WAN, C. et al. Development of a Bridge Management System Based on the Building Information Modeling Technology. Sustainability, v. 11, n. 17, p. 4583, 2019.

WU, S. et al. A technical review of BIM based cost estimating in UK quantity surveying practice, standards and tools. Journal of Information Technology in Construction, v. 19, p. 534–562, 2014.

YANG, J. et al. Intelligent bridge management via big data knowledge engineering. Automation in Construction, v. 135, 1 mar. 2022.

CHAPTER 2 – ENHANCING BRIDGE MANAGEMENT SYSTEMS WITH BIM: DATA INTEGRATION CHALLENGES AND OPPORTUNITIES[1]

Abstract

Current Bridge Management Systems (BMS) are struggling with data sharing and integration. This has led to increased interest in using Building Information Modeling (BIM) to incorporate data collected throughout a structure's lifespan into a BIM-based BMS. This study reviewed recent literature on using BIM in bridge maintenance management. The main challenges identified include the lack of standardized data formats and clear definitions of data requirements. To overcome these challenges, it's important to standardize information and ensure its semantic accuracy. This will allow BIM's potential to be fully utilized alongside various data-driven approaches. As a result, converting and integrating multi-semantic data from different sources into interchangeable information presents significant opportunities for future progress.

Keywords: Bridge maintenance management; Building Information Modeling; Bridge Information Modeling; data management; budgeting; planning.

---

[1] Original manuscript submitted to *Structures* in September 2024.

1. Introduction

Bridges undergo progressive deterioration over their service life due to constant exposure to environmental conditions and traffic [1]. Typically, the costs associated with direct operation and maintenance exceed those of planning and construction [2,3]. However, indirect costs stemming from traffic delays and productivity losses during repair periods are even more substantial, estimated to be ten times higher than the direct maintenance costs [4]. This highlights the critical importance of effectively planning the operational phase.

Concrete is the most widely used man-made material for structural purposes due to its relatively high mechanical strength, availability, and durability [5,6]. Its versatility extends to applications such as bridges [7]. However, even well-designed and constructed, concrete structures undergo gradual deterioration over time [8]. This deterioration can be accelerated in bridges constructed several decades ago and still in use, especially when subjected to loads higher than those considered during their initial design [9]. Consequently, monitoring and implementing appropriate maintenance routines are necessary to ensure the specified service life of reinforced concrete bridges.

Bridge Management Systems (BMS) have become essential tools for overseeing extensive bridge networks and streamlining decision-making processes and maintenance procedures. These systems consist of various tools designed to handle the processes and data throughout the entire life cycle of bridges [10]. Given the crucial role of information management in BMS, the development and implementation of efficient data-related technologies are expected to enhance the overall management system. In this regard, Building Information Modeling (BIM) is seen as a promising approach for integrating life cycle information and improving the efficiency of managing road network infrastructures, thereby optimizing costs, time, and resources [11]. Consequently, BIM can significantly contribute to the automation of modern BMS by enhancing data sharing and integration, which can have implications for operations, maintenance, and safety [10,12].

This work offers an overview of the current advancements and explores the utilization of BIM in managing transport infrastructure, specifically concentrating on bridge maintenance and associated subjects. Employing a bibliometric approach alongside a systematic review helps to elucidate scientific interests and emerging topics, offering insights into the primary processes involved in routine maintenance management and the implementation of BIM in this realm. It identifies challenges and underscores crucial areas for further research and development.

2. Scientific interest in bridge maintenance management

A bibliometric search was conducted using the Scopus database, focusing on titles, abstracts, and keywords. The search included the terms 'bridge maintenance,' 'bridge repair,' 'bridge rehabilitation,' 'bridge renovation,' and 'bridge reinforcement,' combined with the terms 'management,' 'quantification,' 'budgeting,' 'cost,' 'investment,' 'finance,' 'planning,' 'execution,' or 'control.' This search resulted in 584 journal articles (559) and reviews (25) published in English, with 353 of them published between 2013 and August 2024. The search was restricted to the following subject areas: Engineering; Computer Science; Material Science; Earth and Planetary Sciences; Social sciences; Environmental Science; Physics and Astronomy; Business, Management and Accounting; Chemical Engineering; Mathematics; Decision Sciences; Multidisciplinary; and Economics, Econometrics and Finance.

Interest in the subject notably increased in 2019 and remained steady until 2021. In 2022, there was another significant surge, with 52 articles published. In 2023, 42 articles were identified, and in 2024, there have already been 42 (Figure 1).

In the analysis of overall production, the United States emerged as the most collaborative country, contributing 31.6% of the scientific output on the subject, followed by China (12.0%), South Korea (5.6%), Canada (5.0%), the United Kingdom (4.6%), Japan (3.7%), and Australia (2.7%). When focusing on production over the last decade, the United States contributed 21.2%, followed by China (16.4%), South Korea (6.4%), Canada (4.6%), the United Kingdom (4.4%), Japan (4.0%), and Australia (3.8%). Brazil made a modest contribution, with 4 overall publications, 3 of which were in the last decade.

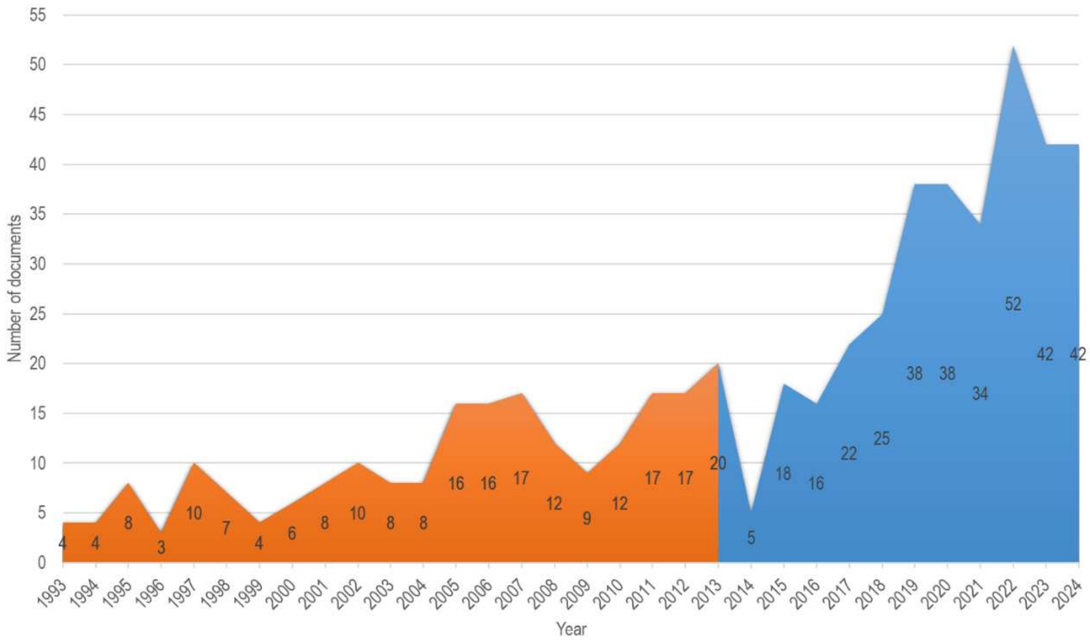


Figure 1. Evolution of the interest in the subject since 1993 and over the last decade.

Excluding the search terms used, the most strongly correlated keywords observed were decision-making, life cycle, and deterioration. Seven clusters were proposed. The first cluster relates to condition assessment, including keywords like ‘decision making,’ ‘information management,’ ‘inspection,’ ‘highway bridges’ and ‘risk assessment.’ Cluster 2 focuses on asset management, emphasizing bridge types, inspection, and damage detection, with keywords such as ‘structural health monitoring,’ ‘damage detection,’ ‘steel bridges,’ ‘cable-stayed bridges,’ and ‘nondestructive examination.’ Cluster 3 deals with reliability analysis and its economic, social, and environmental impacts, highlighted by ‘life cycle,’ ‘budget control,’ ‘cost-benefit analysis,’ ‘cost-effectiveness,’ and ‘multi-objective optimization.’ Cluster 4 centers on bridge parts and materials, including ‘reinforced concrete,’ ‘concrete bridges,’ ‘prestressed concrete,’ ‘vehicle,’ and ‘concrete structures.’ Lastly, Cluster 5 groups keywords related to bridge deterioration and prediction methods, with main terms like ‘deterioration,’ ‘bridge management system,’ ‘forecasting,’ ‘decision support system,’ and ‘condition-based maintenance.’

Figure 2 shows the diagram of keyword strength and trending topics, while Table 1 summarizes the results of the trending topics analysis. Fifteen reviews covering the subject met the selection criteria, as listed in Table 2, which outlines the main subjects, scopes, remarks, and contributions.

Condition-based maintenance emerges as one of the most recent and prominent keywords, closely related to the strongest keywords observed in the bibliometric analysis, particularly deterioration and decision-making [13,14]. The significance of this theme is underscored by its relevance to decision support, with economic, environmental, and social impacts, and its potential enhancement through emerging technologies, such as information- and AI-based systems.

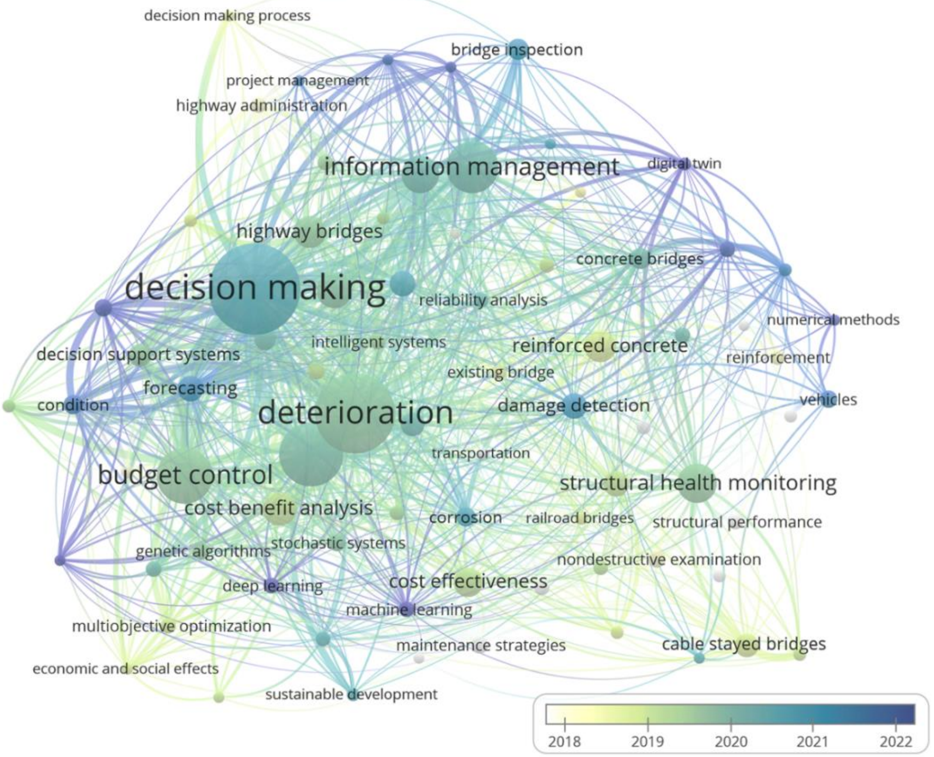


Figure 2. Diagram of keywords strength highlighting the trending topics obtained from the VOSViewer software alanysis (darker blue dots).

Digital twins also emerge as a recent and largely explored topic in the recent literature. This highlights the importance of using BIM technologies in bridge management and how society recognizes the potential of these technologies for optimizing and effectively managing information in this context [15,16]. Decision-making, life cycle, and deterioration—the three most cited keywords in the bibliometric analysis—are also strongly connected to this topic, particularly within the framework of decision-making technological tools.

In condition assessment, information theory is gaining importance, particularly in decision-making, deterioration, and information management. This trend is fueled by the growing need for more informed decision-making. Bayesian decision theory and Markov processes continue to be relevant, and the demand for inspection data to support these data-driven analyses further emphasizes this theme [17,18].

Table 1. Trending topics related to the themes according to the co-occurrence network obtained from the bibliometric analysis.

Trending topic	Remarkable related topics	Cluster	References
Condition-based maintenance	Condition Deterioration Decisiona making Forecasting Life cycle	Bridge deterioration and prediction methods	[13,14,19–21]
Digital Twin	Decision-making Deterioration Life cycle Structural Health Monitoring Information management	Decision-making	[15,16,22–26]
Information theory	Decision-making Deterioration Information management Life-cycle Architectural design	Condition assessment	[17,27–31]
Machine learning	Forecasting Decision making Damage detection Structural Health Monitoring Deterioration	Asset management	[17,19,32–35]
Prestreessed concrete	Information management Deterioration Life-cycle Concrete bridges Digital twins	Bridge parts and materials	[15,17,23,33,36,37]

As seen in other fields, AI-based technologies have rapidly gained interest in bridge management. Topics like machine learning and deep learning are emerging as trends in asset management, particularly in forecasting, decision-making, and damage detection [19,33–35]. This area is highly data-dependent, highlighting the importance of information and driving advances in inspection, data collection, and processing.

Prestressed concrete has gained interest due to its widespread use and importance in the management and safety of global infrastructure. This topic relates to areas like information management, deterioration, and life-cycle analysis, and it also involves approaches using information modeling technologies like digital twins [15,17,23,33,36].

Table 2. List of reviews found in the bibliometric analysis, with the main subject, scopes, and remarks.

Reference	Year	Main subject	Scope	Main remarks and contributions
Jeon et al. [15]	2024	Digital Twins	Defining a digital twin architecture for concrete bridges, integrating maintenance data, and enhancing decision-making	DT architecture for concrete bridges that improves maintenance through integrated data, prescriptive maintenance, and an advanced information system
Martins et al. [38]	2024	Bridge Management Systems	The role of bridge management systems in managing maintenance challenges and incorporating trends in inspection and monitoring	Highlights the need for digitized bridge information, current trends in inspection and monitoring, and addresses challenges and solutions in bridge management systems
Gkoumas et al. [39]	2024	Bridge inspection and minitoring	European policies and technologies for bridge inspection and monitoring	Research on new technologies for bridge inspection, highlighting advancements like drones, AI, and digital twins, and their potential impact on maintenance practices
Yang et al. [16]	2024	Digital Twins	Analysis of applications and technologies involving digital twins in bridge engineering	Concept of digital twins in bridge engineering. Comparison with Bridge Information Models. Applications and technologies throughout the bridge life cycle
Abdelkader, Zayed & Faris [40]	2023	Non-destructive inspection and analysis methods	Non-destructive techniques for assessing defects in reinforced concrete bridges	Highlights the use of fuzzy set theory, computer vision, and AI. Analysis of literature and future research directions
Jiang et al. [41]	2023	Smart bridge maintenance	Tasks and issues regarding bridge maintenance; smart maintenance using advanced technologies	Propose a novel framework and methodology for smart bridge maintenance using a knowledge-driven approach
Hosamo & Hosamo [25]	2022	Digital Twin application in bridges	Machine learning; bridge management systems (BMS); Bridge Information Modeling (BrIM); 3D modeling	Increase in Digital Twin research for bridges, although further behind other subjects; challenges in modeling automation of as-built bridges
Kaiser & Barstow [42]	2022	Rural transportation infrastructure	Relationships between rural transportation infrastructure and socioeconomics benefits; implementation activities	Points out future research, investment, and intervention areas in the rural transportation infrastructure context
Bień & Salamak [27]	2022	Management of bridge structures	Bridge-environment relationship; diagnostics technologies; advanced modelling; AI-based systems; BrIM	Classification of current and future generations of Bridge Management Systems

Bertola et al. [43]	2021	Rehabilitation and strengthening	Reinforced concrete bridges and viaducts using Ultra-High-Performance Fiber Reinforced Cementitious Composite	Efficiency of using UHPFCR in structural rehabilitation regarding project costs, intervention time, and environmental impact
Alampalli et al. [44]	2021	Bridge load testing	Current governing codes and guidelines; recent advances; up-to-date method	Overview of the recommendations in the *Primer for Bridge Load Testing*, pointing out parts that require further research
Srikanth & Arockiasamy [45]	2020	Deterioration models	Timber and concrete bridges	Comparison of different bridge deterioration models, highlining advantages and limitations; recommendations for future research
Kim et al. [46]	2018	Bridge maintenance prioritization	South Korean highway bridges	Determination of probability and impact of risk factors; propose a risk-based maintenance prioritization methodology
Moreu et al. [47]	2018	Bridges structural health monitoring (SHM)	Large highway bridges	Comparison between different SHM publications; considerations for future SHM codes
Chan et al. [48]	2015	Bridge inspection systems	Unmanned Aerial Vehicles (UAV) inspections	Overview of the main challenges and limitations of using UAV in bridge inspection

Table 3. List of documents related to Information Modelling found in the bibliometric analysis, with an overview and main conclusions.

Reference	Year	Overview	Main conclusions
O'Higgins et al. [49]	2024	Research article. Use of data models for monitoring bridge health across a network of bridges, demonstrating effectiveness in detecting frequency shifts and improving maintenance decisions.	Data models can effectively monitor bridge health across different types and sizes of bridges, enhancing maintenance decision-making through accurate frequency shift detection.
Costin et al. [50]	2024	Research article. Potential of digital twin technology to enhance bridge maintenance and management through the integration of sensors, data analytics, and existing technologies.	Digital twin framework, integrating advanced technologies and data, can improve bridge maintenance and management. New knowledge through the integration of information resources.
Jeon et al. [15]	2024	Review article. Application of digital twins in bridge maintenance, proposing an architecture and information system to integrate maintenance data and enhance decision-making with minimal human intervention.	A digital twin architecture for prestressed concrete bridge maintenance was developed, incorporating prescriptive maintenance, an information system, and a detailed workflow for machine learning-enabled diagnosis.
Martins et al. [38]	2024	Review article. The role of BIM-based bridge management systems in standardizing and digitizing information for inspection and damage detection in expanding and aging transportation networks.	BIM-based bridge management systems offer long-term benefits like cost reduction and improved efficiency, but challenges such as data management, interoperability, and implementation barriers persist.
Lee et al. [51]	2024	Research article. Framework for estimating bridge maintenance costs using historical data from the Korean bridge management system, integrating various data phases and employing machine learning models.	Contribution to the enhancement of bridge maintenance cost estimation, improving cost predictions and aiding decision-making despite varying error rates across different bridge elements.
Schatz & Domer [52]	2024	Research article. Semi-automatic approach for creating IFC bridge models from point clouds, introducing new methods for segmentation and 3D modeling, and demonstrating its practicality in handling incomplete data.	Accurate models from point clouds were created, saving time compared to manual methods and showing promise for improving asset management. Further refinement is needed for complex bridge types and detailed elements.
Yang et al. [16]	2024	Review article. Reviews digital twins in bridge engineering, distinguishes from Bridge Information Models, analyzes their life cycle applications and technologies, and proposes a framework for future research.	Identifies BDT research clusters in geometric model generation, finite element model updating, and management, highlighting a focus on operation and maintenance with gaps in design and construction phases.
Lai et al. [53]	2024	Research article: Proposes a digital twin-based NDT method combining 3D modeling, sensors, FE methods, and surrogate models, with each FE node acting as a virtual sensor to monitor the entire bridge's structural performance	The method's feasibility and effectiveness are demonstrated through a suspension bridge

Gao et al. [54]	2023	Research paper. Proposes an AIoT-informed digital twin communication framework for bridge operation and maintenance, addressing data synchronization and fault tolerance issues.	The proposed DT improved bridge operation and maintenance by addressing communication constraints with high efficiency, low latency, and fault tolerance, while also supporting future federated learning and practical application on real bridges.
Chang et al. [55]	2023	Research paper. Develop an optimized bridge condition estimation model using data-driven approaches, selecting the extreme gradient boost (XGBoost) algorithm and identifying key variables like "bridge age" and "first past condition grade of deck" A case study used KOBMS data.	The optimized model demonstrated strong performance, providing a reliable method for estimating future bridge component conditions and supporting strategic maintenance decisions for proactive bridge management.
Kaewunruen et al. [24]	2023	Research article. An innovative digital twin for managing railway bridges was developed using BIM integration. Includes GHG emissions quantification and cost. Maintenance schedule using Navisworks. A real-world use case was considered (Minamurra Railway Bridge, Australia).	DTs can improve efficiency and reduce risks in the project process using Revit and Navisworks. The method can provide real-time updates and access several data layers throughout the life cycle. The case study demonstrated material inventory monitoring. Maintenance and repair can be considered, and Navisworks can efficiently help monitor the activities.
Watanabe et al. [56]	2023	Research article. Development of a methodology to collect bridge and inspection information and automatically develop bridge databases, facilitating the creation of BMS. The inspection data is collected using a smartphone and then sent to a data server.	The system was capable of collecting and classifying the inspection data, but the automated classification still needs improvement to address immediate countermeasures. Advanced functionalities, such as deterioration predicting, are not implemented. It can be used as a basis for the creation of BMS in developed countries, especially when it comes to data acquisition.
Jiang et al. [41]	2023	Review article. Explores the state-of-the-art methods used in bridge maintenance, focusing on data. Proposes a novel knowledge-oriented framework and methodology aiming at the unification and streamlining of different sources of data, contributing to smart bridge maintenance management.	It is necessary to transition from traditional to knowledge-driven approaches, considering the multisource and heterogeneous nature of maintenance big data. To accomplish this, the novel framework and methodology proposed have as the objective to enhance the application of bridge maintenance big data that are often underused, facilitating future developments toward smart bridge maintenance.
Bień & Salamak [27]	2022	Review article. Discuss challenges and possibilities for the management of bridge structures. The scope is vast and includes the relationship with the environment; diagnostic; monitoring; and digitalization using BrIM and AI in integrated BMS	There are many difficulties and constraints for the implementation of new technologies on a large scale; companies equipped with the equipment will be able to provide services at better value; proposal of a 6-generation classification system for BMS; III and IV generation BMS in test and pilot implementations

Nguyen et al. [57]	2022	Research article. Application of a BIM-based mixed reality enhancing and facilitating bridge inspection and management of maintenance works through the acquisition and posterior storage of digital damage information in a single-source data model.	Mixed reality enhanced the interpretation and visualization of inspection and maintenance information, improving collaboration. Centralization and update of inspection data in a single model improve information management and, alongside the proposed code, enable the monitoring of damage development and the development of deterioration models.
Gosliga et al. [58]	2022	Research article. Feasibility of using Population-based Structural Health Monitoring to increase the availability of Structural Health Monitoring data and models through the correlation of similar structures based on an Irreducible Element model representation.	The Irreducible Element model framework developed for Population-based Structural Health Monitoring was capable of describing the addressed bridge types. The graph-matching algorithm used to compare the different representations successfully grouped similar bridges. The presented approach could enable the transfer of data between matched structures.
Zhou [59]	2022	Research article. Proposal of a new approach for a BIM-based BMS; data from inspection and loading to the BIM model; display of damage information by markers and colors; covers bridge damage management and technical condition evaluation; report of an application study in a steel arch existing bridge.	The case study classified the bridge and provided data for management and maintenance strategy (not detailed, data available under request).
Sakiyama et al. [36]	2021	Research article. Development of an algorithm for real-time analysis utilizing random variable correlation for an SHM system using LGFBG sensors. Development and validation of a processing system to manage a large amount of data. Experimental application of the SHM system in the Neckarsulm prestressed hollow-core concrete bridge.	To manage the large amount of raw data generated by the SHM system, a powerful data management system is required. The developed algorithm performs the data evaluation alongside with the measurements, even before data storage and transfer. The datasets are reduced for analysis, conserving the principal components and holding the essential information of the original data.
Byun et al. [60]	2021	Research article. Development of a BIM-based BMS considering an established data schema based on maintenance information. A web data management program (WDMP) was proposed. A BMS prototype was implemented for a bridge in Korea. Includes diagnosis, remaining life, and valuation.	A BMS was developed by establishing a data schema and information system regarding bridge maintenance information, constructing a WDMP according to the established data structure to manage and share all the generated information, and connecting the WDMP with a 3D modeling program.
Nili et al. [61]	2021	Research article. Integration of Genetic Algorithm and Discrete Event Simulation to develop a Simulation-based Bridge Maintenance Optimization framework whose main purpose is to obtain the optimum maintenance plan for a determined number of working crews.	The proposed framework provided more accurate cost estimations, a cheaper sequence for repair activities considering both user and crew costs, and the capability to run different scenario analyses and to work without BrIM models. However, the developed SiBMO framework is limited to individual bridge maintenance planning, and it is necessary to adapt it to enable network-level optimization.

Wu et al. [62]	2021	Research article. Development of a Concrete Bridge Rehabilitation Project Management Ontology through the establishment of relations, constraints, and rules between the standards procedures involved in bridge rehabilitation and the implementation of the collected knowledge in an application programming interface, to promote an improvement of both constraint management and information integration in bridge rehabilitation projects. A case study was carried out to validate the proposed ontology.	The CBRPMO, unlike conventional ontologies, supports the search and use of static and dynamic project information. In the validation, the proposed ontology was capable of efficiently searching for information and performing the project management's functions when there were information updates.
Wójcik & Zarski [63]	2021	Research article. Usage of RGB-D cameras in bridge inspection to acquire defect data for processing, 3D modeling, and embedding in BIM models.	The overall accuracy obtained from the low-cost RGB-D camera surface measurement was 95%. The proposed method was suitable for documenting various types of defects. However, it was not possible to assign an accurate localization of the defects in the BIM model, being necessary the support of a 3D representation acquired by photogrammetry to solve this problem.
Wu et al. [64]	2021	Review article. Explore the state-of-art of data-driven bridge operation and maintenance, identifying the progress, challenges, and opportunities for future research.	Operation and maintenance data management along with the establishment of data definitions are comparatively less covered in literature than the collection and analysis of bridge data. The main challenges related to data management can be summarized in four topics: insufficient definition of data needs, absence of methods to evaluate data quality, insufficient data integration, and inadequate consideration of operational issues.
Wu et al. [65]	2021	Research article. The proposition of a hybrid deep learning model for automating the extraction from project documents of information and its relations, therefore determining their constraints, to partially automate Advanced Working Packaging.	Given the high accuracy obtained, the proposed hybrid model successfully extracted entities and relations based on the train data, composed of different types of documents. Even though some manual refinement was still necessary to address specific relations, the level of automation obtained can significantly reduce the current effort and time used to determine and monitor constraints.
Jensen [66]	2020	Review article. Presents the importance of considering the operation and maintenance issues of bridges already in the planning and design phase, as well as the application possibilities along with the innovative and sustainable findings in this context.	To enable a more efficient management of the operation and maintenance phase of bridges' life cycle, it is important to adopt adequate solutions considering both the experience from past practices and the possibilities ensured by new technologies. It is essential to invest in preventive solutions planned since the early stages of the bridge life cycle.
Assaad & El-Adaway [32]	2020	Research article. Development of a data-driven asset management system using machine learning models to evaluate and predict bridge deck deterioration conditions.	The study identified the variables with the highest impact on the conditions of bridge decks for the analyzed data, enabling a better direction of investments toward improving the status of critical factors. The developed BMS framework was capable of predicting, with high accuracy, the bridge's deck condition.

Nili et al. [67]	2020	Research article. Development of a Decision Support System for optimization of bridge maintenance planning using BrIM data.	The developed system was capable of extracting data from a BrIM model, optimizing the bridge maintenance planning based on the extracted data, and visualizing inspection and maintenance planning data. However, the constraints of repair and maintenance activities should also be considered for more realistic results.
Cha et al. [68]	2019	Research article. Application of terrestrial light detection and ranging – LiDAR – to create 3D models and measure deflection or deformation in steel bridge structures.	The association of terrestrial laser scanner point cloud data and the octree space division method successfully managed the large volume of data, with an overall compress rate of approximately 90%. The deflection estimation in a static load test showed reasonable estimation in the load case that led to more than 4 mm deflection.
Lee & Park [69]	2019	Research article. Use of an unmanned aerial vehicle – UAV – for 3D modeling of a bridge and evaluation by comparison with terrestrial laser scanner data.	When compared to the point cloud laser scanner data, the accuracy of the model based on the UAV data was less than 0.12 m. In addition, the data acquired by the UAV provides image information, which can be particularly useful for a more detailed evaluation of the bridge surface condition.
Shim et al. [23]	2019	Research article. The proposition of a bridge management system using the digital twin concept and its practical application in a precast concrete bridge.	The unification of the information in a single federated model, based on the proposed framework, provides a dense resource for the different uses in the bridge's lifecycle. Models containing specific data or level of detail can be derived from the main BMS. The displacement results obtained through the analytical model were similar in comparison to the experimental data.
Cheng et al. [70]	2019	Research article. Development of a novel and integrated model for simulation of the probability of bridge maintenance and cost estimation, named risk-based evaluation model for bridge life-cycle maintenance strategy (REMBMS).	The proposed solution obtained significantly better results when compared with the current practices used for bridge maintenance by the country authorities, due to the risk factors considered, the probabilistic simulation to determine risk, and the extrapolation of bridge maintenance costs estimation based on historical data.
Quirk et al. [71]	2018	Research article. Quantitative estimation of the actual benefits of implementing visual inspections in BMS using the Value of Information (Vol) approach.	The Value of Information is sensible to optimistic and pessimistic inspections, and information from multiple inspectors could reduce bias. Value on visual inspections decreases as the precision also decreases but in a nonlinear fashion. The greatest benefits from adopting a visual inspection strategy are observed where the condition rating signalizes between some and significant damage.
Markiz & Jrade [28]	2018	Research article. Development of a fuzzy-logic decision support system integrated with a Bridge Management System to predict the bridge's deterioration.	The system was capable of predicting the degradation with little or no information available. The overall accuracy ranged from 10 to 15 %. The observed discrepancies could be due to the multiple assumptions made and the availability of deterioration data.

Adarkwa et al. [72]	2017	Research article. Use of tensor factorization to support the analysis and prediction of the performance of bridges at a network level.	The tensor factorization approach was capable of decomposing part of the original multidimensional dataset into lower-order forms, preserving variations over time and capturing trends. The predictions, in most cases, presented better results after decomposition.
Shim et al. [73]	2017	Research article. Proposition of a data scheme for application in a BIM-based Bridge Management System focused on cable-stayed bridge maintenance.	The schematic information system proposed enabled the generation of a bridge data management system that can also be adapted for other types of bridges. The information requirements should be defined by the stakeholders, and documented in a unified format for data exchange.
Khan et al. [74]	2016	Review article. Presents the current status of the integration between Intelligent Transportation Systems and Structural Health Monitoring, discusses the identified challenges, and provides directions for future research.	The integration of Intelligent Transportation Systems can improve Structural Health Monitoring through the identification of critical events and reduce erroneous results. However, it is still necessary to enhance the overall structure and acquisition of data, and the institutional coordination required for its implementation.
Liu & Madanat [75]	2015	Research article. The proposition of Open-Loop Feedback Control (OLFC), an adaptive control method for updating deterioration models.	The proposed method, when compared with the Certainty-Equivalent Control (CEC) method, led to lower system costs and more accurate models of deterioration. OLFC guarantees improvement in model accuracy, while CEC does not.
Yanev & Richards [76]	2013	Research article. Analysis of the effectiveness of different maintenance tasks and impact of elements in bridge global condition.	The deterioration models should consider the bridge's particularities instead of assuming the same average behavior. At a network level, preventive maintenance strategies should aim for approximately 75 years of expected life. At a project level, specific strategies need to be applied.

BIM continues to gain importance, as it is closely related to trending topics identified in the bibliometric analysis, particularly in 'bridge inspection' and 'information management' within the 'decision-making' cluster. Documents containing Information Modeling-related keywords were selected from the analysis results. The keywords included 'Information Management,' 'BIM,' 'Building Information Modeling (BIM),' 'Digital Twin,' 'Information Modeling,' 'Bridge Information Management System,' 'Bridge Information Model,' 'Bridge Information Modeling (BrIM),' 'Bridge Model,' 'Information Model,' 'Information Integration,' 'Information Management,' and 'Information Management Systems.' This filtering process resulted in 38 documents, including eight review papers. Table 3 provides a summary of these documents, along with their main conclusions.

3. Bridge Management Systems (BMS)

An effective maintenance plan that identifies the optimal timing and appropriate repair activities is essential for extending the service life of bridges and reducing expenses over their lifecycle [9,61]. Such a plan should be incorporated at the design stage [66]. Considering the impact of bridge closures, it's crucial to account for the indirect costs associated with usage when planning interventions [4,61]. Additionally, resource constraints, work sequencing, staff travel time, and traffic management should all be taken into consideration [61].

Typically, bridge maintenance is overseen by agencies responsible for sections of the road network, which can encompass multiple bridges [1]. Due to the multitude of parameters involved and the complexity of the task, maintenance planning is highly intricate, necessitating computer-aided systems for swift and accurate execution [9]. The diversity and volume of available information underscore the need for efficient exchange and data sharing among various software platforms, driving the imperative to enhance information integration across bridge maintenance projects [77,78].

A BMS is a comprehensive set of functions integrated through processes to assist the management agency responsible for a bridge in administering resources and achieving strategic goals. These goals may include identifying needs and prioritizing maintenance, rehabilitation, and replacement [79,80]. Typically, BMS incorporate functions to aid in inventory management, inspection, maintenance, cost analysis, and condition assessment. To operate effectively, BMS require extensive input information. Due to the substantial amount of data involved and the system's complexity, BMS are usually implemented as software applications integrated with a shared database [81].

Several computational BMS have been developed and implemented over the years, with their properties, capabilities, and processes documented in works by Ryall [81], Mirzaei et al. [82], and Bello et al. [83]. However, the lack of standardization has resulted in independent deployments, which vary from country to country or even between jurisdictions within a country [84]. While some level of differentiation is necessary due to the diversity of resources, infrastructure, and climate across different regions, it also poses significant barriers to information sharing and hampers the dissemination of knowledge regarding bridge operation, maintenance, and management.

Furthermore, advancements in technology and knowledge, particularly in structural health monitoring (SHM) of bridges, have facilitated the collection of large volumes of detection and monitoring data. These datasets, which include heterogeneous, multi-source, and autonomous sensory 'Big Data,' alongside traditional sources of information, constitute extensive datasets. Coupled with improvements in data processing, these datasets have the potential to enable intelligent bridge management, shifting the current paradigm towards knowledge-driven decision-making approaches. However, despite efforts, the development and application of data-driven and knowledge-driven approaches in BMS remain insufficient [41,85]. Moreover, achieving common and open-source data-sharing remains an unresolved challenge.

4. Building Information Modeling for infrastructure

BIM is not a specific technology or object but rather an activity that involves numerous changes in project design, execution, and construction management processes [86]. Its purpose is to consolidate all information and characteristics of a building [87], enabling the visualization of its entire lifecycle [88]. Bradley et al. [11] emphasized collaboration, representation, processes, and lifecycle as key aspects of BIM. The most significant benefits of BIM include improved constructability, visualization, productivity, and reduced conflicts in projects [89], as well as better estimates, cost reduction, and enhanced project quality overall [90].

BIM models are typically characterized by dimensions based on the type of information and purposes they serve. Some dimensions have achieved consensus in their definitions: 3D represents the spatial design associated with information including geometry, materials, and suppliers; 4D adds time, enabling simulation and planning of the construction process; 5D incorporates cost, allowing for budgeting [88,91,92]. However, conceptualizations of the sixth (6D) and seventh (7D) dimensions still face controversies. Generally, 6D BIM is associated with sustainability, while 7D is linked with facilities management [91]. References are also made to 8D BIM, which includes information on project safety [93,94].

The interest in and implementation of BIM in civil construction have increased, but its adoption in transport infrastructure is progressing slowly [87,88,95–97]. Since BIM was initially proposed for buildings, it requires adaptation for use in transport infrastructure projects, necessitating the development of specific solutions and tools tailored to their unique characteristics [87,95]. Bradley et al. [11] illustrate that while detailed geometry and component information are crucial in building models, they are less critical in infrastructure projects, where data on cost, material specifications, and performance hold greater importance. Nevertheless, the application of BIM in transportation infrastructure projects offers numerous advantages, including improved visualization and information exchange, enhanced life cycle information management, and integration with emerging technologies [97].

Bradley et al. [11] identified several gaps that hinder the full implementation of BIM in infrastructure projects, including the lack of a data format supporting information exchange for most infrastructure constructions, the absence of data integration tools, the need for organizations to align with BIM processes, and the necessity to define 'data utility,' which involves analyzing and validating data efficiency during information generation and consumption processes. Bazán et al. [95] emphasized the absence of specialized software for infrastructure projects as a significant barrier to implementing the BIM methodology. According to the authors, the most commonly used software for infrastructure projects does not allow for the creation of all elements associated with their characteristics, resulting in 'empty' geometries that do not qualify as BIM models. As noted by Kaewunruen et al. [98] these software tools are not effectively adapted for modeling infrastructure elements and require further development to enhance compatibility.

In addition to the challenges of implementing BIM in the infrastructure sector, some obstacles are not confined to specific areas but are inherent in transitioning from traditional to BIM processes. Generally, the most common hurdles include cultural resistance, insufficient knowledge and experience, conflicts between BIM processes and organizational structures, lack of interoperability between software tools, absence of guidelines and standards, and difficulties in measuring the impact of BIM [90,99].

5. Applicability of BIM in bridges design and management

BIM may also be referred as Bridge Information Modeling (BrIM) in the field of bridge engineering, is consistently recognized as a promising technology for digitally sharing project and life-cycle management data [85]. Its scope extends beyond geometric representation, improving drawing quality, accuracy, constructability, and facilitating collaboration across different disciplines [87]. Jiang et al. [41] proposed an integrated bridge object-oriented database containing comprehensive bridge life-cycle information and electronic data exchange protocols to enhance interoperability. However, currently, BrIM is primarily associated with the bridge design stage [88], with its application in monitoring and maintenance phases starting relatively late [31].

Given their inherent ability to manage information [100], BIM models could serve as a database for extensive inspection data [87] and unify information from various teams [31]. However, most current bridge models mainly focus on three-dimensional representations of the structure [85]. They often lack sufficient semantic interoperability and knowledge representation [41], which limits their potential as open-data repositories for bridge information.

The potential of using BrIM with BMS has been extensively researched, with a notable increase in studies since 2019. Dayan et al. [101] highlight the importance of input data in BMS for optimizing maintenance and discuss new methods for inspecting and testing concrete structures. They also identify research gaps and limitations, including the need for network-level maintenance optimization, automation of data collection, integration of sustainability information into BrIM-based models, development of compatible augmented reality technologies, and the use of machine learning to predict bridge health conditions.

6. Quantification and budgeting

Quantifying engineering projects has traditionally involved manually extracting information from two-dimensional representations. This method is not only time-consuming but also prone to errors [102–105]. Alternatively, BIM enables automatic material quantification from a model [86,106–108]. In this approach, estimators become reviewers of quantifications, greatly simplifying their tasks [104]. BIM tools enhance the reliability of cost estimation and information visualization and allow for quick predictions of the financial impact of project changes [107].

Despite the significant potential of BIM, its application in quantification lags behind other areas. Emerging tools have primarily focused on geometric design, which does not fully address the specific needs of the quantification process [109]. BIM tools perform well in quantifying materials for simple elements. For instance, Cheng and Chen [106] found that the volumes of reinforced concrete automatically determined by BIM were within 2.0% of those calculated by a senior budget engineer. However, the process is more complex for composite materials. Ma et al. [105] proposed a semi-automatic algorithm for quantifying and budgeting building projects using IFC data. This algorithm decomposes elements into products and service packages, but it requires that the products be of the same material, making it challenging to quantify different components of composite materials. For cast-in-place concrete structures, the algorithm does not quantify reinforcements, as they are designed independently in specific software and quantified separately at the end of the design process.

The efficiency of quantification depends on the model's level of detail. Besides individual information about materials and elements, it is crucial to define the relationships between component properties and product characteristics with costs [110]. Changing a component's property can affect work team productivity without impacting material costs. Understanding these effects allows estimates to be reused for a specific component, even if some properties change during the project. This detail is particularly important for large-scale projects, such as transport infrastructure and bridges.

If the estimator only has access to the final exported file (such as an IFC), retrieving necessary data for quantification can be challenging due to the diverse range of professionals involved in the project. Additionally, data exchange between different software and model formats can result in the loss of specific information, which must be retrieved manually, increasing the amount of human work [105]. To address these challenges, establishing a standardization for BIM models, even if contractual, is essential for the efficient use of data by the estimator [104,108].

Using 5D models helps stakeholders visualize reconstruction activities and costs over time, allowing all participants to review the project scope if design changes occur [24,111]. Quantities derived from these models are linked to a cost database during the budgeting process. To enable this integration, it is essential to adapt the tools to classification systems [102,112].

Automating the quantification process has significant limitations, especially for service quantification [103]. Automatic identification of exceptional construction conditions by BIM tools is challenging [86]. Additionally, the variety of solutions for similar situations can make quantifications subjective, depending on the estimator's interpretation and analysis, as noted by Shen and Issa [103]. Therefore, while tools for extracting quantitative data from BIM models do not replace the budget officer's work [86], they can reduce the time spent on searching, clarifying, and aggregating information, and improve the accuracy of estimates [103].

Quantifying bridge renovations and repair works requires specific data that differs in some aspects from standard practices for new constructions. However, for systematic inclusion in a BMS, information on repairs and strengthening is essential. Byun et al. [60] collected the necessary information on repair and strengthening from various maintenance manuals, ensuring a consistent level of organization and detail compared to the diagnostic level.

The cost of monitoring measures throughout the life cycle of bridge structures is significant. Track inspection is a primary source of data for managing bridges, ensuring their maintainability, reliability, and quality. Therefore, optimizing inspection frequency is necessary for both system safety and cost-effective management [24]. In their study, Kaewunruen et al. [24] used a preventive maintenance approach for the Minnamurra railway bridge, incorporating a maintenance schedule, cost estimation, and greenhouse gas (GHG) emission estimation into a life cycle assessment (LCA). They compiled a list of inspection, maintenance, and repair activities with associated unit costs, which allowed them to integrate temporal maintenance data into BIM-based digital twin models. The total monitoring cost was calculated by multiplying inspection time by material costs, considering the bridge's length, material, and components.

7. Planning and Control

Like budgeting, construction schedules are often generated manually, which is time-consuming and makes reuse in other projects difficult [113]. Understanding the construction process from graphic schedules, such as the Critical Path Method, requires interpreting the associations between graphic components and related activities. This can make it challenging to grasp the reasoning and assumptions behind the schedule, leading to potential misinterpretation. 4D BIM models, which include both spatial and temporal aspects of planning, offer a more accurate representation of construction procedures [114]. They enhance understanding of the schedule and help in identifying potential problems [115].

BIM technologies enable simulation of the construction process during the planning phase, allowing for decision optimization and validation of construction steps [92,116]. This capability helps predict conflicts and make necessary project changes before execution, reducing potential losses [92,117]. Visual information from 4D models can decrease accidents and enhance constructability by assessing interference between work areas of different teams [114,118]. 4D models significantly improve monitoring and control, facilitate information updates [119], and enhance function control [120]. Integrating new technologies with BIM processes, such as real-time monitoring, virtual reality, and neural networks, boosts monitoring quality and decision-making accuracy [121]. Additionally, data from BIM models can automatically generate construction schedules, reducing the need for manual planning work [122].

The effectiveness of a BIM 4D model in tracking construction progress relies on regular updates [123]. Monitoring and updating the 4D model's schedule is time-consuming and considered an additional contractual responsibility, which can discourage its use [123,124]. However, several studies explore alternatives for automating the progress monitoring of the construction process [122,123,125–130]. Reviews on this subject can be found in Kopsida et al. [131], Omar and Nehdi [132], and Yang et al. [133].

Planning construction activities involves not only efficient workspace allocation but also ensuring safety during simultaneous tasks [134]. With 4D models, which provide space-time information, conflict analysis can be conducted to optimize resource use [114] and improve worker safety as activities change throughout construction [135]. Simulations and spatiotemporal analysis help detect conflicts in workforce work areas [118,134] between large equipment [136–138], and support risk management and visualization through augmented reality [139]. They also enable automatic detection of risk areas based on design safety rules [140–143], safety planning, and temporary structures [144], fire simulation and evacuation [145,146], and general emergency evacuation plans [135]. Literature reviews on BIM's role in security management are available in Akram et al. [147], Lee et al. [142], Martínez-Aires et al. [148], and Zou et al. [149].

The operation and maintenance phase typically represents the longest and most costly period in a facility's lifecycle [2,3]. Ideally, preventive maintenance schedules—favored over corrective maintenance for their predictability [66] —are planned during the design phase due to their importance for structural durability. As with other processes, creating work order schedules for maintenance is largely manual, heavily reliant on project information and data collected continuously throughout the facility's service life.

Managing the information generated throughout a facility's lifecycle is a major challenge [30]. While building maintenance management tools are available, they primarily act as information managers and do not support functions such as automatic scheduling of maintenance [150]. Facility managers often struggle with accessing this information. BIM offers a potential solution by integrating fragmented data and providing an intuitive user interface [151]. BIM can enhance access to information and allow visualization of work orders within models [150]. However, despite existing specifications for planning operational and maintenance phases using BIM, there remains a lack of methodologies, tools, and standards to support its full implementation [30].

For bridges, there is no standardized definition of the necessary data (such as type, descriptions, level of detail, and quality) for planning and managing operation and maintenance [64]. The Industry Foundation Classes (IFC) 4.3 schema, which is designed to represent bridges, is incomplete, which complicates representing all lifecycle information [31]. Much of this data is unstructured [77,132,152] and cannot be directly represented by the IFC [31]. Another challenge is the limited access to information from external sources. While BIM can integrate data, it typically focuses on individual projects, which is insufficient for managing the operation and maintenance of bridges [64]. Therefore, maintenance systems should shift from being project-based to network-based, linking multiple projects together [73].

Applying BIM-based planning systems presents challenges, including the need for high levels of commitment and system knowledge [92]. For larger projects, preparing plans using 4D simulation can take longer than traditional methods [119]. Although this makes the modeling phase more time-consuming, it is important to note that modeling construction processes with detailed attributes allows for the reuse of definitions in similar future projects. With each new project, the effort to build the model decreases as definitions from previous projects can be reused [113]. Additionally, sharing and exchanging planning data remains challenging. Despite the IFC format supporting many project management practices and including appropriate classes for planning and estimates [123,153], data created with external tools and imported into BIM models may not always comply with IFC requirements. This can lead to interoperability issues between construction schedules and the IFC format [124].

8. Data management

Managing large volumes of data is a challenging task that requires significant computational effort and effective strategies [36]. More detailed inventories lead to more accurate and realistic predictions but necessitate a vast and complex database infrastructure and advanced algorithms. Some studies have focused on specific assets, offering limited databases for those cases with promising results [24]. However, extending this approach to a network of bridges across diverse regions, with varying environmental and market conditions, as well as different bridge types and materials, involves managing a complex array of information influenced by highly subjective decision processes.

BIM models serve as data repositories organized in a way that supports interoperability and collaborative management. As new needs and possibilities arise, various structures have been proposed to accommodate them. However, it is important to recognize that multiple stakeholders will manage the model, requiring proper knowledge and training to handle the data effectively. Additionally, the large volume of information within the model demands significant computational effort and storage space.

BIM-based BMS integrated with SHM systems have advanced within the context of Industry 4.0 and Cyber-Physical Systems (CPS) [27]. The application of new technologies has enhanced monitoring quality and increased decision-making accuracy [121]. Additionally, using Unmanned Aerial Vehicles (UAVs) alongside BIM and SHM technologies can boost productivity, accuracy, and documentation for data management [154]. However, effective integration between BIM and SHM still presents challenges [155]. Panah and Kioumarsi [121] and Sadhu et al. [155] identified several issues, including the need to extend IFC standards for data exchange, manage various types of sensing data, ensure interoperability among different BIM platforms and standards, incorporate and link dynamic information, and handle large databases and metadata related to localized damage.

Geographic information is another important data source for infrastructure projects. Traditionally managed by Geographic Information Systems (GIS), which act as geographical databases linking graphical objects on digital maps through common identifiers [156], GIS implementation has historically reduced costs and improved the accuracy and timeliness of transportation infrastructure projects [157]. Integrating GIS with BIM enhances data integration, quantitative analysis, and semantic richness [156]. Research has increasingly focused on this potential, as evidenced by the rise in related publications since 2015, highlighting the importance of this integration [158]. Detailed reviews on geospatial data management and the integration of BIM and GIS, particularly in bridge projects, are available in studies by Breunig et al. [158], Carrasco et al. [156], and Wei et al. [157].

The growing demand for real-time data exchange, driven by advances in monitoring, has led to the development of network-associated technologies such as digital twins and the Internet of Things (IoT). Digital twins are highly accurate virtual representations of physical assets, including single elements, products, or systems, that allow real-time, two-way communication through the network [22,26]. IoT refers to the network of physical "things" connected to the Internet and to each other, facilitating information sharing and service utilization [159]. When combined with BIM, these technologies can greatly enhance various project stages, as network communication capabilities are crucial for maintaining a common, real-time updated model. Reviews by Hu, Lim, and Cai [26] and Malagnino et al. [159] cover the integration of digital twins, IoT, and BIM in the construction industry. Additionally, Adibfar and Costin [22] provide a practical application of these concepts in a BrIM model for monitoring real-time traffic data.

The information from design, inspections, SHM systems, and other sources throughout a bridge's lifecycle exhibits significant Big Data characteristics. Large volumes of heterogeneous data are accumulated, but much of it is not effectively utilized in bridge management decision-making [41,85]. This creates a need for both data-driven approaches and robust hardware capable of fast and efficient data storage and processing [36]. A key trend in BMS evolution is the extensive use of artificial intelligence (AI) tools, which can learn, recognize, make conclusions, and achieve goals [27]. These AI tools automate processes and extract valuable insights from diverse data sets [35]. The integration of AI with BIM is thoroughly examined in the reviews by Zabin et al. [35] and Zhang et al. [160].

The emerging concept of Cloud-BIM offers a promising solution to meet the high computational power and storage demands required for the digital processes described, by integrating cloud computing with BIM technology. Cloud computing utilizes a network to distribute tasks across multiple computers or access services from remote hosts, reducing the need for high local computer performance. It also addresses issues related to BIM collaboration, integration, and sharing, as Cloud-BIM is inherently a network-based technology. Zhao and Taib [161] reviewed the current development of Cloud-BIM, highlighting its limitations and potential future research areas.

9. Concluding remarks

This paper presents a systematic literature review on bridge maintenance and management, focusing on the development of BIM in this field. It identifies scientific interests and current trends. A summary of the main challenges and opportunities is provided in Table 4.

The widespread availability of affordable data acquisition technologies has greatly increased the amount of data available for bridge management. However, having more data does not necessarily lead to improved management processes. In fact, the large volume of multi-source, heterogeneous data can complicate database management and require powerful hardware for storage and processing. There is still a significant need for improvements in the quality, organization, integration, and interoperability of information related to the maintenance of reinforced concrete bridges.

Table 4. Challenges and opportunities for research and development.

Topic	Challenges	Opportunities
BMS	Differences from country to country and different regions. Heterogenous, multi-sourced and volume of information.	Establishment of standards and minimum requirements. National and international cooperation and knowledge exchange. Improvement in data-processing.
Infrastructure works	Support for specific data related to infrastructure works. Alignment of organizations with BIM processes. Application at project and management levels. Cultural resistance, inadequate knowledge and lack of relevant experience	Improvements in BIM protocols for supporting infrastructure specificities. Data-integrated computational tools. Pressure at governmental and organizational levels through policies, procedures and mandates.
Bridge management	Lack of enough semantic interoperability and knowledge representation.	Data gathering automation Models containing sustainability information Development of compatible augmented reality technology. Implementation and use of machine learning techniques.
Quantification and budgeting	Efficiency dependent on the level of detail of the model. Quantification of different components of composite materials. Service quantification, productivity, exceptional construction conditions. Loss of information in the exchanging processes. Subjectivity of the estimator's interpretation and analysis. Specific data demanded for renovation and repair works. Cost of monitoring measures along the life cycle.	Establishment of standards for BIM models. Adaptability of the tools to classification systems and cost databases. Implementation and use of machine learning techniques.
Planning and control	High levels of subjectivity. Dependency of regular updates. Allocation of workspaces at the construction site aimed at efficiency and safety. Management and access to the information generated throughout the lifecycle. IFC format standard for bridges is still incomplete. Models more complex, detailed and time-consuming.	New technologies associated with BIM processes, such as real-time monitoring and virtual reality. Use of simulations and spatiotemporal analysis of construction. BIM integrating fragmented data. Establishment of methodologies, tools and standards. Definition of necessary data regarding planning and management of operation and maintenance. Dedicated external tools and data import into the BIM model. Implementation and use of machine learning techniques.

Data management	Several stakeholders and participants managing the model. Volume of information contained in the model. Management of various types of sensing data. Interoperability among different BIM platforms and the existing standards. Incorporation and linkage of dynamic information. Inclusion of large databases and metadata. Geographic information. Real-time data exchange.	Extend IFC standards. Implementation of GIS in transportation infrastructure programs interacted with BIM models. Network-associated technologies, such as digital twins and Internet of Things (IoT). Deployment of data-driven approaches, robust hardware, storing and processing of huge amounts of data. Extensive use of AI-based expert tools. Cloud-BIM.

To effectively leverage this data, current research trends in bridge management and maintenance are shifting towards automated, data-driven decision-making approaches. This reflects an evolving paradigm in the field.

The role of information in BIM and its focus on information management make it increasingly valuable, especially with ongoing advancements in data-oriented technologies. In the bridge management sector, combining BIM with BMS has improved efficiency and data integration. However, the application of BIM in maintenance management is less explored compared to other areas, revealing numerous research gaps.

Several gaps and challenges in bridge management and maintenance have been identified in the literature. Key challenges include the lack of unified data formats and a comprehensive definition of data requirements, which are necessary for consolidating all information collected throughout the structure's lifecycle into a single, shareable repository. Currently, fragmented and heterogeneous bridge databases hinder automated decision-making, even with data-driven approaches.

Although BIM is a promising tool for unifying information in maintenance management, it faces difficulties in this area. The IFC standard, widely used for BIM interoperability, suffers from issues of redundancy and ambiguity, which undermine one of the main advantages of BIM in bridge management.

To address these challenges, BIM must be adapted for infrastructure projects. This adaptation should include developing common guidelines for the quality and organization of information and improving common data formats like IFC to ensure semantic accuracy in model representations. Additionally, new software needs to be developed to handle the interdisciplinary nature of management processes and integrate emerging technologies. By investing in information standardization and enhancing the semantic quality of representations, the bridge management industry can fully harness the potential of BIM and data-driven approaches.

10. References

[1] X. Hu, C. Daganzo, S. Madanat, A reliability-based optimization scheme for maintenance management in large-scale bridge networks, Transp. Res. Part C Emerg. Technol. 55 (2015) 166–178. https://doi.org/10.1016/j.trc.2015.01.008.

[2] C. Chen, L. Tang, BIM based integrated management workflow design for schedule and cost planning of building fabric maintenance, Autom. Constr. 107 (2019) 102944. https://doi.org/10.1016/j.autcon.2019.102944.

[3] M.N. Grussing, L.R. Marrano, Building component lifecycle repair/replacement model for institutional facility management, Congr. Comput. Civ. Eng. Proc. (2007) 550–557. https://doi.org/10.1061/40937(261)65.

[4] P. Thoft-Christensen, Life-cycle cost-benefit (LCCB) analysis of bridges from a user and social point of view, Struct. Infrastruct. Eng. 5 (2009) 49–57. https://doi.org/10.1080/15732470701322818.

[5] R. Rodrigues, S. Gaboreau, J. Gance, I. Ignatiadis, S. Betelu, Reinforced concrete structures: A review of corrosion mechanisms and advances in electrical methods for corrosion monitoring, Constr. Build. Mater. 269 (2021) 121240. https://doi.org/10.1016/j.conbuildmat.2020.121240.

[6] C. Scope, M. Vogel, E. Guenther, Greener, cheaper, or more sustainable: Reviewing sustainability assessments of maintenance strategies of concrete structures, Sustain. Prod. Consum. 26 (2021) 838–858. https://doi.org/10.1016/j.spc.2020.12.022.

[7] A. Abdul-Ameer, K. Alhefeiti, Statistical Analysis of Reinforced Concrete Bridge Defects for Optimum Maintenance Planning and Budgeting, MATEC Web Conf. 83 (2016). https://doi.org/10.1051/matecconf/20168306001.

[8] M. Alexander, H. Beushausen, Durability, service life prediction, and modelling for reinforced concrete structures – review and critique, Cem. Concr. Res. 122 (2019) 17–29. https://doi.org/10.1016/j.cemconres.2019.04.018.

[9] A.P. Chassiakos, P. Vagiotas, D.D. Theodorakopoulos, A knowledge-based system for maintenance planning of highway concrete bridges, Adv. Eng. Softw. 36 (2005) 740–

749. https://doi.org/10.1016/j.advengsoft.2005.03.020.

[10] V. Dayan, N. Chileshe, R. Hassanli, A Scoping Review of Information-Modeling Development in Bridge Management Systems, J. Constr. Eng. Manag. 148 (2022) 1–14. https://doi.org/10.1061/(asce)co.1943-7862.0002340.

[11] A. Bradley, H. Li, R. Lark, S. Dunn, BIM for infrastructure: An overall review and constructor perspective, Autom. Constr. 71 (2016) 139–152. https://doi.org/10.1016/j.autcon.2016.08.019.

[12] A. Costin, A. Adibfar, H. Hu, S.S. Chen, Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations, Autom. Constr. 94 (2018) 257–281. https://doi.org/10.1016/j.autcon.2018.07.001.

[13] C. Gong, D.M. Frangopol, Condition-Based Multiobjective Maintenance Decision Making for Highway Bridges Considering Risk Perceptions, J. Struct. Eng. (United States). 146 (2020). https://doi.org/10.1061/(ASCE)ST.1943-541X.0002570.

[14] R. Arismendi, A. Barros, A. Grall, Piecewise deterministic Markov process for condition-based maintenance models — Application to critical infrastructures with discrete-state deterioration, Reliab. Eng. Syst. Saf. 212 (2021). https://doi.org/10.1016/j.ress.2021.107540.

[15] C.-H. Jeon, C.-S. Shim, Y.-H. Lee, J. Schooling, Prescriptive maintenance of prestressed concrete bridges considering digital twin and key performance indicator, Eng. Struct. 302 (2024) 117383. https://doi.org/10.1016/j.engstruct.2023.117383.

[16] Y. Yang, Y. Zhu, C. Cai, Research progress and prospect of digital twin in bridge engineering, Adv. Struct. Eng. 27 (2024) 333–352. https://doi.org/10.1177/13694332231218764.

[17] X. Hu, C. Daganzo, S. Madanat, A reliability-based optimization scheme for maintenance management in large-scale bridge networks, Transp. Res. Part C Emerg. Technol. 55 (2015) 166–178. https://doi.org/10.1016/j.trc.2015.01.008.

[18] O. Larsson Ivanov, I. Björnsson, D. Honfi, J. Leander, The practical value of structural

health information for time dependence in bridge maintenance, Struct. Infrastruct. Eng. 18 (2022) 476–491. https://doi.org/10.1080/15732479.2021.1890141.

[19] H. Jaafaru, B. Agbelie, Bridge maintenance planning framework using machine learning, multi-attribute utility theory and evolutionary optimization models, Autom. Constr. 141 (2022) 104460. https://doi.org/10.1016/j.autcon.2022.104460.

[20] K. Liu, N. El-Gohary, Deep Learning–Based Analytics of Multisource Heterogeneous Bridge Data for Enhanced Data-Driven Bridge Deterioration Prediction, J. Comput. Civ. Eng. 36 (2022). https://doi.org/10.1061/(ASCE)CP.1943-5487.0001018.

[21] G. Xu, F. Guo, Sustainability-oriented maintenance management of highway bridge networks based on Q-learning, Sustain. Cities Soc. 81 (2022). https://doi.org/10.1016/j.scs.2022.103855.

[22] A. Adibfar, A.M. Costin, Creation of a Mock-up Bridge Digital Twin by Fusing Intelligent Transportation Systems (ITS) Data into Bridge Information Model (BrIM), J. Constr. Eng. Manag. 148 (2022). https://doi.org/10.1061/(ASCE)CO.1943-7862.0002332.

[23] C.-S. Shim, N.-S. Dang, S. Lon, C.-H. Jeon, Development of a bridge maintenance system for prestressed concrete bridges using 3D digital twin model, Struct. Infrastruct. Eng. 15 (2019) 1319–1332. https://doi.org/10.1080/15732479.2019.1620789.

[24] S. Kaewunruen, M. AbdelHadi, M. Kongpuang, W. Pansuk, A.M. Remennikov, Digital Twins for Managing Railway Bridge Maintenance, Resilience, and Climate Change Adaptation, Sensors. 23 (2023). https://doi.org/10.3390/s23010252.

[25] H.H. Hosamo, M.H. Hosamo, Digital Twin Technology for Bridge Maintenance using 3D Laser Scanning: A Review, Adv. Civ. Eng. 2022 (2022). https://doi.org/10.1155/2022/2194949.

[26] W. Hu, K.Y.H. Lim, Y. Cai, Digital Twin and Industry 4.0 Enablers in Building and Construction: A Survey, Buildings. 12 (2022) 2004. https://doi.org/10.3390/buildings12112004.

[27] J. Bień, M. Salamak, The management of bridge structures – challenges and possibilities

, Arch. Civ. Eng. 68 (2022) 5–35. https://doi.org/10.24425/ace.2022.140627.

[28] N. Markiz, A. Jrade, Integrating fuzzy-logic decision support with a Bridge Information Management System (BRIMS) at the conceptual stage of bridge design, J. Inf. Technol. Constr. 23 (2018) 92–121.

[29] V.K. Bansal, Integrated Framework of BIM and GIS Applications to Support Building Lifecycle: A Move toward nD Modeling, J. Archit. Eng. 27 (2021) 1–18. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000490.

[30] J. Heaton, A.K. Parlikad, J. Schooling, Design and development of BIM models to support operations and maintenance, Comput. Ind. 111 (2019) 172–186. https://doi.org/10.1016/j.compind.2019.08.001.

[31] C. Wan, Z. Zhou, S. Li, Y. Ding, Z. Xu, Z. Yang, Y. Xia, F. Yin, Development of a Bridge Management System Based on the Building Information Modeling Technology, Sustainability. 11 (2019) 4583. https://doi.org/10.3390/su11174583.

[32] R. Assaad, I.H. El-Adaway, Bridge Infrastructure Asset Management System: Comparative Computational Machine Learning Approach for Evaluating and Predicting Deck Deterioration Conditions, J. Infrastruct. Syst. 26 (2020). https://doi.org/10.1061/(ASCE)IS.1943-555X.0000572.

[33] G. Marasco, F. Oldani, B. Chiaia, G. Ventura, F. Dominici, C. Rossi, F. Iacobini, A. Vecchi, Machine learning approach to the safety assessment of a prestressed concrete railway bridge, Struct. Infrastruct. Eng. (2022) 1–15. https://doi.org/10.1080/15732479.2022.2119581.

[34] J. Feng, K. Gao, W. Gao, Y. Liao, G. Wu, Machine learning-based bridge cable damage detection under stochastic effects of corrosion and fire, Eng. Struct. 264 (2022). https://doi.org/10.1016/j.engstruct.2022.114421.

[35] A. Zabin, V.A. González, Y. Zou, R. Amor, Applications of machine learning to BIM: A systematic literature review, Adv. Eng. Informatics. 51 (2022) 101474. https://doi.org/10.1016/j.aei.2021.101474.

[36] F.I.H. Sakiyama, F. Lehmann, H. Garrecht, A Novel Runtime Algorithm for the Real-

Time Analysis and Detection of Unexpected Changes in a Real-Size SHM Network with Quasi-Distributed FBG Sensors, Sensors. 21 (2021) 2871. https://doi.org/10.3390/s21082871.

[37] S. Hasan, S. Hasan, E. Elwakil, National Bridge Inventory Data-Based Stochastic Modeling for Deck Condition Rating of Prestressed Concrete Bridges, Pract. Period. Struct. Des. Constr. 25 (2020). https://doi.org/10.1061/(ASCE)SC.1943-5576.0000505.

[38] A.C.P. Martins, J.M. Franco de Carvalho, M.C.S. Alvarenga, D.S. de Oliveira, K.M.L. César Júnior, J.C.L. Ribeiro, G.S. Santos, R.C. Verly, Detecting, monitoring and modeling damage within the decision-making process in the context of managing bridges: a review, Struct. Infrastruct. Eng. (2024) 1–23. https://doi.org/10.1080/15732479.2024.2331103.

[39] K. Gkoumas, M. Stepniak, I. Cheimariotis, F. Marques dos Santos, New technologies for bridge inspection and monitoring: a perspective from European Union research and innovation projects, Struct. Infrastruct. Eng. 20 (2024) 1120–1132. https://doi.org/10.1080/15732479.2024.2311898.

[40] E.M. Abdelkader, T. Zayed, N. Faris, Synthesized Evaluation of Reinforced Concrete Bridge Defects, Their Non-Destructive Inspection and Analysis Methods: A Systematic Review and Bibliometric Analysis of the Past Three Decades, Buildings. 13 (2023) 800. https://doi.org/10.3390/buildings13030800.

[41] Y. Jiang, G. Yang, H. Li, T. Zhang, Knowledge driven approach for smart bridge maintenance using big data mining, Autom. Constr. 146 (2023). https://doi.org/10.1016/j.autcon.2022.104673.

[42] N. Kaiser, C.K. Barstow, Rural Transportation Infrastructure in Low-and Middle-Income Countries: A Review of Impacts, Implications, and Interventions, Sustain. 14 (2022). https://doi.org/10.3390/su14042149.

[43] N. Bertola, P. Schiltz, E. Denarié, E. Brühwiler, A Review of the Use of UHPFRC in Bridge Rehabilitation and New Construction in Switzerland, Front. Built Environ. 7 (2021). https://doi.org/10.3389/fbuil.2021.769686.

[44] S. Alampalli, D.M. Frangopol, J. Grimson, M.W. Halling, D.E. Kosnik, E.O.L.

Lantsoght, D. Yang, Y.E. Zhou, Bridge Load Testing: State-of-The-Practice, J. Bridg. Eng. 26 (2021). https://doi.org/10.1061/(ASCE)BE.1943-5592.0001678.

[45] I. Srikanth, M. Arockiasamy, Deterioration models for prediction of remaining useful life of timber and concrete bridges: A review, J. Traffic Transp. Eng. (English Ed. 7 (2020) 152–173. https://doi.org/10.1016/j.jtte.2019.09.005.

[46] D. Kim, Y. Lee, M. Lee, Development of Risk-Based Bridge Maintenance Prioritization Methodology, KSCE J. Civ. Eng. 22 (2018) 3718–3725. https://doi.org/10.1007/s12205-018-2058-3.

[47] F. Moreu, X. Li, S. Li, D. Zhang, Technical Specifications of Structural Health Monitoring for Highway Bridges: New Chinese Structural Health Monitoring Code, Front. Built Environ. 4 (2018). https://doi.org/10.3389/fbuil.2018.00010.

[48] B. Chan, H. Guan, J. Jo, M. Blumenstein, Towards UAV-based bridge inspection systems: A review and an application perspective, Struct. Monit. Maint. 2 (2015) 283–300. https://doi.org/10.12989/smm.2015.2.3.283.

[49] C. O’Higgins, D. Hester, P. McGetrick, W.K. Ao, E.J. Cross, Refinement and Validation of the Minimal Information Data-Modelling (MID) Method for Bridge Management, Sensors. 24 (2024) 3879. https://doi.org/10.3390/s24123879.

[50] A. Costin, A. Adibfar, J. Bridge, Digital Twin Framework for Bridge Structural Health Monitoring Utilizing Existing Technologies: New Paradigm for Enhanced Management, Operation, and Maintenance, Transp. Res. Rec. J. Transp. Res. Board. 2678 (2024) 1095–1106. https://doi.org/10.1177/03611981231208908.

[51] G. Lee, T. Chang, S. Chi, Data-Driven Bridge Maintenance Cost Estimation Framework for Annual Expenditure Planning, J. Manag. Eng. 40 (2024). https://doi.org/10.1061/JMENEA.MEENG-5706.

[52] Y. Schatz, B. Domer, Semi-automated creation of IFC bridge models from point clouds for maintenance applications, Front. Built Environ. 10 (2024). https://doi.org/10.3389/fbuil.2024.1375873.

[53] X. Lai, Z. Kan, W. Sun, X. Song, B. Tian, T. Yuan, Digital twin-based non-destructive

testing for structural health monitoring of bridges, Nondestruct. Test. Eval. 39 (2024) 57–74. https://doi.org/10.1080/10589759.2023.2239434.

[54] Y. Gao, H. Li, G. Xiong, H. Song, AIoT-informed digital twin communication for bridge maintenance, Autom. Constr. 150 (2023) 104835. https://doi.org/10.1016/j.autcon.2023.104835.

[55] T. Chang, G. Lee, S. Chi, Development of an Optimized Condition Estimation Model for Bridge Components Using Data-Driven Approaches, J. Perform. Constr. Facil. 37 (2023). https://doi.org/10.1061/JPCFEV.CFENG-4359.

[56] M. Watanabe, T. Goso, K. Ibayashi, Method for the Rapid Creation of Bridge Database Systems and Practices in Developing Countries, Pract. Period. Struct. Des. Constr. 28 (2023). https://doi.org/10.1061/(ASCE)SC.1943-5576.0000754.

[57] D.-C. Nguyen, T.-Q. Nguyen, R. Jin, C.-H. Jeon, C.-S. Shim, BIM-based mixed-reality application for bridge inspection and maintenance, Constr. Innov. 22 (2022) 487–503. https://doi.org/10.1108/CI-04-2021-0069.

[58] J. Gosliga, D. Hester, K. Worden, A. Bunce, On Population-based structural health monitoring for bridges, Mech. Syst. Signal Process. 173 (2022). https://doi.org/10.1016/j.ymssp.2022.108919.

[59] Z. Zhou, An Intelligent Bridge Management and Maintenance Model Using BIM Technology, Mob. Inf. Syst. 2022 (2022) 1–9. https://doi.org/10.1155/2022/7130546.

[60] N. Byun, W.S. Han, Y.W. Kwon, Y.J. Kang, Development of bim-based bridge maintenance system considering maintenance data schema and information system, Sustain. 13 (2021). https://doi.org/10.3390/su13094858.

[61] M.H. Nili, H. Taghaddos, B. Zahraie, Integrating discrete event simulation and genetic algorithm optimization for bridge maintenance planning, Autom. Constr. 122 (2021) 103513. https://doi.org/10.1016/j.autcon.2020.103513.

[62] C. Wu, P. Wu, J. Wang, R. Jiang, M. Chen, X. Wang, Ontological knowledge base for concrete bridge rehabilitation project management, Autom. Constr. 121 (2021). https://doi.org/10.1016/j.autcon.2020.103428.

[63] B. WÓJCIK, M. ZARSKI, The measurements of surface defect area with an RGB-D camera for a BIM-backed bridge inspection, Bull. Polish Acad. Sci. Tech. Sci. 69 (2021). https://doi.org/10.24425/bpasts.2021.137123.

[64] C. Wu, P. Wu, J. Wang, R. Jiang, M. Chen, X. Wang, Critical review of data-driven decision-making in bridge operation and maintenance, Struct. Infrastruct. Eng. 18 (2021). https://doi.org/10.1080/15732479.2020.1833946.

[65] C. Wu, X. Wang, P. Wu, J. Wang, R. Jiang, M. Chen, M. Swapan, Hybrid deep learning model for automating constraint modelling in advanced working packaging, Autom. Constr. 127 (2021). https://doi.org/10.1016/j.autcon.2021.103733.

[66] J.S. Jensen, Innovative and sustainable operation and maintenance of bridges, Struct. Infrastruct. Eng. 16 (2020) 72–83. https://doi.org/10.1080/15732479.2019.1604772.

[67] M.H. Nili, B. Zahraie, H. Taghaddos, BrDSS: A decision support system for bridge maintenance planning employing bridge information modeling, Smart Struct. Syst. 26 (2020) 533–544. https://doi.org/10.12989/sss.2020.26.4.533.

[68] G. Cha, S. Park, T. Oh, A Terrestrial LiDAR-Based Detection of Shape Deformation for Maintenance of Bridge Structures, J. Constr. Eng. Manag. 145 (2019). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001701.

[69] K.W. Lee, J.K. Park, Modeling and Management of Bridge Structures Using Unmanned Aerial Vehicle in Korea, Sensors Mater. 31 (2019) 3765. https://doi.org/10.18494/SAM.2019.2467.

[70] M.-Y. Cheng, Y.-F. Chiu, C.-K. Chiu, D. Prayogo, Y.-W. Wu, Z.-L. Hsu, C.-H. Lin, Risk-based maintenance strategy for deteriorating bridges using a hybrid computational intelligence technique: a case study, Struct. Infrastruct. Eng. 15 (2019) 334–350. https://doi.org/10.1080/15732479.2018.1547767.

[71] L. Quirk, J. Matos, J. Murphy, V. Pakrashi, Visual inspection and bridge management, Struct. Infrastruct. Eng. 14 (2018) 320–332. https://doi.org/10.1080/15732479.2017.1352000.

[72] O. Adarkwa, N. Attoh-Okine, T. Schumacher, Using tensor factorization to predict

network-level performance of bridges, J. Infrastruct. Syst. 23 (2017). https://doi.org/10.1061/(ASCE)IS.1943-555X.0000339.

[73] C.C.-S. Shim, H. Kang, N.S.N.S. Dang, D. Lee, Development of BIM-based bridge maintenance system for cable-stayed bridges, Smart Struct. Syst. 20 (2017) 697–708.

[74] S.M. Khan, S. Atamturktur, M. Chowdhury, M. Rahman, Integration of structural health monitoring and intelligent transportation systems for bridge condition assessment: Current status and future direction, IEEE Trans. Intell. Transp. Syst. 17 (2016) 2107–2122. https://doi.org/10.1109/TITS.2016.2520499.

[75] H. Liu, S. Madanat, Adaptive optimisation methods in system-level bridge management, Struct. Infrastruct. Eng. 11 (2015) 884–896. https://doi.org/10.1080/15732479.2014.920038.

[76] B. Yanev, G.A.C. Richards, Designing bridge maintenance on the network and project levels, Struct. Infrastruct. Eng. 9 (2013) 349–363. https://doi.org/10.1080/15732479.2012.657651.

[77] S. Jeong, R. Hou, J.P. Lynch, H. Sohn, K.H. Law, An information modeling framework for bridge monitoring, Adv. Eng. Softw. 114 (2017) 11–31. https://doi.org/10.1016/j.advengsoft.2017.05.009.

[78] C. Wu, P. Wu, J. Wang, R. Jiang, M. Chen, X. Wang, Ontological knowledge base for concrete bridge rehabilitation project management, Autom. Constr. 121 (2021) 103428. https://doi.org/10.1016/j.autcon.2020.103428.

[79] AASHTO, The Manual for Bridge Evaluation, 2nd., American Association of State Highway and Transportation Officials, 2011.

[80] S.D. Hurt, M. A.; Schrock, Highway bridge maintenance planning and scheduling, Butterworth-Heinemann, 2016.

[81] M.J. Ryall, J.E. Harding, G.A.R. Parke, Bridge Management: Inspection, Maintenance, Assessment and Repair, Springer US, 2013.

[82] P. Mirzaei, Z., Adey, B. T., Klatter, L., Thompson, The IABMAS bridge management committee overview of existing bridge management systems, Sapporo, 2014.

[83] V.S. de Freitas Bello, C. Popescu, T. Blanksvärd, B. Täljsten, Bridge management systems: overview and framework for smart management, in: IABSE Congr. 2021 Struct. Eng. Futur. Soc. Needs, Ghent, Belgium, Sept. 22-24, 2021, International Association for Bridge and Structural Engineering (IABSE), 2021: pp. 1014–1022. https://doi.org/10.2749/ghent.2021.1014.

[84] M.M. Melhem, C. Caprani, A. Ng, Bridge Management in Australia and New Zealand: Current Approaches and Future Needs, in: N. Powers, D.M. Frangopol, R. Al-Mahaidi, C. Caprani (Eds.), Maintenance, Safety, Risk, Manag. Life-Cycle Perform. Bridg., CRC Press, 2018: p. 7. https://doi.org/10.1201/9781315189390.

[85] J. Yang, F. Xiang, R. Li, L. Zhang, X. Yang, S. Jiang, H. Zhang, D. Wang, X. Liu, Intelligent bridge management via big data knowledge engineering, Autom. Constr. 135 (2022) 104118. https://doi.org/10.1016/j.autcon.2021.104118.

[86] C.M. Eastman, P. Teicholz, R. Sacks, K. Liston, BIM Handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors, 2nd ed, Wiley, Hoboken, NJ, 2011.

[87] A. Costin, A. Adibfar, H. Hu, S.S. Chen, Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations, Autom. Constr. 94 (2018) 257–281. https://doi.org/10.1016/j.autcon.2018.07.001.

[88] W. Shou, J. Wang, X. Wang, H.Y. Chong, A Comparative Review of Building Information Modelling Implementation in Building and Infrastructure Industries, Arch. Comput. Methods Eng. 22 (2015) 291–308. https://doi.org/10.1007/s11831-014-9125-9.

[89] L.K. Newton, N. Chileshe, Awareness, usage and benefits of building information modelling (BIM) adoption - the case of South Australian construction organizations, (2012). https://doi.org/10.13140/RG.2.1.2352.3363.

[90] D.W.M. Chan, T.O. Olawumi, A.M.L. Ho, Perceived benefits of and barriers to Building Information Modelling (BIM) implementation in construction: The case of Hong Kong, J. Build. Eng. 25 (2019) 100764. https://doi.org/10.1016/j.jobe.2019.100764.

[91] R. Charef, H. Alaka, S. Emmitt, Beyond the third dimension of BIM: A systematic

review of literature and assessment of professional views, J. Build. Eng. 19 (2018) 242–257. https://doi.org/10.1016/j.jobe.2018.04.028.

[92] O.G. Sánchez-Rivera, J.A. Galvis-Guerra, H. Porras-Díaz, Y.D. Ardila-Chacón, C.A. Martínez-Martínez, BrIM 5D models and Lean Construction for planning work activities in reinforced concrete bridges, Rev. Fac. Ing. 26 (2017). https://doi.org/10.19053/01211129.v26.n46.2017.7314.

[93] I. Kamardeen, 8D BIM modelling tool for accident prevention through design, Assoc. Res. Constr. Manag. ARCOM 2010 - Proc. 26th Annu. Conf. (2010) 281–289.

[94] A. Sidani, F.M. Dinis, J. Duarte, L. Sanhudo, D. Calvetti, J.S. Baptista, J.P. Martins, A. Soeiro, Recent tools and techniques of BIM-Based Augmented Reality: A systematic review, J. Build. Eng. 42 (2021) 102500. https://doi.org/10.1016/j.jobe.2021.102500.

[95] Á.M. Bazán, M.G. Alberti, A.A. Álvarez, J.A. Trigueros, New Perspectives for BIM Usage in Transportation Infrastructure Projects, Appl. Sci. 10 (2020) 7072. https://doi.org/10.3390/app10207072.

[96] H.Y. Chong, R. Lopez, J. Wang, X. Wang, Z. Zhao, Comparative Analysis on the Adoption and Use of BIM in Road Infrastructure Projects, J. Manag. Eng. 32 (2016) 5016021. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000460.

[97] C.Z. Li, Z. Guo, D. Su, B. Xiao, V.W.Y. Tam, The Application of Advanced Information Technologies in Civil Infrastructure Construction and Maintenance, Sustainability. 14 (2022) 7761. https://doi.org/10.3390/su14137761.

[98] S. Kaewunruen, J. Sresakoolchai, Z. Zhou, Sustainability-Based Lifecycle Management for Bridge Infrastructure Using 6D BIM, Sustainability. 12 (2020) 2436. https://doi.org/10.3390/su12062436.

[99] V.L.B. Viana, M.T.M. Carvalho, Prioritization of risks related to BIM implementation in brazilian public agencies using fuzzy logic, J. Build. Eng. 36 (2021) 102104. https://doi.org/10.1016/j.jobe.2020.102104.

[100] B. McGuire, R. Atadero, C. Clevenger, M. Ozbek, Bridge Information Modeling for Inspection and Evaluation, J. Bridg. Eng. 21 (2016) 4015076.

https://doi.org/10.1061/(ASCE)BE.1943-5592.0000850.

[101] V. Dayan, N. Chileshe, R. Hassanli, A Scoping Review of Information-Modeling Development in Bridge Management Systems, J. Constr. Eng. Manag. 148 (2022). https://doi.org/10.1061/(ASCE)CO.1943-7862.0002340.

[102] C.E. Firat, D. Arditi, J.-P. Hämäläinen, J. Stenstrand, J. Kiiras, Quantity Take-off in Model-based Systems, in: Proc. CIB W78 2010 27ª Int. Conf., Cairo, Egito., 2010: p. 8.

[103] Z. Shen, R.R.A. Issa, Quantitative evaluation of the BIM-assisted construction detailed cost estimates, (2010) 26.

[104] S. Vitásek, P. Matějka, Utilization of BIM for automation of quantity takeoffs and cost estimation in transport infrastructure construction projects in the Czech Republic, IOP Conf. Ser. Mater. Sci. Eng. 236 (2017) 12110. https://doi.org/10.1088/1757-899X/236/1/012110.

[105] Z. Ma, Z. Wei, X. Zhang, Semi-automatic and specification-compliant cost estimation for tendering of building projects based on IFC data of design model, Autom. Constr. 30 (2013) 126–135. https://doi.org/10.1016/j.autcon.2012.11.020.

[106] Y.M. Cheng, J.Y. Chen, Application of BIM on Quantity Estimate for Reinforced Concrete, Appl. Mech. Mater. 357–360 (2013) 2402–2405. https://doi.org/10.4028/www.scientific.net/AMM.357-360.2402.

[107] N.A.A. Ismail, R. Drogemuller, S. Beazley, R. Owen, A Review of BIM Capabilities for Quantity Surveying Practice, MATEC Web Conf. 66 (2016) 42. https://doi.org/10.1051/matecconf/20166600042.

[108] S. Wu, G. Wood, K. Ginige, S.W. Jong, A technical review of BIM based cost estimating in UK quantity surveying practice, standards and tools, J. Inf. Technol. Constr. 19 (2014) 534–562.

[109] A.-M. Mahamadu, L. Mahdjoubi, P. Manu, C. Aigbavboa, Attributes That Determine the Building Information Modelling Capability Maturity of Quantity Surveying Practice, MATEC Web Conf. 312 (2020) 2002. https://doi.org/10.1051/matecconf/202031202002.

[110] S. Staub-French, M. Fischer, Formalisms and Mechanisms Needed to Maintain Cost Estimates Based on an IFC Product Model, in: Comput. Civ. Build. Eng., American Society of Civil Engineers, Stanford, California, United States, 2000: pp. 716–723. https://doi.org/10.1061/40513(279)94.

[111] D. Bryde, M. Broquetas, J.M. Volm, The project benefits of Building Information Modelling (BIM), Int. J. Proj. Manag. 31 (2013) 971–980. https://doi.org/10.1016/j.ijproman.2012.12.001.

[112] Z. Ma, Z. Wei, X. Zhang, S. Qiu, P. Wang, Intelligent Generation of Bill of Quantity from IFC Data Subject to Chinese Standard, in: Proc. 28th ISARC, Seoul, Korea, 2011: pp. 740–745. https://doi.org/10.22260/ISARC2011/0138.

[113] E. Tauscher, E. Mikulakova, K. Beucke, M. König, Automated generation of construction schedules based on the IFC object model, Proc. 2009 ASCE Int. Work. Comput. Civ. Eng. 346 (2009) 666–675. https://doi.org/10.1061/41052(346)66.

[114] J.P. Zhang, Z.Z. Hu, BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 2. Development and site trials, Autom. Constr. 20 (2011) 155–166. https://doi.org/10.1016/j.autcon.2010.09.013.

[115] B. Koo, M. Fischer, Feasibility Study of 4D CAD in Comercial Construction, J. Constr. Eng. Manag. 126 (2000) 251–260.

[116] H. Liu, M. Al-Hussein, M. Lu, BIM-based integrated approach for detailed construction scheduling under resource constraints, Autom. Constr. 53 (2015) 29–43. https://doi.org/10.1016/j.autcon.2015.03.008.

[117] D. Heesom, L. Mahdjoubi, Trends of 4D CAD applications for construction planning, Constr. Manag. Econ. 22 (2004) 171–182. https://doi.org/10.1080/0144619042000201376.

[118] H. Moon, N. Dawood, L. Kang, Development of workspace conflict visualization system using 4D object of work schedule, Adv. Eng. Informatics. 28 (2014) 50–65. https://doi.org/10.1016/j.aei.2013.12.001.

[119] A. Candelario-Garrido, J. García-Sanz-Calcedo, A.M. Reyes Rodríguez, A quantitative

analysis on the feasibility of 4D Planning Graphic Systems versus Conventional Systems in building projects, Sustain. Cities Soc. 35 (2017) 378–384. https://doi.org/10.1016/j.scs.2017.08.024.

[120] S.M. Chen, F.H. Griffis, P.H. Chen, L.M. Chang, A framework for an automated and integrated project scheduling and management system, Autom. Constr. 35 (2013) 89–110. https://doi.org/10.1016/j.autcon.2013.04.002.

[121] R.S. Panah, M. Kioumarsi, Application of Building Information Modelling (BIM) in the Health Monitoring and Maintenance Process: A Systematic Review, Sensors. 21 (2021) 837. https://doi.org/10.3390/s21030837.

[122] C. Kim, B. Kim, H. Kim, 4D CAD model updating using image processing-based construction progress monitoring, Autom. Constr. 35 (2013) 44–52. https://doi.org/10.1016/j.autcon.2013.03.005.

[123] H. Hamledari, B. McCabe, S. Davari, A. Shahi, Automated Schedule and Progress Updating of IFC-Based 4D BIMs, J. Comput. Civ. Eng. 31 (2017) 04017012. https://doi.org/10.1061/(asce)cp.1943-5487.0000660.

[124] R. Lopez, H.-Y. Chong, X. Wang, J. Graham, Technical Review: Analysis and Appraisal of Four-Dimensional Building Information Modeling Usability in Construction and Engineering Projects, J. Constr. Eng. Manag. 142 (2016) 06015005. https://doi.org/10.1061/(asce)co.1943-7862.0001094.

[125] M. Golparvar-Fard, F. Peña-Mora, S. Savarese, Automated Progress Monitoring Using Unordered Daily Construction Photographs and IFC-Based Building Information Models, J. Comput. Civ. Eng. 29 (2015) 04014025. https://doi.org/10.1061/(asce)cp.1943-5487.0000205.

[126] K.K. Han, D. Cline, M. Golparvar-Fard, Formalized knowledge of construction sequencing for visual monitoring of work-in-progress via incomplete point clouds and low-LoD 4D BIMs, Adv. Eng. Informatics. 29 (2015) 889–901. https://doi.org/10.1016/j.aei.2015.10.006.

[127] K.K. Han, M. Golparvar-Fard, Appearance-based material classification for monitoring of operation-level construction progress using 4D BIM and site photologs, Autom.

Constr. 53 (2015) 44–57. https://doi.org/10.1016/j.autcon.2015.02.007.

[128] C. Kropp, C. Koch, M. König, Interior construction state recognition with 4D BIM registered image sequences, Autom. Constr. 86 (2018) 11–32. https://doi.org/10.1016/j.autcon.2017.10.027.

[129] Z. Pučko, N. Šuman, D. Rebolj, Automated continuous construction progress monitoring using multiple workplace real time 3D scans, Adv. Eng. Informatics. 38 (2018) 27–40. https://doi.org/10.1016/j.aei.2018.06.001.

[130] Y. Turkan, F. Bosche, C.T. Haas, R. Haas, Automated progress tracking using 4D schedule and 3D sensing technologies, Autom. Constr. 22 (2012) 414–421. https://doi.org/10.1016/j.autcon.2011.10.003.

[131] M. Kopsida, I. Brilakis, P. Vela, A Review of Automated Construction Progress and Inspection Methods, Proc. 32nd CIB W78 Conf. Constr. IT. (2015) 421–431.

[132] T. Omar, M.L. Nehdi, Data acquisition technologies for construction progress tracking, Autom. Constr. 70 (2016) 143–155. https://doi.org/10.1016/j.autcon.2016.06.016.

[133] J. Yang, M.W. Park, P.A. Vela, M. Golparvar-Fard, Construction performance monitoring via still images, time-lapse photos, and video streams: Now, tomorrow, and the future, Adv. Eng. Informatics. 29 (2015) 211–224. https://doi.org/10.1016/j.aei.2015.01.011.

[134] V. Getuli, P. Capone, A. Bruttini, S. Isaac, BIM-based immersive Virtual Reality for construction workspace planning: A safety-oriented approach, Autom. Constr. 114 (2020) 103160. https://doi.org/10.1016/j.autcon.2020.103160.

[135] M. Marzouk, I. Al Daour, Planning labor evacuation for construction sites using BIM and agent-based simulation, Saf. Sci. 109 (2018) 174–185. https://doi.org/10.1016/j.ssci.2018.04.023.

[136] Y. Ji, F. Leite, Automated tower crane planning: leveraging 4-dimensional BIM and rule-based checking, Autom. Constr. 93 (2018) 78–90. https://doi.org/10.1016/j.autcon.2018.05.003.

[137] A.N. Tak, H. Taghaddos, A. Mousaei, A. Bolourani, U. Hermann, BIM-based 4D mobile

crane simulation and onsite operation management, Autom. Constr. 128 (2021) 103766. https://doi.org/10.1016/j.autcon.2021.103766.

[138] J. Wang, X. Zhang, W. Shou, X. Wang, B. Xu, M.J. Kim, P. Wu, A BIM-based approach for automated tower crane layout planning, Autom. Constr. 59 (2015) 168–178. https://doi.org/10.1016/j.autcon.2015.05.006.

[139] C.S. Park, H.J. Kim, A framework for construction safety management and visualization system, Autom. Constr. 33 (2013) 95–103. https://doi.org/10.1016/j.autcon.2012.09.012.

[140] J.P. Cortés-Pérez, A. Cortés-Pérez, P. Prieto-Muriel, BIM-integrated management of occupational hazards in building construction and maintenance, Autom. Constr. 113 (2020) 103115. https://doi.org/10.1016/j.autcon.2020.103115.

[141] G. Hongling, Y. Yantao, Z. Weisheng, L. Yan, BIM and Safety Rules Based Automated Identification of Unsafe Design Factors in Construction, Procedia Eng. 164 (2016) 467–472. https://doi.org/10.1016/j.proeng.2016.11.646.

[142] Y. Lee, I. Kim, J. Choi, Development of BIM-Based Risk Rating Estimation Automation and a Design-for-Safety Review System, Appl. Sci. 10 (2020) 3902. https://doi.org/10.3390/app10113902.

[143] S. Zhang, J. Teizer, J.K. Lee, C.M. Eastman, M. Venugopal, Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules, Autom. Constr. 29 (2013) 183–195. https://doi.org/10.1016/j.autcon.2012.05.006.

[144] K. Kim, Y. Cho, S. Zhang, Integrating work sequences and temporary structures into safety planning: Automated scaffolding-related safety hazard identification and prevention in BIM, Autom. Constr. 70 (2016) 128–142. https://doi.org/10.1016/j.autcon.2016.06.012.

[145] U. Rüppel, K. Schatz, Designing a BIM-based serious game for fire safety evacuation simulations, Adv. Eng. Informatics. 25 (2011) 600–611. https://doi.org/10.1016/j.aei.2011.08.001.

[146] Q. Sun, Y. Turkan, A BIM-based simulation framework for fire safety management and investigation of the critical factors affecting human evacuation performance, Adv. Eng. Informatics. 44 (2020) 101093. https://doi.org/10.1016/j.aei.2020.101093.

[147] R. Akram, M.J. Thaheem, A.R. Nasir, T.H. Ali, S. Khan, Exploring the role of building information modeling in construction safety through science mapping, Saf. Sci. 120 (2019) 456–470. https://doi.org/10.1016/j.ssci.2019.07.036.

[148] M.D. Martínez-Aires, M. López-Alonso, M. Martínez-Rojas, Building information modeling and safety management: A systematic review, Saf. Sci. 101 (2018) 11–18. https://doi.org/10.1016/j.ssci.2017.08.015.

[149] Y. Zou, A. Kiviniemi, S.W. Jones, A review of risk management through BIM and BIM-related technologies, Saf. Sci. 97 (2017) 88–98. https://doi.org/10.1016/j.ssci.2015.12.027.

[150] W. Chen, K. Chen, J.C.P. Cheng, Q. Wang, V.J.L. Gan, BIM-based framework for automatic scheduling of facility maintenance work orders, Autom. Constr. 91 (2018) 15–30. https://doi.org/10.1016/j.autcon.2018.03.007.

[151] X. Gao, P. Pishdad-Bozorgi, BIM-enabled facilities operation and maintenance: A review, Adv. Eng. Informatics. 39 (2019) 227–247. https://doi.org/10.1016/j.aei.2019.01.005.

[152] R. Aragao, T.E. El-Diraby, Network analytics and social BIM for managing project unstructured data, Autom. Constr. 122 (2021) 103512. https://doi.org/10.1016/j.autcon.2020.103512.

[153] T. Froese, M. Fischer, F. Grobler, J. Ritzenthaler, K. Yu, S. Sutherland, S. Staub, B. Akinci, R. Akbas, B. Koo, A. Barron, J. Kunz, Industry foundation classes for project management - A trial implementation, Electron. J. Inf. Technol. Constr. 4 (1999) 17–36.

[154] T.S.N. Rachmawati, S. Kim, Unmanned Aerial Vehicles (UAV) Integration with Digital Technologies toward Construction 4.0: A Systematic Literature Review, Sustainability. 14 (2022) 5708. https://doi.org/10.3390/su14095708.

[155] A. Sadhu, J.E. Peplinski, A. Mohammadkhorasani, F. Moreu, A Review of Data

Management and Visualization Techniques for Structural Health Monitoring Using BIM and Virtual or Augmented Reality, J. Struct. Eng. 149 (2023). https://doi.org/10.1061/(ASCE)ST.1943-541X.0003498.

[156] C.A. Carrasco, I. Lombillo, J.M. Sánchez-Espeso, F.J. Balbás, Quantitative and Qualitative Analysis on the Integration of Geographic Information Systems and Building Information Modeling for the Generation and Management of 3D Models, Buildings. 12 (2022) 1672. https://doi.org/10.3390/buildings12101672.

[157] J. Wei, G. Chen, J. Huang, L. Xu, Y. Yang, J. Wang, A.-M. Sadick, BIM and GIS Applications in Bridge Projects: A Critical Review, Appl. Sci. 11 (2021) 6207. https://doi.org/10.3390/app11136207.

[158] M. Breunig, P.E. Bradley, M. Jahn, P. Kuper, N. Mazroob, N. Rösch, M. Al-Doori, E. Stefanakis, M. Jadidi, Geospatial Data Management Research: Progress and Future Directions, ISPRS Int. J. Geo-Information. 9 (2020) 95. https://doi.org/10.3390/ijgi9020095.

[159] A. Malagnino, T. Montanaro, M. Lazoi, I. Sergi, A. Corallo, L. Patrono, Building Information Modeling and Internet of Things integration for smart and sustainable environments: A review, J. Clean. Prod. 312 (2021) 127716. https://doi.org/10.1016/j.jclepro.2021.127716.

[160] F. Zhang, A.P.C. Chan, A. Darko, Z. Chen, D. Li, Integrated applications of building information modeling and artificial intelligence techniques in the AEC/FM industry, Autom. Constr. 139 (2022) 104289. https://doi.org/10.1016/j.autcon.2022.104289.

[161] Y. Zhao, N. Taib, Cloud-based Building Information Modelling (Cloud-BIM): Systematic literature review and Bibliometric-qualitative Analysis, Autom. Constr. 142 (2022) 104468. https://doi.org/10.1016/j.autcon.2022.104468.

CHAPTER 3 – PLATBRIM: A PARAMETRIC METHODOLOGY FOR QUANTIFYING AND COSTING WORKING PLATFORMS FOR BRIDGE MAINTENANCE [2]

Abstract

Work platforms are essential temporary structural systems used at various stages of a structure's lifecycle. In the bridge's context, it remains indispensable for many bridge maintenance tasks. However, automated, BMS-compatible methods for selecting, quantifying, and budgeting working platforms are scarce. This paper proposes PlatBriM, a parametric methodology that determines the most economic platform type per span, its arrangement, quantities, and estimated cost, using minimal bridge geometry and simple ground-profile inputs. PlatBriM was implemented in Python and evaluated on a case study using 88 bridge records and maintenance plans. Parameters were calibrated via automated optimisation within a ten-fold cross-validation. Results indicate that PlatBriM performs satisfactorily on suspended platforms but substantially underestimates ground-supported platform quantities, with a total predicted cost 42% lower than the reference. These findings show that a minimal input parametric approach is promising for preliminary budget, particularly for suspended platforms, but requires additional contextual data to improve quantification of ground-supported working platforms. Considering its low information requirement and straightforward implementation, PlatBriM offers a practical tool to support and enhance decision-making in bridge maintenance management.

Keywords: Working platforms; bridge maintenance; parametric modelling; quantification; cost estimation; Bridge Management System (BMS); budgeting.

---

[2] Original manuscript submitted to *Structures and Infrastructure Engineering* in September 2025.

1. Introduction

The use of working platforms has been intrinsically connected to the construction industry since its beginnings. Records of workers standing on timber trestle scaffolds were found in ancient Egyptian illustrations dating back to 2100-1700 BC, being the first documented use of a type of elevated working platform (Doughty 1991). In the contemporary world, working platforms remain essential for the workforce to perform several activities in different stages of a structure's lifecycle. It is estimated that around 65% of construction workers are regularly involved in elevated working platform usage (Burkart et al. 2004). Then, since damage or failure of this temporary structural system will probably lead to severe consequences for workers and the public, most research, manuals, and guidelines are focused on its safety (Zhu et al. 2020). In addition to the safety importance, the design, planning, and management of scaffoldings and working platforms also significantly impact project delivery (Kim and Teizer 2014; Yin and Caldas 2022). However, despite its visible importance, the overall project of these temporary structures is considered insufficient (Kim et al. 2016; Kim and Teizer 2014).

Particularly in the operation phase of a bridge, working platforms have been utilized extensively in inspection and maintenance activities. Although several researches are addressing viable alternatives to the traditional inspection method, such as Unmanned Aerial Vehicles (Chan et al. 2015; Chun et al. 2020), elevated working platforms are still necessary to enable workers to access and perform maintenance services in elevated bridge structures.

To reduce time, manual effort, and subjectivity, researchers proposed approaches associated with 3D building models that enable automated design, planning (Kim and Teizer 2014; Løvset et al. 2013), and hazard detection (Kim et al. 2016) of temporary structures. However, there is still a lack of automation of working platform design primarily focused on bridge maintenance.

To address this gap, we propose a parametric methodology that provides an estimated design focused on working platform quantification for bridge maintenance. The proposed methodology input use only essential geometric information from the structure and its surroundings, not depending on a 3D as-built structure model. In this way, the proposed framework can be easily incorporated into even the most basic Bridge Management System (BMS), figuring as a simple but powerful tool to enhance decision-making regarding bridge maintenance management.

2. Background and related work

This study was developed in the Brazilian context and builds on national reference practices for platform quantification in public tendering. In particular, the infrastructure cost system Sistema de Custos Referenciais de Obras (SICRO) differentiates two main types of working platforms used in bridge maintenance: ground-supported and suspended. This distinction imposes specific requirements on any parametric quantification workflow that aims to handle both volumetric and areal computations within a single framework.

Prior research on temporary structures has mainly focused on design and planning automation, BIM integration, and safety (Kim et al. 2015, 2016, 2018; Kim and Teizer 2014; Løvset et al. 2013). Despite these advances, there is limited published work specifically on the parametric design and quantification of working platforms for bridge maintenance. Moreover, many studies concerning the design of temporary structures rely on detailed 3D models, which limits their applicability in contexts that require integration with conventional BMS.

The PlatBriM method proposed in this paper addresses that gap by providing a compact set of parametric equations to estimate platform quantities for each span from minimal inputs, implementing decision rules that select the economically preferred platform type given site constraints, and enabling total-cost estimation using configurable parameters. To the authors' knowledge, an integrated, BMS-compatible parametric framework for the quantification of bridge maintenance working platforms has not been previously published.

3. Research design

The objective of this study is to propose and evaluate a parametric methodology that, using principally basic bridge geometric characteristics and simple ground-profile measurements, determines working-platform configurations and estimates associated quantities and costs for bridge and viaduct maintenance on an economic basis. The primary research question is: Can the proposed parametric framework reproduce the decisions of cost estimators and provide quantity and cost estimates with sufficient fidelity to support maintenance budgeting under realistic data availability? To achieve this objective and answer the research question, this work is designed as illustrated in Figure 1.

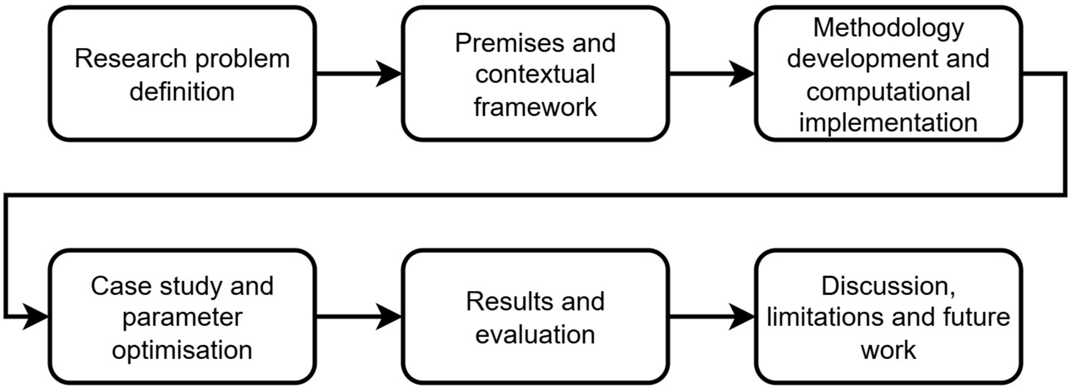


Figure 1. Research design and validation strategy of the proposed methodology.

The study was motivated by a specific demand from the Brazilian federal agency responsible for managing national infrastructure, the Departamento Nacional de Infraestrutura de Transportes (DNIT). The primary need was for a simple, software-independent methodology to quantify and budget working platforms for bridge and viaduct maintenance, suitable both for standardisation and for use in tendering processes. Our literature review indicated no existing method that met these requirements, thereby defining the research gap addressed by this work.

Following the problem identification, we analysed the budgeting practices in the local context and examined relevant references to define the quantification and budgeting premises that underpin the method. This contextual framework summarises the input data usually available in DNIT's BMS, the relevant measurement units, and the simplifications considered necessary to ensure broad applicability across different contexts and BMS implementations.

From these premises, we formulated PlatBriM, a parametric methodology for bridge maintenance platforms. The method computes span-level platform layouts, aggregates quantities and costs, and embeds decision rules to choose between ground-supported and suspended solutions. The calculations are expressed in terms of configurable parameters enabling the adaption of the approach to differing conditions. The methodology is designed to be implemented without the need for detailed 3D as-built models and is therefore suitable even for simple BMS databases.

The methodology was implemented in Python to enable systematic testing, visual inspection of platform configurations, and evaluation of parameter settings. Validation was carried out through a case study using data and maintenance plans provided by DNIT. In the case study, parameters were optimised against the dataset, and the method's capacity to reproduce reference quantities predicted originally by experienced budgeters was assessed.

Finally, results were evaluated and discussed to assess the method’s applicability, to identify limitations arising from both the approach and the dataset, and to outline directions for future work. A detailed account of each research step is presented in the subsequent sections.

4. Methodology framework

4.1. Assumption and premises

To simplify the input data and the decision-making process it was assumed that only one type of working platform – ground-supported or suspended – would be employed in a single bridge span. Therefore, it was necessary to establish criteria to choose the most suitable type for each span.

The primary criterion was the span's ground condition evaluation. Since the presence of roads, water flows, and other obstacles prevents the usage of ground-supported working platforms independently of the remaining parameters, this criterion should be the first step of the evaluation process. Furthermore, it is necessary to consider an input feature to represent the presence of obstacles in the span. After the evaluation of the physical conditions of the span ground, the following criterion will be the cost. The working platform type for each span will be determined by the one that led to the minimal cost between the available options.

It was also assumed that the working platforms could be reused in different spans, with the maximum quantity dictated by the greater quantity. An additional possibility is the simultaneous use of working platforms in different spans, leading the total quantity to be, by simplification, the sum of the larger individual quantities simultaneously used.

The ground-supported working platform volume is calculated by multiplying the bridge width by the platform length and height. The bridge’ width is assumed constant along its extent. The platform height varies according to the ground elevation within the span and the working distance between the top of the platform and the bottom of the bridge deck.

The platform length can be calculated based on the bridge geometry or based on a predefined limit. If the ground-supported platform covers the entire span, it will be calculated based on the bridge geometry, with its total length being the distance between the centers of the columns or the free span in the case of abutment existence. Otherwise, considering the possibility of the platform reuse, disassembling, and assembling it according to the progress of the maintenance services carried out in a single span, a predefined length limit could be stipulated to limit the span covering and significantly influencing the platforms' total cost in cases of long spans. Although the quantity of ground-supported platform is expressed in volume, it would be impractical to use this unit of measurement as a limit, due to the variable nature of the height and the difficulty of visualizing its magnitude.

The area of the suspended working platforms can be simplified and calculated by multiplying the bridge width by its length. The platform length will be based on the characteristics of the spans in which they will be assembled. The suspended working platforms are generally assembled around the columns and extend to both centers of the adjacent spans. However, some particularities can occur based on the span characteristics. If the suspended platform starts from the abutment, it will extend to the only possible side, in the direction of the center of the span. Similarly, in columns that separate spans with different types of working platform usage, the platform will extend only to the side of the span that will use suspended platforms.

In long spans, the length of the suspended working platforms adjacent to the columns or the abutments could be limited by the platform's structural and functional limitations or cost. If that is the case, one or more intermediary suspended working platforms should be assembled between the ones adjacent to columns or abutments, preventing the length of an individual platform from being overly large. Short spans can be covered by a single platform if the extension is under the platform's structural and functional limitations. Moreover, suspended platforms can extend for two or more spans, being connected and treated as a single platform.

4.2. Input data and parameters

4.2.1. Input data

Based on the collected assumptions and premises, a set of minimal input features was defined. These features were divided into common features, constant across all spans, and span features, used in the platform-type evaluation for each span.

The common features comprise the structure width (y in the equations) and the platform working height (h in the equations). The span features included span length, ground elevation, and presence of obstacles. Ground elevation was simplified to three levels, indicating initial, central, and final heights. Obstacle presence is expressed as a Boolean indicator, according to the chosen implementation.

To organize these data, a bridge feature matrix was proposed, as represented in Table 1. An illustrative representation of these features the bridge span geometry is presented in Figure 2.

Table 1. Bridge feature matrix.

		Features				
		Initial elevation (m)	Central elevation (m)	Final elevation (m)	Span length (m)	Obstacle presence (bin)
Spans	Span 1	z_{11}	z_{12}	z_{13}	x_1	0 or 1
	Span 2	z_{21}	z_{22}	z_{23}	x_2	0 or 1
	...	$z_{...1}$	$z_{...2}$	$z_{...3}$	$x_{...}$	0 or 1
	Span *n*	z_{n1}	z_{n2}	z_{n3}	x_n	0 or 1

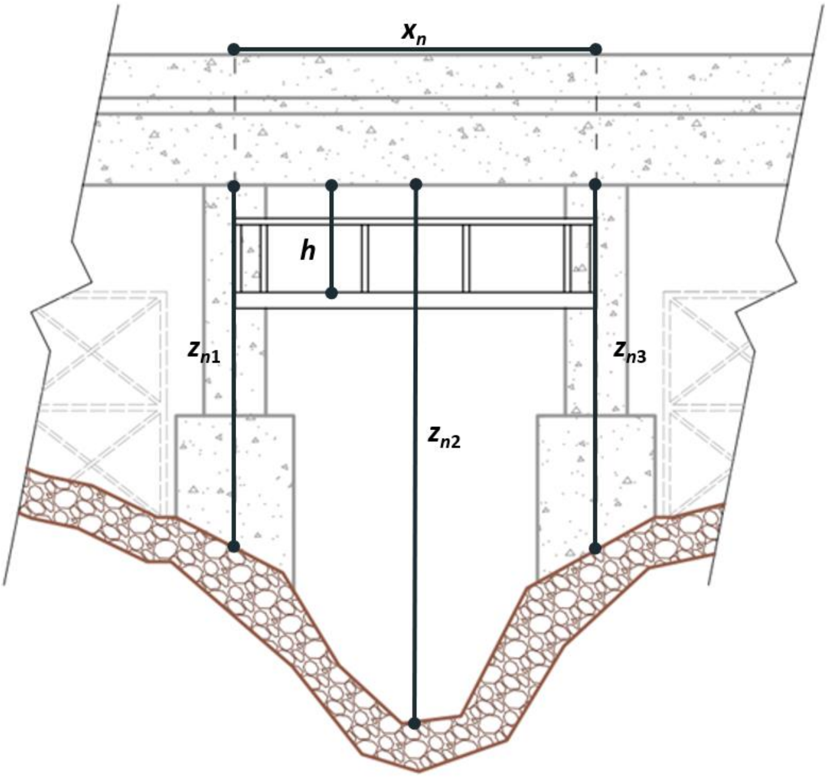


Figure 2. Span input data.

In addition to these geometrical features, the evaluation of the working platform type requires the unit cost of each platform, with ground-supported platforms priced per cubic meter, and suspended platforms priced per square meter.

4.2.2. Ground-supported platforms parameters

In accordance with the previous establishment of a limit for the ground-supported platform's length and the possibility of reuse, the variable L_{GSMax} is defined. For spans greater than L_{GSMax}, the platform will partially cover its extension, and the remaining will be gradually covered by disassembling and reassembling the temporary structure.

Additionally, simultaneous ground-supported platforms could be assembled in different spans depending on the total number of spans. To address this premise the following thresholds are created: N_{GSMin}, the minimal number of ground-supported platforms employed on a singular bridge beyond which a simultaneous platform use will be considered, and N_{GCIn}, the number of platforms that, for each increment above N_{GSMin}, indicates the necessity of an additional platform to be simultaneously used.

4.2.3. Suspended platforms parameters

For reference purposes, the suspended working platforms can be subdivided into two subtypes: attached-suspended or intermediate-suspended platforms. Attached-suspended platforms are those that, as the name implies, are attached to columns or abutments, while intermediate-suspended platforms are assembled between the first, without attachment to one of those vertical structural elements. Additionally, the calculation process was simplified by differing the maximum length of a suspended platform in "maximum length from the attached structure" (column or abutment) and "total maximum length". While the "maximum length from the attached structure" will be relevant to calculating the platform extension within the span, the "total maximum length" will evaluate the merger of adjacent suspended platforms from different spans.

Firstly, the parameter for the minimal length of the suspended platforms, L_{SMin}, was defined. In cases where the span length is less than L_{SMin}, a single suspended platform could cover the total extent and eventually continue to adjacent spans, depending on its maximum length limit.

For attached-suspended platforms, which start from the center of the vertical structural element of the bridge, a length limit within the span, L_{SMax}, could be defined. This way, in a single span, the maximum distance that can be covered by two suspended platforms attached to the vertical structure without the need for intermediate-suspended platforms is equal to double L_{SMax}. For spans larger than 2 L_{SMax}, intermediate suspended platforms need to be assembled, and the total length of the span will be equally divided between the employed platforms, up to their respective limits.

The total maximum length limit, LT_{SMax}, encompasses cases where suspended platforms from multiple spans are connected and merged. The multi-span connection is anticipated in bridges with sequential small spans with lengths inferior to L_{SMin}. In those cases, a single suspended platform can cover multiple spans until it reaches the LT_{SMax} length.

Intermediate-suspended platforms also have a maximum length limit defined by L_{ISMax}. As already stated, their length will be equal to the attached-suspended platforms existent in the span until one of them reaches its limit. The number of intermediate-suspended platforms will be as much as necessary, as they can be calculated by dividing the total span length minus 2 L_{SMax} by L_{ISMax}. In the case of intermediate-suspended platforms, a minimum length limit variable is not necessary since its quantity is calculated based on its maximum extension, and the minimum length will be greater than 2/3 L_{SMax}.

5. PlatBriM: a parametric methodology for bridge maintenance platforms

5.1. Individual span cost evaluation

In the PlatBriM methodology, the premise assumes only one type of working platform in a span. Therefore, the evaluation must compare the two alternatives - ground-supported and suspended - and adopt the most adequate to the assessed span in terms of physical restrictions or economic value. The decision process for the determination of the platform type for each span is illustrated in Figure 3:

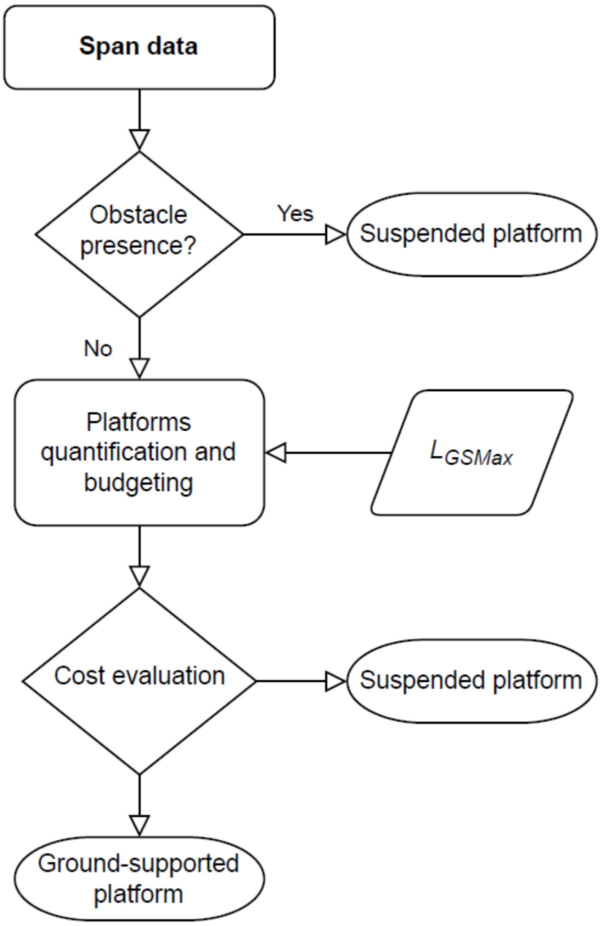


Figure 3. Process for determination of the platform type employed in a span.

In this evaluation, the “obstacle presence” parameter is mandatory when choosing the platform type. An existing obstacle, such as a river or a road, implies employing suspended platforms. However, if an alternative such as temporary road closure or detours is feasible, the obstacle could be ignored, and the financial aspect of the platform types be directly evaluated.

In the absence of obstacles or restrictions, the cost of the platforms is calculated. The cost is calculated by multiplying the quantity of each platform type by the corresponding unitary price. The calculation of the quantities differs for each type of platform, given the differences in the units of measurement and the particularities of each one.

The approach to determine the ground-supported platform quantity in a span depends on the relation between the maximum length of the platform, L_{GSMax}, and the total length of the span. If the assessed span length is less than or equal to L_{GSMax}, the platform will cover the entire span in just one assembly. Therefore, in this case, the volume of the ground-supported platforms is given by the proposed Eq. (1):

$$Ground\ supported\ platftorm\ volume\ (m^3) = \frac{yx}{4} \cdot (z_{n1} + 2z_{n2} + z_{n3} - 4h) \quad (1)$$

where, as illustrated in Figure 2, y is the width of the bridge or viaduct structure (or of the platform, if it extends beyond the width of the structure), x is the length of the assessed section, which for the current study is the length of the span between the axis of the columns, z_{n1}, z_{n2}, and z_{n3} are the ground elevations at the start, middle, and end points of the span, starting from the underside of the bridge deck and h is the working height, the distance between the top of the supported platforms and the underside of the bridge deck.

For span lengths greater than L_{GSMax}, the ground-supported platform extension will partially cover the span in each assembly. It was considered that using the mean value of the span ground elevations when calculating the total quantity would be an acceptable approximation. Thus, the volume of the ground-supported platform in this case is given by Eq. (2):

$$Ground\ supported\ platftorm\ volume\ (m^3) = L_{GSMax} \cdot y \cdot (z_{Med} - h) \qquad (2)$$

where z_{Med} is z_{n1}, z_{n2}, and z_{n3} mean value.

For suspended platforms, the area is given by Eq. (3):

$$Suspended\ platform\ area\ (m^2) = y \cdot x \qquad (3)$$

After calculating the required quantities, the most economically viable solution is determined. It's essential to emphasize that, according to the assumptions made, the solution is the most viable only in the section evaluated. Since the evaluated section comprises the entire span, the platform should be employed throughout the entirety of the section. However, the proposed methodology can also be adapted and applied to smaller span sections.

5.2. Determination of ground supported platform cost

In spans with ground-supported working platforms, the cost is computed by multiplying the unitary price by the total volume, provided either by Eq. (1) to spans less than or equal to L_{GSMax} as represented in Figure 5, or Eq. (2) to spans greater than L_{GSMax} as represented in Figure 6.

The determination of the maximum extension of the platform within the evaluated span is illustrated in Figure 4:

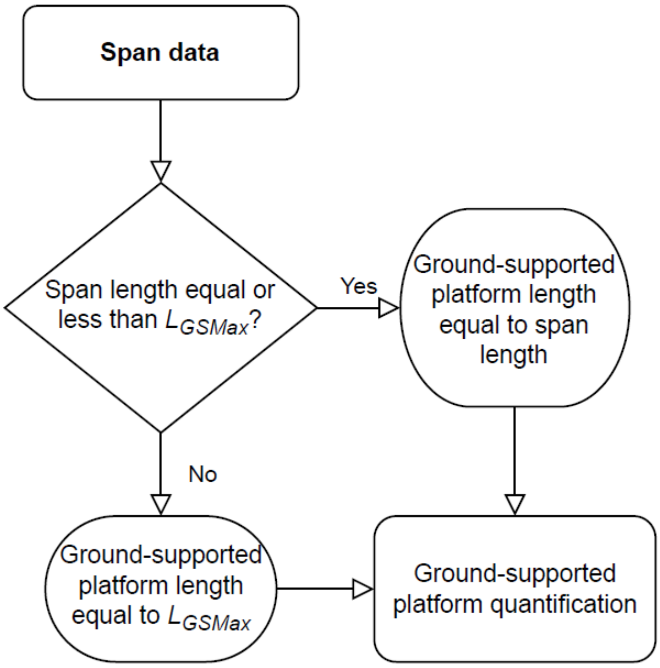


Figure 4. Maximum ground-supported platform length within the evaluated span.

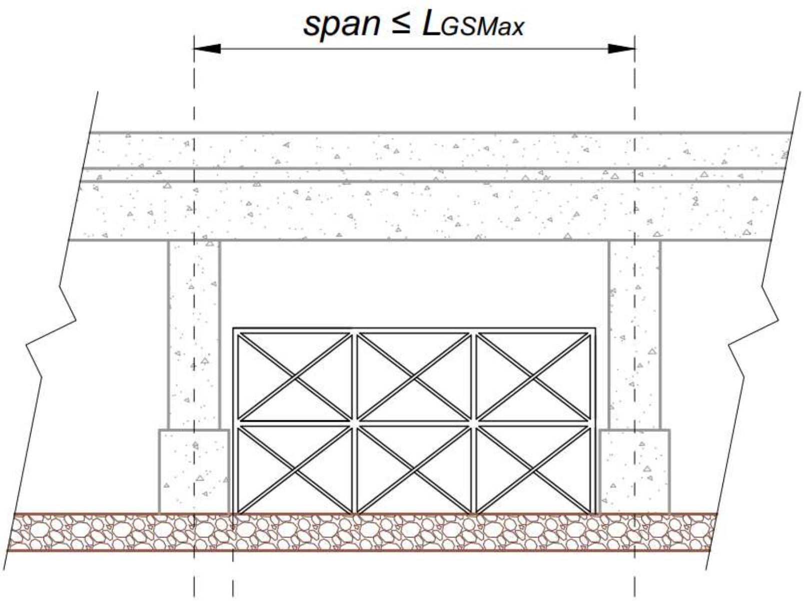


Figure 5. Ground-supported platform configuration to span length less or equal to L_{GSMax}.

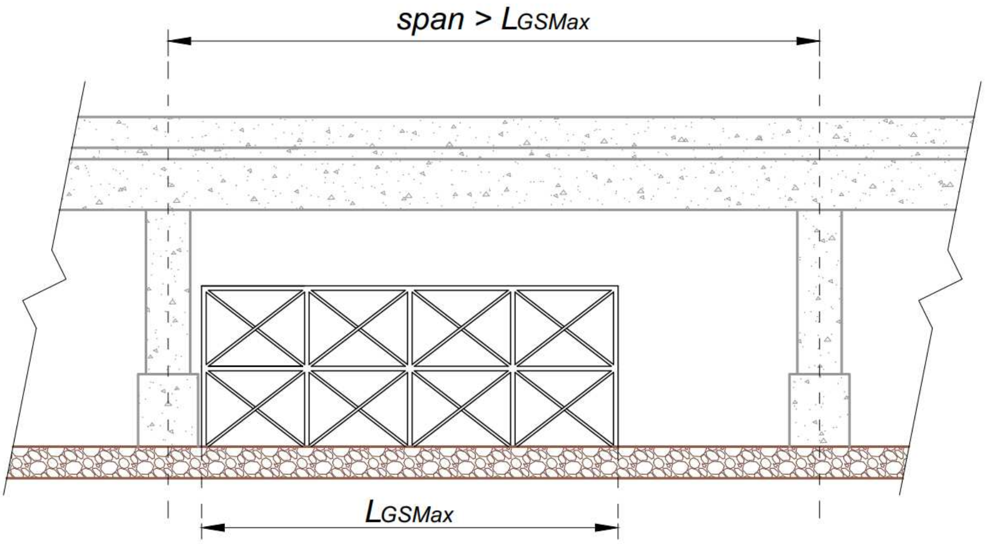


Figure 6. Ground-supported platform configuration to span length greater than L_{GSMax}.

After establishing the individual costs for each span, the overall cost of the bridge's ground-supported platforms is determined according to the parameters N_{GSMin} and N_{GCIn} and the evaluation of the number of spans in a bridge that will simultaneously use these platforms.

If the number of spans covered by the ground-supported platform is less than N_{GSMin}, then only one platform will be assembled at the time. However, if the number of spans covered by this platform type is equal to or greater than N_{GSMin} and less than $N_{GSMin} + N_{GCIn}$, two platforms will be simultaneously used. An additional simultaneous platform is added to each increment of N_{GCIn}, starting from N_{GSMin}, in the total number of ground-supported platforms employed simultaneously.

Once the number of supported platforms simultaneously employed on the bridge has been determined, the total quantity is calculated. If there is no simultaneous use of supported platforms, the maximum total quantity equals the highest individual quantity found. In cases with simultaneous ground-supported platforms utilization, the maximum total quantity is assumed to be the summation of the n highest individual quantities, with n corresponding to the number of concurrent platforms employed.

5.3. Determination of suspended platform cost

5.3.1. General considerations

Contrary to ground-supported platforms, the individual cost from suspended platforms may consider platform segments' grouping from different spans as a single instance. To evaluate the multiple-span platform grouping, it is necessary to determine whether the suspended platforms will be mounted in isolated spans or adjacent to others with the same type of platform since this determines whether or not the platform will continue in two or more spans, as illustrated in Figure 7. Although the design process for isolated or adjacent suspended platforms is analogous, some particularities must be considered in each scenario.

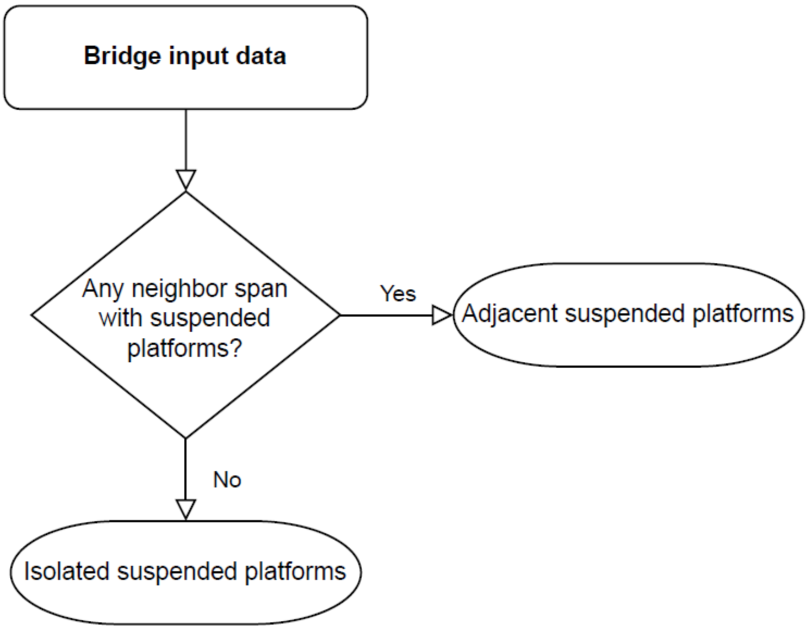


Figure 7. Distinction between isolated or adjacent suspended platforms.

5.3.2. Suspended platforms in isolated spans

For spans that use suspended platforms and are isolated from the others, the platform's continuity beyond the pillars is disregarded. Therefore, there are three possible configurations of suspended platforms for this type of span: a single platform covering the entire span, two platforms adjacent to the columns extending to the center of the span, or two platforms adjacent to the columns with intermediate suspended platforms between them. The parameters L_{SMax} and L_{ISMax} will determine the appropriate configuration according to the process illustrated in Figure 8:

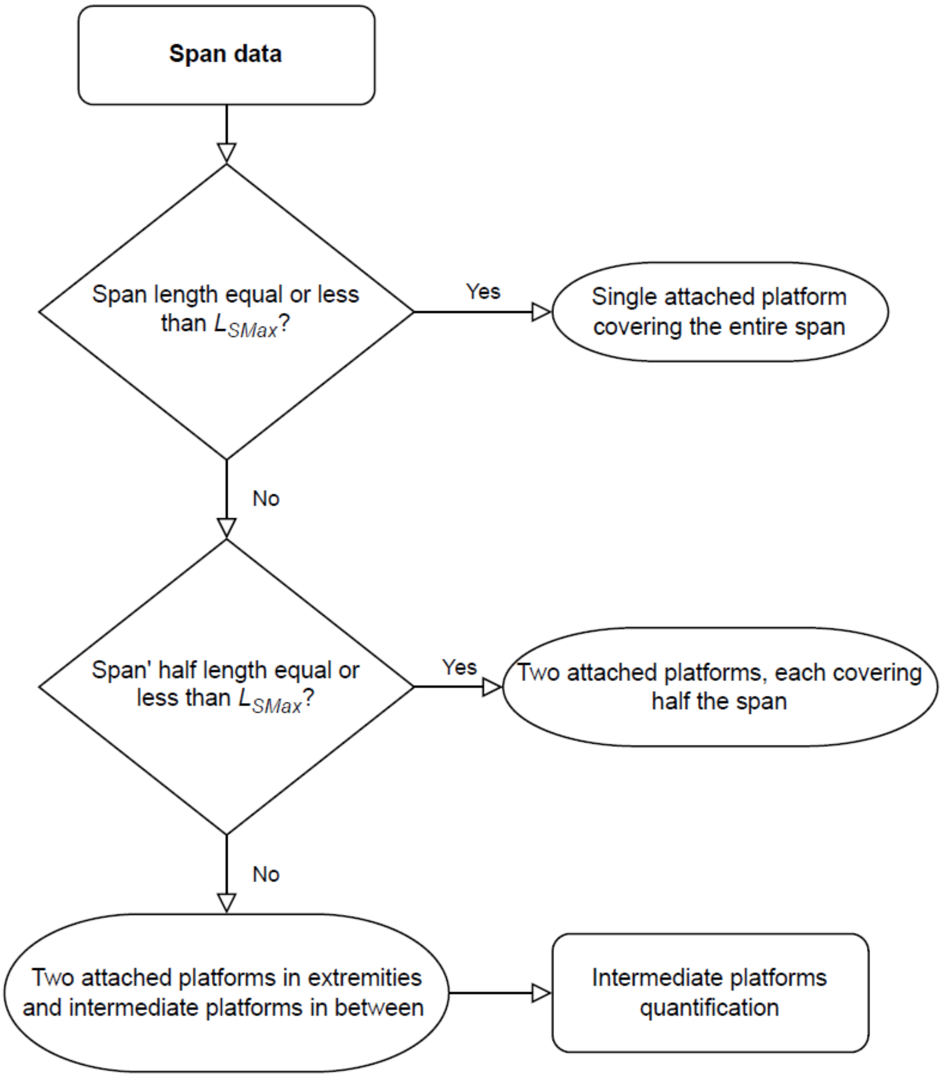


Figure 8. Determination of isolated spans platform configuration.

If the total length of the span is equal to or less than L_{SMax}, the maximum length limit of the suspended platform within one span, it is understood that a single continuous platform can cover the entire span length. Therefore, the length of the platform will be equal to the total length of the span, as illustrated in Figure 9.

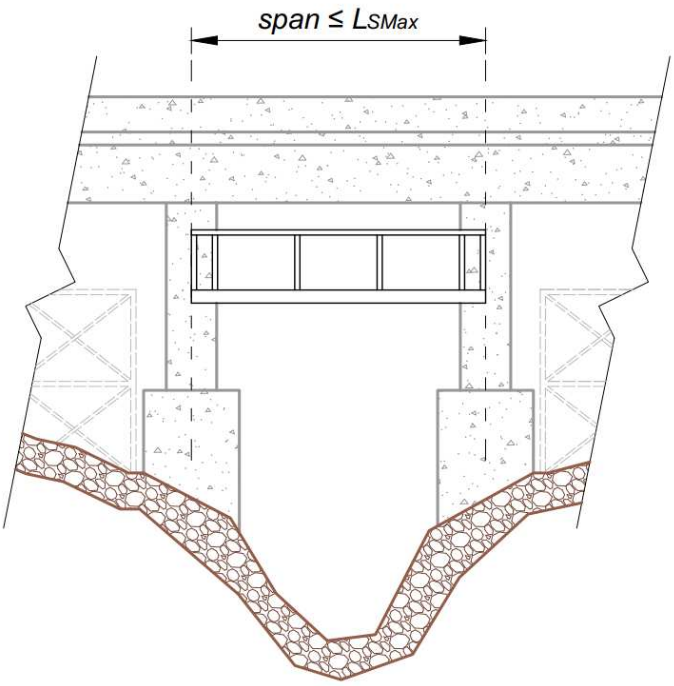


Figure 9. Suspended platform configuration for isolated spans with length less or equal to L_{SMax}.

If half of the total span length is less or equal to L_{SMax}, two suspended platforms adjacent to the pillars will be used, extending to the center of the span. In this case, the platform's length will be half the length of the span, as represented in Figure 10.

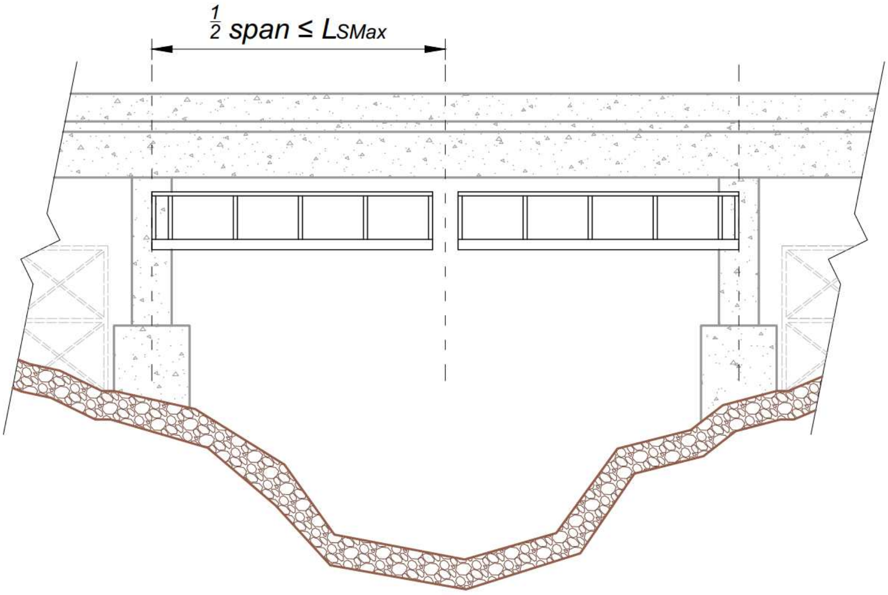


Figure 10. Suspended platform configuration for isolated spans with length less or equal to L_{SMax}.

When half the total span length exceeds L_{SMax}, it is necessary to include intermediate-suspended platforms to cover the entire span. The length of the attached-suspended platforms adjacent to the columns and the intermediate-suspended platforms will be the total length of the span divided by the number of platforms, as exemplified in Figure 11. If L_{SMax} and L_{ISMax} values are different, either attached or intermediate suspended platforms can first reach their length limit, maintaining a limit-fixed length, with the remaining gap divided between the type of platform that has not reached its limit yet. If both attached and intermediate-suspended platforms reach their limits, an additional intermediate-suspended platform must be used. The number of intermediate suspended platforms is calculated by Eq. (4), rounded up to the nearest integer.

$$Float\ number\ of intermediate\ platforms\ (un) = \left(\frac{span\ length}{2 \cdot L_{SMax}}\right) \qquad (4)$$

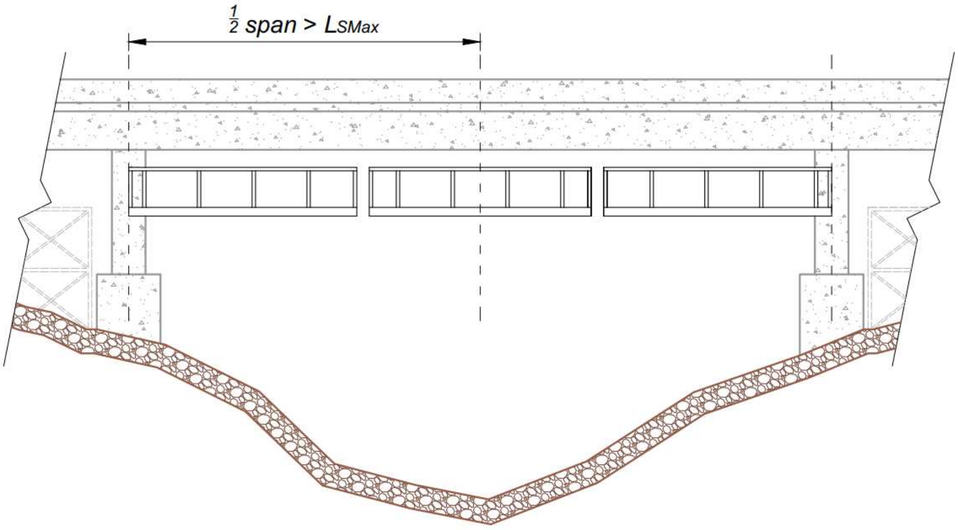


Figure 11. Suspended platform configuration for isolated spans with length greater than L_{SMax}.

5.3.3. *Suspended platforms in adjacent spans*

In cases where spans using suspended platforms are adjacent to other spans that also require suspended platforms, the possibility of the platform continuation in more than one span must be considered in conformity with the length limits established for it. Neighbor spans with suspended platforms form a continuous group where several platform configurations can exist, including:

- Isolated platforms: positioned at the ends of the group, starting from the pillars or abutments that delimit the group, towards the center of their respective spans;
- Continuous platforms between two spans: positioned around the pillars from the group's center and extending themselves towards the center of the two neighbor spans;

- Continuous platforms between more than two spans: similar to the above, but also covering entire short spans between their extremities;
- Intermediate platforms: positioned between the platforms adjacent to the pillars.

In addition to the parameters used to calculate suspended platforms in isolated spans, LT_{SMax} will also be used to determine the most suitable configuration.

To simplify the methodology application, it is recommended that the platforms initially be evaluated using the same methodology applied for suspended platforms from isolated spans, as represented in Figure 12. After determining the configuration of the platforms individually for each span, the interaction of the platforms between adjacent spans should be evaluated, establishing their continuity.

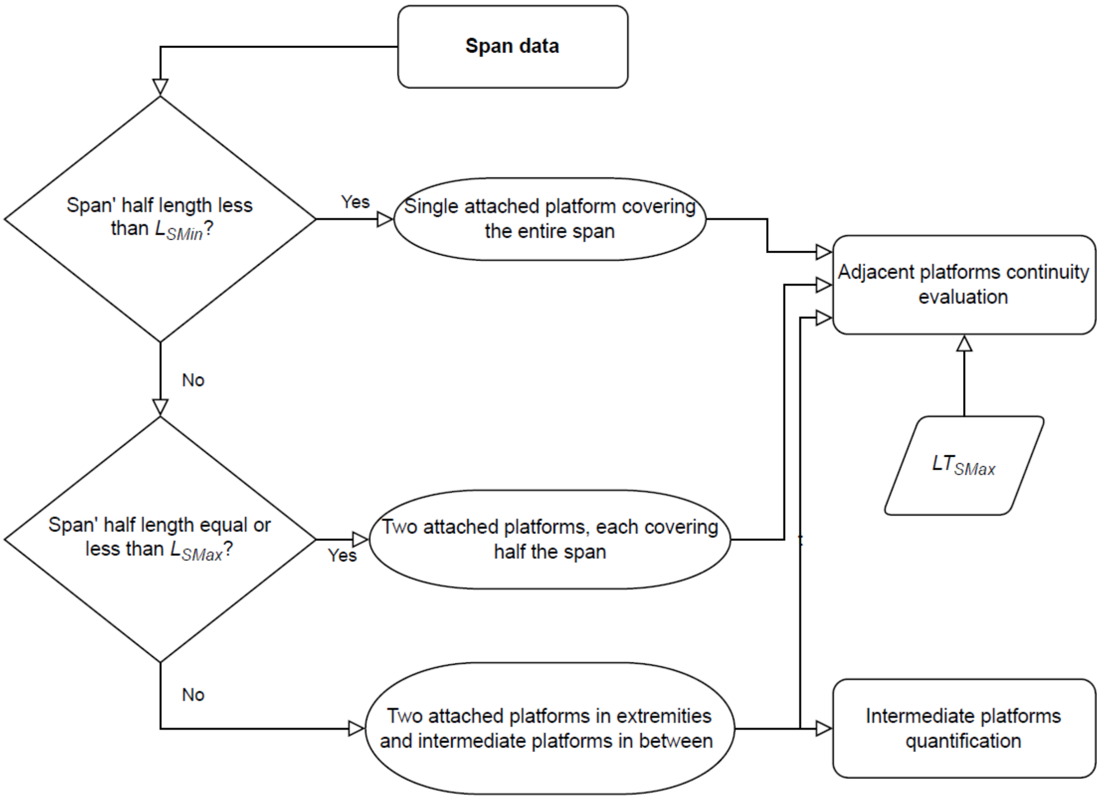


Figure 12. Adjacent suspended platform span's evaluation.

For spans in the group of adjacent spans that will use suspended platforms, if half their length is less than or equal to the minimum suspended platform length, L_{SMin}, the suspended platform must be considered to be continuous throughout the entire span and will be attached to the suspended platforms of the adjacent spans, on both or just one of the two sides, depending on the surrounding conditions. An example of this scenario is represented in Figure 13. However, for parameterization and computer implementation of the process, a limit on the total length of the suspended platform, LT_{SMax}, should be used to avoid the possibility that, in the case of bridges with several adjacent spans with a length less than or equal to L_{SMin}, these platforms be infinitely attached to their neighbors. In scenarios where the merged platforms would have a total extension greater than LT_{SMax}, an additional assessment is required to divide the continuous platform into smaller segments with lengths less than or equal to LT_{SMax}, keeping these segments with compatible lengths in order of magnitude, as represented in Figure 14.

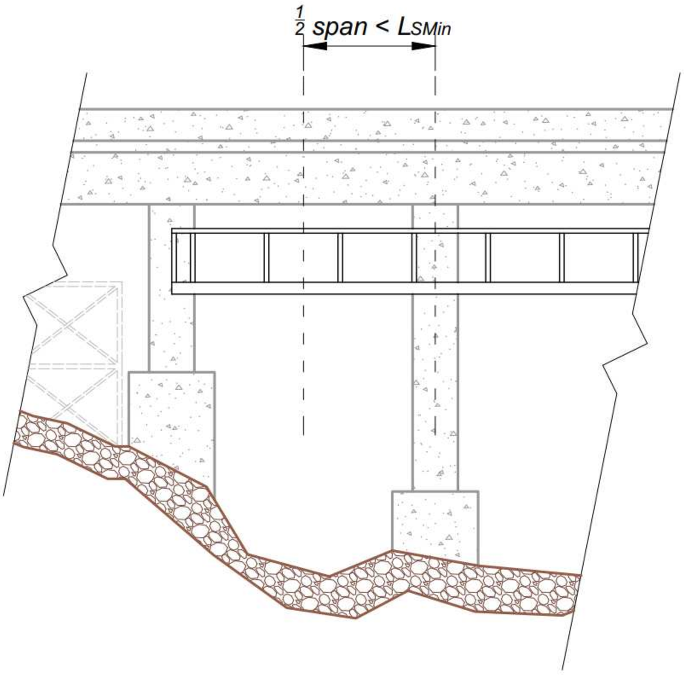


Figure 13. Suspended platform configuration for adjacent spans with length less or equal to L_{SMin}.

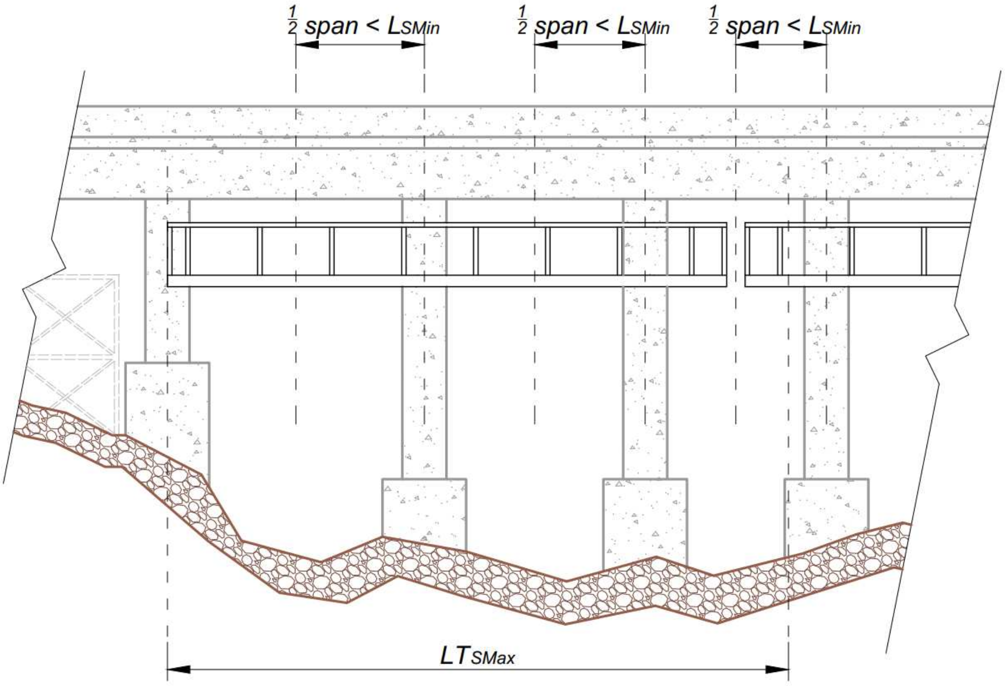


Figure 14. Configuration for suspended platforms covering more than one adjacent spans with length less or equal to L_{SMin}, limited by the suspended platform total length, LT_{SMax}.

If half of the total span length is greater than L_{SMin} and less than or equal to L_{SMax}, two suspended platforms will be used adjacent to the columns, extending to the center of the span. The partial length of the platforms, calculated individually for each span, will be equivalent to half the span. However, for quantification and budgeting, it is vital to determine the total length, which will depend on whether or not there is continuity of the evaluated suspended platform, depending on the surrounding conditions. If the adjacent spans have also suspended platforms planned to be used, they will be merged into a single platform that extends for two or more spans. A possible occurrence of this configuration is illustrated in Figure 15.

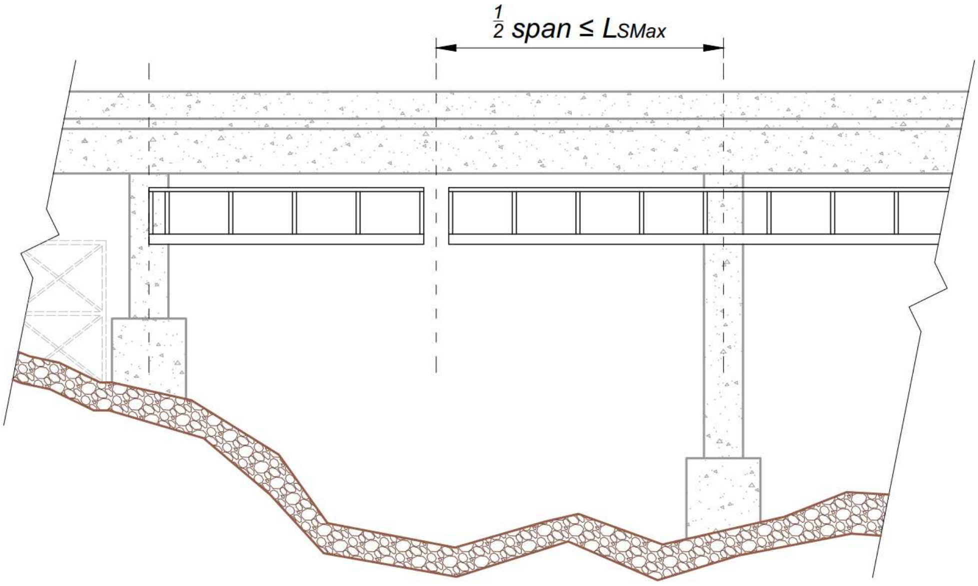


Figure 15. Suspended platform configuration for adjacent spans with half-length greater than L_{SMin} and less or equal to L_{SMax}.

For spans whose half of the total length exceeds L_{SMax}, intermediate platforms should be added to cover the entire span, following the criteria established in 5.3.2. The only difference from the suspended platforms in isolated spans is that the attached suspended platforms will be merged with the neighbor attached platform, with a total length equal to the summation of individual segments from this merge, as exemplified in Figure 16.

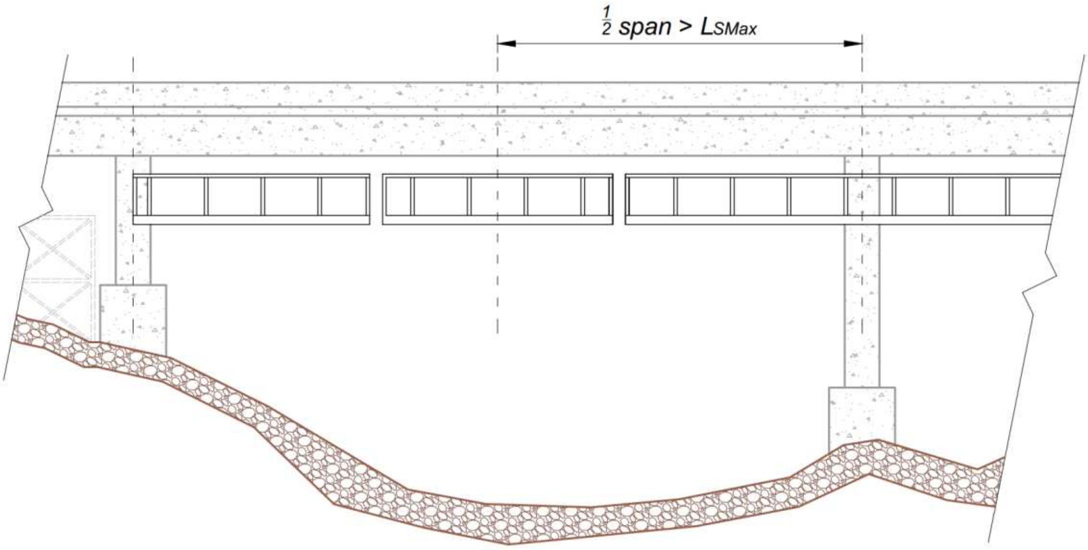


Figure 16. Suspended platform configuration for adjacent spans with half-length greater than L_{SMax}.

Once the platforms have been individually dimensioned for each span, it is necessary to assess their continuity to determine the total suspended platform lengths. The two possible cases for considering continuity are:

- From merges between two platforms adjacent to the center columns of two consecutive spans that cover it partially;
- From merges between platforms covering the entire span, as defined by the L_{SMin} limit, with the adjacent.

In both cases, the total length of the resulting merged platform results from the sum of the individual platforms' lengths that compose it.

5.3.4. Total cost of suspended platforms

The maximum cost of suspended platforms is determined following the same criteria used for supported platforms but using their parameters, N_{SMin} and N_{SIn}. After designing the structure of suspended platforms across the bridge, the cost of each occurrence will be the multiplication of the unitary cost by their area, given by Eq. (3). Considering the reuse of the platform structure, the total cost will be equivalent to the maximum quantity simultaneously being used. The concurrent utilization configurations evaluated are:

- A single suspended platform in bridges with fewer total suspended platforms than N_{SMin};
- Two concurrent platforms when the number of employed suspended platforms reaches or exceeds N_{SMin};
- An additional simultaneous platform for each subsequent N_{SIn} increment in the total number of suspended platforms employed in the bridge.

From the final configuration, the maximum total quantity is calculated by the sum of the n largest individual quantities, with n corresponding to the number of simultaneous suspended platforms employed.

6. Methodology implementation and case study

6.1. Computational implementation

To evaluate its practical application in a case study, the methodology was implemented using the Python programming language. The implementation focused on defining bridge and platform classes, whose attributes and methods enabled the application of the proposed methodology. However, the implementation also comprised visualization functions to facilitate tests and analysis of the results and an optimization process to adjust the parameters in the case study.

In the definition of the Python classes, the Bridge class was created to represent each bridge instance, to evaluate the input data and quantify the working platforms according to the methods defined, and to store all its information. The methods were defined according to the methodology, determining the platform type in each span, calculating and instantiating the platform configuration in each span individually, evaluating the continuity of platforms across spans, and, based on its final configuration and in the reutilization parameters, determining the final quantity and cost of working platforms for the bridge instance.

To support the evaluations on the Bridge class methods, platform classes were created. From the base Platform class, subclasses to all possible platform configurations were derived, each with its corresponding parameters and quantification methods. In the Bridge methods evaluation, the calculated platforms were instantiated and stored in the Bridge class parameters. With this approach, the bridge instances had an array containing each platform instance employed.

The visualization module, developed to evaluate the results, was based on the Matplotlib library, commonly used to generate visualizations in Python. The bridge feature matrix was employed to create the bridge representation and the ground elevation profile, as seen in Figure 17. A red dashed line was also included near the ground profile to symbolize spans with obstacles, where the employment of suspended working platforms was mandatory.

Using the instances from the bridge's final platform configuration, their simplified representation was created. Ground-supported platforms were represented by green lines near the ground profile and differed by covering the span partially or integrally. Suspended platforms, represented by blue lines near the bridge slab, differed between one-side attached, two-side attached, continuously attached, or intermediate. In the example from Figure 17, the designed platforms were a left-side attached suspended, a continuous attached suspended, an intermediate suspended, a right attached suspended, and an integral ground-supported.

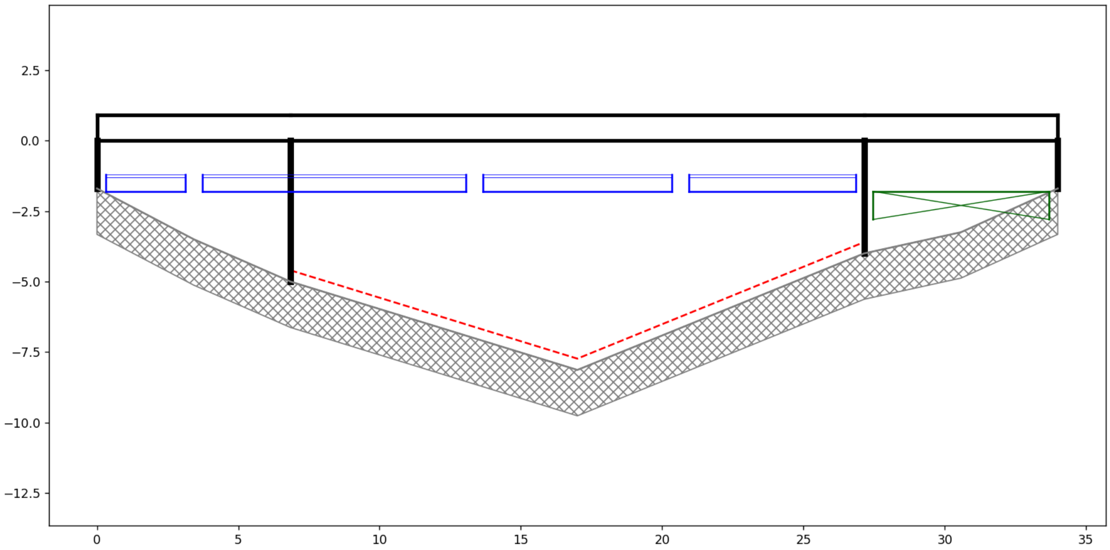


Figure 17. Example of representation of the platform configuration generated by the visualization module.

The optimization module, used to adjust and optimize the methodology parameters to the case study data, was based on the Optuna library. Optuna is an open-source hyperparameter optimization framework designed to automate and accelerate optimization studies. Besides its performance advantages when compared to alternatives for this study, Optuna allowed the definition of parameter dependencies dynamically, ensuring that the search space was restricted only to valid values. This was particularly useful to define limitations such as $L_{SMin} \leq L_{SMax} \leq LT_{SMax}$.

The optimization was based on the minimization of an objective function. In this case, the objective function expressed the mean absolute error between predicted and reference platform quantities from ground-supported and suspended platforms. To ensure that the error scale was compatible between the two different platform types, the predicted and reference quantities were normalized to values between 0 and 1. The search space used in the optimization trials was defined by intervals, delimited by minimum and maximum values. The search intervals, although kept broad to ensure a wide search range, were limited by feasible values according to typical limitations. The parameter value type, integer or floating point, was also defined.

The parameter optimization was structured along with cross-validation to improve the representativeness of the results metrics since the dataset had a limited number of samples. Therefore, for each cross-validation fold, the data were normalized and divided into train and test datasets, the parameters were optimized with the train data, and the quantities were predicted. With this approach, each fold would have its set of optimized parameters and individual metrics to mitigate the influence of the limited dataset division into the results.

The sampler used in the optimization configuration was the Tree-structured Parzen Estimator, considering 500 startup trials. The sampler seed was not fixed to evaluate the variations between each execution and explore if the objective functions have well-defined global minimums. In each cross-validation optimization, 1000 different trials or parameter combinations were performed. The cross-validation, based on the K-Fold cross-validator from the scikit-learn library, was configured to use 10 folds.

6.2. Case study

6.2.1. Data acquisition

The data used in the case study was ceded by the Departamento Nacional de Infraestrutura de Transportes (DNIT), the Brazilian federal department responsible for transportation infrastructure management. The data related to the geometrical characteristics of the bridge and the ground elevation profile was manually measured and retrieved from 2D design drawings stored in DWG files. The reference values of quantities and unitary costs from working platforms were retrieved from maintenance work plans. The reference quantities and costs of ground-supported and suspended platforms, manually calculated by specialists, were retrieved from maintenance work plans. The final dataset retrieved consisted of 88 entries, structured as shown in Table 2:

Table 2. Example of entries from the dataset used in the case study.

Entry	**Bridge width**	**Bridge feature matrix**	**GS unitary cost (R$)**	**S unitary cost (R$)**	**GS quantity (m^3)**	**S quantity (m^2)**
1	10.0	[[5.7, 5.7, 5.7, 7.8, True]]	32.92	57.35	204.75	0.00
2	9.9	[[2.39, 3.55, 4.48, 6.0, False], [4.48, 6.55, 5.21, 24.0, True], [5.21, 4.02, 2.44, 6.0, False]]	28.15	40.99	157.41	238.65
3	9.8	[[2.67, 5.33, 8.59, 6.75, False], [8.59, 12.95, 6.09, 32.0, True], [6.09, 5.54, 2.75, 6.75, False]]	27.57	42.93	71.40	125.40
4	13.0	[[2.97, 8.10, 12.0, 43.75, False], [12.0, 12.0, 12.0, 44.85, True], [12.0, 12.0, 12.0, 72.25, True], [12.0, 12.0, 12.0, 75.25, True], [12.0, 12.0, 12.0, 99.75, True], [12.0, 12.0, 12.0, 140.0, True], [12.0, 12.0, 12.0, 119.9, True], [12.0, 12.0, 2.6, 75.3, True]]	28.87	40.90	170.00	500.00
5	8.3	[[2.2, 2.2, 2.2, 13.8, True]]	31.35	56.12	38.40	0.00
...	...	...	...	...	...	...

6.2.2. Parameter optimization

Using the implementation described, an optimization of the methodology parameters was performed. Considering the limited amount of samples in the dataset, using a single division of train and test datasets could result in heavily biased optimization results, which justified the employment of 10-fold cross-validation. The parameter values for each fold optimization and their median, to minimize outlier parameter values, are represented in Table 3.

Table 3. Optimized parameter values obtained in each cross-validation step, along with their median.

Fold nº	L_{GSMax}	N_{GSMin}	N_{GCIn}	L_{SMin}	L_{SMax}	LT_{SMax}	N_{SMin}	N_{SIn}	L_{ISMax}
0	11.862	3	4	3.085	10.375	19.759	8	9	11.628
1	15.438	2	4	0.770	16.579	26.235	9	8	32.866
2	12.275	2	3	1.791	13.626	27.314	7	10	36.685
3	11.731	9	4	2.519	16.231	27.066	7	8	17.329
4	10.952	2	1	0.883	3.811	7.042	6	6	14.909
5	16.597	1	2	0.869	11.742	26.014	8	9	47.799
6	14.159	7	3	7.060	7.945	16.918	5	8	25.136
7	11.744	10	1	2.270	3.651	4.905	8	10	18.095
8	12.031	6	8	6.314	9.825	24.531	7	10	43.207
9	16.977	9	4	2.357	3.120	3.502	9	10	18.274
Median	12.153	4.5	3.5	2.314	10.100	22.145	7.5	9	21.705

As can be seen, most of the parameters presented a considerable variance in each fold. Nonetheless, this variance is observed even when the optimization process is repeated over the same dataset without a sampler seed. This variance is prevalent in parameters with less importance for the optimization, as can be seen when comparing the optimized parameter values with the Optuna visualization from Figure 18. These observations suggest that, for the analysed data, the objective function has multiple local minimums in the space defined.

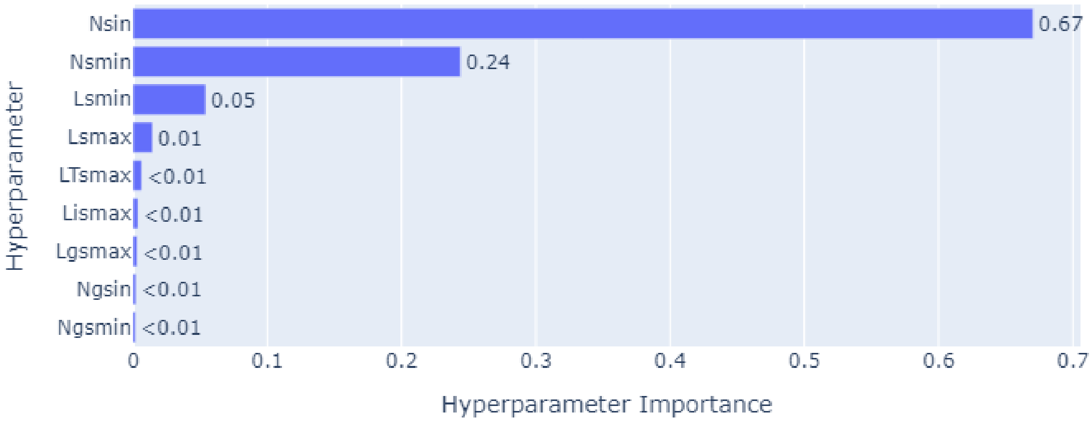


Figure 18. Optimization parameter importance according to the Optuna analysis.

When comparing the ground-supported and suspended platform quantities predicted in each fold with their respective reference values, Figure 19 and Figure 20, respectively, show their distribution. For ground-supported platforms, the distribution resulted in a mean absolute error (MAE) of 229.90 m³ and an R² score of -0.086. For suspended platforms, the MAE was 106.25 m², while the R² score was -0.104.

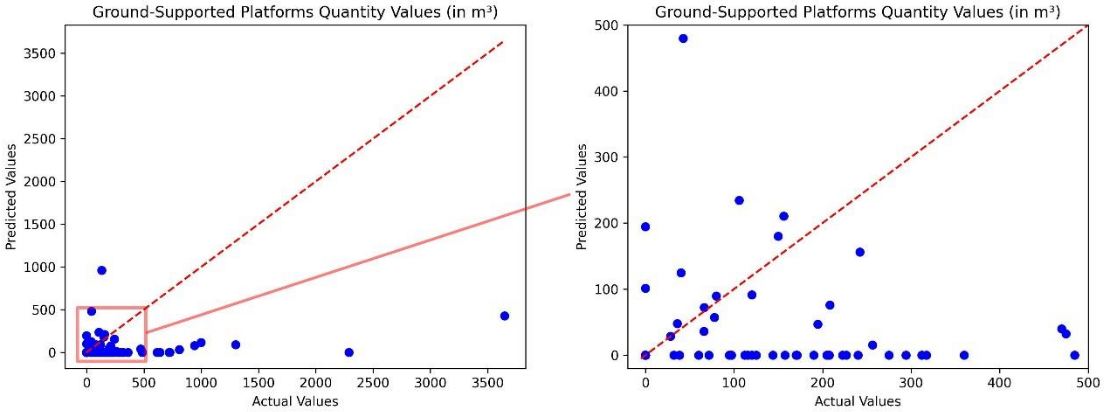


Figure 19. Comparison between predicted and actual quantity values of ground-supported platforms, in a complete and a scaled view.

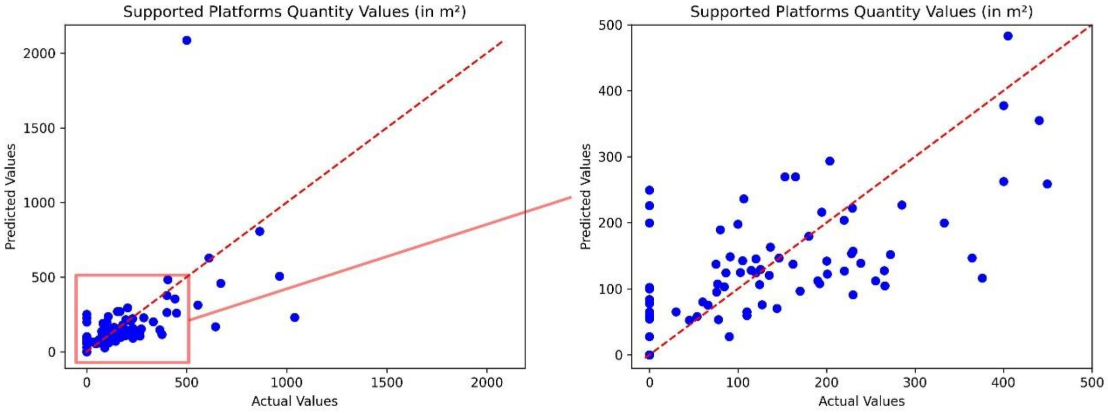


Figure 20. Comparison between predicted and actual quantity values of suspended platforms, in a complete and a scaled view.

In Figure 19, the actual versus predicted values distribution shows that, in many cases, the methodology did not estimate the ground-supported platforms where they were employed. In contrast, although much less prominent than ground-supported platforms, the suspended platforms behave oppositely. The distribution tests in Figure 20 show the predictions of suspended platforms in some cases where they were not employed. These contrasting results exemplify that, for the employed dataset, the methodology was favourable to the suspended platform usage.

To analyse the imbalance between ground-supported and suspended platform quantities predicted, an evaluation of the whole dataset was performed. The values of parameters used in this evaluation were the median of the parameters optimized in the 10-fold cross-validation. Although not ideal, considering the high variance of some parameters, the MAE of the analysis with median values was approximately the same as the values optimized in the folds. This behaviour is due to the low importance of high variance parameters in the objective function of the optimization.

When instantiating all the bridges from the dataset with the median parameters, the total platform quantities and costs found are presented in Table 4. The sum of all predicted quantities for ground-supported platforms was approximately 20% of the reference values, congruent with the distribution tendency observed in Figure 19. The sum of predicted suspended platform quantities, contrary to the slight tendency shown in Figure 20, was also less than the reference values, with a 15.8% difference. These smaller predicted quantities reflected a total cost 42.2% lower than the total cost of reference maintenance work plans.

Table 4. Comparison of total quantities and costs of working platforms from the analysed dataset.

	Total ground-supported platform quantities (m³)	**Total suspended platform quantities (m²)**	**Total platform cost (BRL)**
Reference	20472.085	16881.805	1334447.37
Predicted	4213.538	14216.542	771592.49

7. Discussion

The PlatBriM parametric methodology was developed to automate the quantification and budgeting of working platforms for bridge maintenance using only basic bridge geometry and simplified ground-profile inputs. The case study results reveal a contrast in method performance between suspended and ground-suspended platforms. For suspended platforms, predictions presented an approximately symmetric distribution across expected values, with a total quantity predicted of 14,216.542 m² against the reference total of 16,881.805 m², indicating a shortfall of 15.79%. By contrast, the results of ground-supported platforms were substantially underestimated, which was evidenced by the multiple zero-value predictions in the value distributions. This underestimation resulted in a total quantity of only 4,213.538 m³ compared to the expected 20,472.085 m³, a decrease of almost 80%. Combined, these differences led to a predicted total platform cost 42.18% lower than the reference cost derived from maintenance plans.

Several factors and limitations can be drawn in this study and likely explain the underperformance of ground-supported platforms. First, premises such as the assumption of a single platform type per span, although plausible and observed for most cases, had exceptions across samples and therefore impacted the results. Second, operational and contextual factors that affect the choice or extent of ground-support platforms, such as local availability of labour/equipment, temporary road-closure feasibility, or detailed topography, were not included in the input. Finally, optimization analysis indicated multiple local minima and a discrepant importance across parameters, suggesting a complex interaction of the objective function when applied to the current dataset.

Despite these limitations, PlatBriM demonstrated practical value, performing reasonably for suspended platforms and providing a low-input framework for preliminary budgeting and scenario analysis that can easily be adapted to any BMS. Moreover, the transparency and possibility of configuration allow the user to adjust parameters accordingly, enabling the adaptation to different contexts and the re-evaluation of costs. PlatBriM can serve as a fast evaluation tool to support budgeting and decision-making in bridge maintenance, especially for suspended working platforms, while recognizing its present limitations for ground-supported solutions.

To improve the performance and applicability of the PlatBriM methodology, we recommend the following actions: enlarge the dataset, both in sample size and geographic diversity; incorporate additional input data, such as constraints and labour/equipment limitations; and apply the method in different regions to compare the performance against practitioners' estimates of other contexts.

8. Conclusion

This study introduced PlatBriM, a parametric framework for quantification and budgeting of working platforms in bridge and viaduct maintenance using minimal geometric and ground-profile inputs. Regarding the primary research question, the results show that PlatBriM can reproduce cost-estimator decisions and provide quantity and cost estimates with satisfactory fidelity for suspended platforms under the tested conditions, but its accuracy for ground-supported platforms is still insufficient.

The main contribution of this work is a simple, configurable, and BMS-compatible methodology that supports preliminary budgeting and decision-making, without the need for complex data or as-built 3D models. Future work should prioritise dataset expansion, inclusion of additional input, and parameter refinements to improve the performance gap of ground-supported platforms and move towards operational adoption.

9. References

Burkart, M. J., M. Mccann, and D. M. Paine. 2004. *Elevated Work Platforms and Scaftolding - Job Site Safety Manual*.

Chan, B., H. Guan, J. Jo, and M. Blumenstein. 2015. "Towards UAV-based bridge inspection systems: A review and an application perspective." *Structural Monitoring and Maintenance*, 2 (3): 283–300. Techno Press. https://doi.org/10.12989/smm.2015.2.3.283.

Chun, P. J., J. Dang, S. Hamasaki, R. Yajima, T. Kameda, H. Wada, T. Yamane, S. Izumi, and K. Nagatani. 2020. "Utilization of unmanned aerial vehicle, artificial intelligence, and remote measurement technology for bridge inspections." *Journal of Robotics and Mechatronics*, 32 (6): 1244–1258. Fuji Technology Press. https://doi.org/10.20965/jrm.2020.p1244.

Doughty, R. 1991. *Scaffolding*. (H. Lansdell and W. Lansdell, eds.). Essex: Longman Scientific & Technical.

Kim, J., M. Fischer, J. Kunz, and R. Levitt. 2015. "Semiautomated Scaffolding Planning: Development of the Feature Lexicon for Computer Application." *Journal of Computing in Civil Engineering*, 29 (5). American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(asce)cp.1943-5487.0000399.

Kim, K., Y. Cho, and K. Kim. 2018. "BIM-Driven Automated Decision Support System for Safety Planning of Temporary Structures." *J Constr Eng Manag*, 144 (8). American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(asce)co.1943-7862.0001519.

Kim, K., Y. Cho, and S. Zhang. 2016. "Integrating work sequences and temporary structures into safety planning: Automated scaffolding-related safety hazard identification and prevention in BIM." *Autom Constr*, 70: 128–142. Elsevier B.V. https://doi.org/10.1016/j.autcon.2016.06.012.

Kim, K., and J. Teizer. 2014. "Automatic design and planning of scaffolding systems using building information modeling." *Advanced Engineering Informatics*, 28 (1): 66–80. Elsevier Ltd. https://doi.org/10.1016/j.aei.2013.12.002.

Løvset, T., D. M. Ulvang, T. C. Bekkvik, K. Villanger, and I. Viola. 2013. "Rule-based method for automatic scaffold assembly from 3D building models." *Computers and Graphics (Pergamon)*, 37 (4): 256–268. Elsevier Ltd. https://doi.org/10.1016/j.cag.2013.01.007.

Yin, Z., and C. Caldas. 2022. "Scaffolding in industrial construction projects: current practices, issues, and potential solutions." *International Journal of Construction Management*, 22 (13): 2554–2563. Taylor and Francis Ltd. https://doi.org/10.1080/15623599.2020.1808562.

Zhu, Y., G. Chen, X. Li, Y. Lu, J. Liu, and T. Xu. 2020. "Comfort assessment for rehabilitation scaffold in road-railway bridge subjected to train-bridge-scaffold coupling vibration." *Eng Struct*, 211. Elsevier Ltd. https://doi.org/10.1016/j.engstruct.2020.110426.

CHAPTER 4 – MACHINE LEARNING FOR QUANTIFICATION AND BUDGETING OF BRIDGE MAINTENANCE SERVICES USING INSPECTION DATA[3]

Abstract

Bridges require continuous assessment of their operating condition to ensure user safety against progressive deterioration. The large amount of inspection data stored in Bridge Management Systems (BMS) must be effectively processed to support reliable maintenance decision-making. This study explores the potential of machine learning (ML) to automate the quantification and budgeting of non-structural bridge maintenance services using inspection records. Data from the federal Brazilian BMS were manually acquired, pre-processed, and used to train and evaluate multiple ML algorithms across different maintenance labels. Results showed satisfactory predictive performance for maintenance services with high occurrence frequency, producing estimates consistent with expectations. However, performance declined for low occurrence frequency services, where correlations between features and labels were inconsistent. These findings highlight both the potential and the current limitations of ML for bridge maintenance management, emphasizing the need for larger, richer datasets and the development of targeted ML approaches to enable reliable operational adoption.

Keywords: Machine learning, bridge maintenance, inspection data, quantification, budgeting, data-driven decision-making, infrastructure management.

---

[3] Original manuscript submitted to *Automation in Construction* in September 2025.

1. Introduction

Bridges are essential structures in the context of land transportation. Through their use, they enable not only the crossing of obstacles but also the design of optimized and safe networks for users, positively impacting the local society. The operability of these structures is guaranteed by periodic inspections, assessing their condition against deterioration resulting from high exposure to environmental and traffic conditions [1]. Based on inspection data, it is possible to plan preventive maintenance interventions to extend the useful life and reduce costs during the operating phase of bridges [2,3].

The information generated during inspections, monitoring, and other processes carried out throughout the life cycle of a bridge needs to be managed efficiently to optimize the use of resources. The management of all this information, as well as the bridge network itself and the involved processes, is performed by Bridge Management Systems (BMS). These systems, generally implemented as software, have integrated functions that help decision-making regarding inspection, maintenance, cost, and capital allocation, among other processes [4–6]. However, using a BMS does not necessarily mean automating all processes or decision-making. In the Brazilian reality discussed in this paper, the choice and quantification of bridge maintenance services is performed by budgeteers, who rely on inspection records to propose the most appropriate solutions for each case.

Considering the richness and density of information found in well-established BMS databases, data-driven approaches are the most suitable alternative for handling, processing, and interpreting this large quantity of multi-source heterogeneous bridge data. The application of artificial intelligence and machine learning in the infrastructure context is gaining popularity, and this new reality is thoroughly explored in the works of Jiang et al. [7] and Yang et al. [8], who present extensive literature reviews of data-driven approaches within BMSs. However, despite the development and application of this type of approach in BMSs, its use is still considered insufficient [7,8].

To explore the capabilities of the application of machine learning models to assist decision-making in the bridge maintenance process, this work gathered bridge and inspection data available in the Brazilian Federal BMS, processed and structured the information acquired, and trained models to predict maintenance service quantities to elaborate bridge maintenance budgets. The overall performance of the models was assessed by comparing predictions and actual quantities for all maintenance services, highlighting critical cases. Based on the results, directions to potentially enhance the results in future work are presented.

2. Method

2.1. Research design

This exploratory study investigates the feasibility of applying machine learning models to automate or assist the quantification of bridge maintenance services using structured inspection data. The primary research question is whether ML models trained on raw, tabular inspection records can predict maintenance services quantities with an accuracy sufficient to support budgeting processes and provide reliable input for decision-making in bridge maintenance management. A secondary objective is to identify limitations of this approach, outlining improvements required for its potential operational adoption.

The scope of the study is restricted to reinforced and prestressed concrete bridges and viaducts. Each sample comprises bridge-related information, including geometrical characteristics, structured inspection data, and the maintenance services quantified. The prediction targets are the quantities of services, with the remaining information used as explanatory variables. The inspection data included only structured tabular information, such as damage type, damaged element, and damage extension. Unstructured data sources, such as photographic records or unstructured text, were excluded.

Given the exploratory nature of the work, emphasis is placed on assessing feasibility and methodological validity rather than on definitive deployment. Accordingly, the research design follows standard ML development procedures while maintaining minimal preprocessing of the input data. This approach aims to reduce introduction of bias and to capture unfiltered insights from the application of ML models to raw inspection datasets.

2.2. Data collection

2.2.1. Data acquisition

The Departamento Nacional de Infraestrutura de Transportes (DNIT), the Brazilian federal department responsible for transportation infrastructure management, provided the data used in this study. The selected bridges were part of maintenance work plans developed two years before the data collection date. These documents included the maintenance services estimated to repair a set of bridges. The services and their quantities, manually estimated by budgeteers based on the damage information registered in field inspections, were used as labels in the analysis. The maintenance work plans selected date from September 2020 to October 2022.

After defining the maintenance work plans, the data of the bridges included were acquired to be used as features in the analysis. The data from each bridge was manually acquired from the interface of the Sistema de Gerenciamento de Obras de Arte Especiais (SGO), the principal system and database for bridge and viaduct management maintained by the DNIT. Based on the bridge identification, the system returned its properties, which were manually copied from the interface and stored in spreadsheets.

When the data acquisition started, the total population of the DNIT database was composed of 6833 bridges and viaducts. However, only part of the bridges and viaducts had been included in recent maintenance work plans and had their data available for this study. The percentage of contribution from each Brazilian geopolitical region to the total population of bridges and viaducts was considered in order to select a representative set of maintenance work plans capable of depicting the national panorama. In the end, 19 maintenance work plans were selected, which were composed of a total of 529 bridges and viaducts.

The acquired data could be categorized into three groups, general structure information, inspection data, and maintenance services data. The general structure information group comprises all data that characterizes the bridge or viaduct, such as its structure type, dimensions, and location, among others. All the features from the general structure information and some examples of the content of the data are represented in Table 1.

Table 1. General bridge information data structure and examples.

Database entry	Structure type	Standard project load	Year of construction	Length	Width	Latitude	Longitude	Altitude
Bridge 1	Reinforced concrete slab	Class 36	1960	59.2	10.1	-5.8746	-38.6076	123.0
Bridge 2	Prestressed concrete box girder	Class 45	1985	45.4	13.0	-7.5452	-39.0166	412.0
Bridge 3	Reinforced concrete beam	Class 36	1960	55.0	10.0	-6.3348	-38.7434	156.0
…	…	…	…	…	…	…	…	…

The inspection data group is composed of data generated by on-site inspections. Typically, each bridge or viaduct is subjected to periodic inspections to monitor its condition, generating damage data. The generated data includes the properties of each damage instance, photographic records, and additional information that is not always structured. In this study, data was collected from the most recent inspection prior to maintenance. Each dataset entry has as features a single value of the structure's condition state and a matrix of the structure damage data. The damage data, represented by an $(n, 3)$ matrix, contains each instance of damage occurrence in the structure, with parameters to identify the damage type, the element where it occurs, and the extent of the damage, as structured and exemplified in Table 2.

Table 2. Inspection data structure and examples.

Database entry	Condition state	Damage data matrix		
		Type of damage	**Damaged element**	**Damage extension**
Bridge 1	3	Efflorescence	Reinforced concrete slab	2.75
		Concrete delamination	Reinforced concrete slab	0.4
		Concrete spalling	Reinforced concrete T-beam or I-beam	0.9
		Concrete delamination	Reinforced concrete slab	1.3
		Efflorescence	Reinforced concrete retaining wall	1.5
Bridge 2	3	Efflorescence	Reinforced concrete slab	0.65
		Crack	Reinforced concrete slab	1.25
Bridge 3	2	Concrete spalling	Reinforced concrete retaining wall	2.2
		Concrete delamination	Reinforced concrete retaining wall	0.73
		Efflorescence	Reinforced concrete slab	0.4
		Concrete delamination	Reinforced concrete column	2.1
		Crack	Reinforced concrete slab	1.87
		Crack	Reinforced concrete column	3.2
...	…	...	...	...

The maintenance services data group was composed of data from the maintenance work plans. The maintenance data, label of this study, was structured as an (*m*, 2) matrix, where the first column represents the identifier of the service, and the second column represents the correspondent service quantity. The maintenance service data of each entry is structured as illustrated in Table 3.

Table 3. Maintenance services data structure and examples.

Database entry	Maintenance services data matrix	
	Service identification	**Service quantity**
Bridge 1	Bridge cleaning	465.8
	Hydrodemolition	1.8
	Dry splayed concrete	2.1
	Suspended working platform	90.5
	Manual application of cement slurry coating	465.8
Bridge 2	Bridge cleaning	273.3
	Crack injection	1.25
	Structural adhesive	0.94
	Suspended working platform	53.5
	Manual application of cement slurry coating	273.3
Bridge 3	Bridge cleaning	930.8
	Hydrodemolition	4.45
	Concrete drilling	1.2
	Rebar CA-50	8.89
	Structural adhesive	3.81
	Crack injection	5.07
	Dry splayed concrete	5.51
	Ground-supported working platform	312.7
	Manual application of cement slurry coating	930.8
...	...	...

Both damage data and maintenance service data matrices have a variable number of rows per bridge to represent multiple damages and maintenance services, but they differ in the uniqueness of each instance they represent. While the damage data matrix can contain multiple instances of the same damage or even the same combination between damage and bridge element, each service within the maintenance services data matrix is unique, with its numerical quantity value representing a summation of all occurrences of that service due to the individual instances of related damages.

A compilation of the all the parameters collected, their data types and a comprehensive description of each is provided in Table 4.

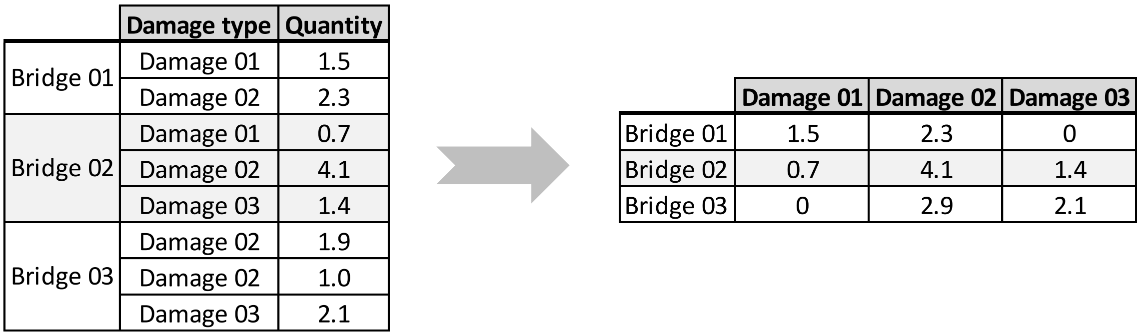
Table 4. Parameters presents in the analysed dataset.

Data group	Parameter		Data type	Description
General structure information	Structure type		Categorical	Represents the structure type based on the primary structural element
	Standard project load		Categorical	Standard load considered in the structure design
	Year of construction		Categorical	Year of completion of the structure's construction, usually approximated
	Length		Numerical	Total length of the structure
	Width		Numerical	Width of the structure
	Latitude		Numerical	Latitude of the structure's location
	Longitude		Numerical	Longitude of the structure's location
Inspection data	Condition state		Categorical	Rating factor that reflects the condition state of the bridge, ranging from 5 (best condition) to 1 (worst condition)
	Damage data	Type of damage	Categorical	Represent the type of non-structural damage
		Damaged element	Categorical	Describes the element that contain the referred damage
		Damage extension	Numerical	Extension of the damage, according to its measurement unit
Maintenance services data	Maintenance services data	Service identification	Categorical	Identification that represents a maintenance service
		Quantity	Numerical	Quantity of the correspondent maintenance service, according to its measurement unit

Correlations between features and labels values were expected, considering the origin of the data. The physical properties of the structures, length, and width are directly related to general maintenance services, such as structure cleaning. The damage information affects more specific maintenance services which repair the non-structural damages, such as crack injection and concrete recomposition. The labels also include some standard services performed in any maintenance intervention unrelated to any specific feature. The remaining input features, a priori, cannot be directly related to the labels.

2.2.2. Feature structuration

Each original dataset entry included a matrix of damage information, which contained the type, damaged element, and extension for each damage instance. This nested matrix was restructured to meet the information input requirements of most machine learning algorithms. Each combination of a damage type and a damaged element originated a single feature whose value reflected the damage extension of that feature on the bridge entry, which was considered zero if the feature was not present. A simplified example of the approach is shown in Figure 1. When applied to the sample data from Table 2, the approach results in the structured data showed in Table 5.



	Damage type	Quantity
Bridge 01	Damage 01	1.5
	Damage 02	2.3
Bridge 02	Damage 01	0.7
	Damage 02	4.1
	Damage 03	1.4
Bridge 03	Damage 02	1.9
	Damage 02	1.0
	Damage 03	2.1

	Damage 01	Damage 02	Damage 03
Bridge 01	1.5	2.3	0
Bridge 02	0.7	4.1	1.4
Bridge 03	0	2.9	2.1

Figure 1. Example of the damage matrix data structuration.

Table 5. Restructuring of the example data from Table 2.

	Damage - damaged element combination									
Database entry	Crack - Reinforced concrete column	Crack - Reinforced concrete slab	Concrete delamination - Reinforced concrete column	Concrete delamination - Reinforced concrete retaining wall	Concrete delamination - Reinforced concrete slab	Concrete spalling - Reinforced concrete retaining wall	Concrete spalling - Reinforced concrete T-beam or I-beam	Efflorescence - Reinforced concrete retaining wall	Efflorescence - Reinforced concrete slab	...
Bridge 1	0	0	0	0	1.7	0	0.9	1.5	2.75	...
Bridge 2	0	1.25	0	0	0	0	0	0	0.65	...
Bridge 3	3.2	1.87	2.1	0.73	0	2.2	0	0	0.4	...
...	...	...	...	...	...	...	...	...	...	...

Considering that the matrix from a singular entry could have multiple instances of the same damage-damaged element combination, the quantities of repeated combinations should be added up before their inclusion in the final dataset. This way, each damage-damaged element feature would represent the total extent of that combination in the entry. The sum of repeated damage-damaged element combinations is exemplified in the “Bridge 1” entry from Table 2, where two instances of the “Concrete delamination” damage occur in the “Reinforced concrete slab” element. The individual extensions of the damage instances, 0.4 and 1.3, were added, and their total value, 1.7, was included in Table 5 in the correspondent “Concrete delamination - Reinforced concrete slab” feature.

With the restructuring, the damage data, earlier represented in a row-variable matrix, becomes a single-row array. This structure allows the damage data to be concatenated with the remaining data and employed in most machine learning algorithms. However, the drawback of this approach is the inclusion of several features as much as combinations of damage-damaged elements exist. In this case, the number of combinations and, consequently, the number of features relative to the damage-damaged element data was 217.

2.3. Data preprocessing

2.3.1. Data cleaning

The maintenance services data required some adjustment. As the data was obtained from documents dated between 2020 and 2022, it was necessary to verify changes in the identification or the content of the maintenance service compositions. One example of change over time was the shotcrete service, which initially had a single cost regardless of the application surface and was later decomposed into three different services according to the orientation of the concrete projection plane. The strings that identified the maintenance service type were also checked for misspellings since any unique string would be considered a different category.

A few maintenance services differed in subtle characteristics in which the feature data would certainly not be sufficient to determine the most suitable option. One example was the presence of different types of ground-supported work platforms, differentiated by the maximum height range of the platforms. Since this differentiation could only be made with specific knowledge of the elevations of the terrain around the bridge and information that is not available in the features, it is not justifiable to maintain this differentiation in the services in the labels. In these cases, the individual services were grouped into a single general service that encompassed all the variations.

Some very recurrent maintenance services were unrelated to the features. Activities such as tree pruning or mowing were determined based on the structure's surroundings and could only be quantified by visual analysis of the photographic documentation. Therefore, services that clearly could not be associated with any feature data were excluded from the labels to avoid a negative influence on the metrics, which could significantly disturb the evaluation and the choice of regression algorithms.

After the data cleaning, 55 unique maintenance services remained in the dataset. Although several maintenance services have low occurrence in the dataset entries, it was decided to maintain it in the construction of the models and focus on the individual analysis of the results, prioritizing the more relevant labels.

2.3.2. Data transformation

While each algorithm has its unique specifications regarding data input, such as encoding, null data handling, normalization, and standardization, the transformation methods used sought to suit a wide array of algorithms. Therefore, the features in the datasets were transformed using the most suitable technique based on their data type.

The features composed of numerical data, identified in Table 4, should be either normalised or standardized. According to Brownlee [9], choosing between normalizing and standardizing continuous numerical data relies on the feature's distribution. Given that most continuous data in the analysed features do not follow a normal distribution, the most appropriate and chosen scaling technique was normalization, within the 0 to 1 range. The normalization is particularly interesting when transforming the damage data, as it would maintain the values equal to zero unaffected, denoting the absence of a particular damage-damaged element combination in an entry.

The categorical features of the dataset were transformed using either the One-Hot Encoding or the Ordinal Encoding method. As already mentioned, the One-Hot Encoding method creates binary columns for each unique category of the original evaluated feature, assigning “1” in the column corresponding to the entry category and “0” for the remaining columns. In contrast, the Ordinal Encoding method maintains its data on a singular column but transforms its values to integers according to their order and scale, which preserves a sense of magnitude between the values. As their description suggests, Ordinal Encoding is suitable in cases where the feature values have any meaningful relationship or ranking, while One-Hot Encoding should be prioritized in features with independent categories.

The categorical feature ‘Structure type’, in which values did not express any ordinal relationship but only categorized the type of the structure, was transformed using the One-Hot Encoding method. The ‘Standard project load’ feature, whose categorical data was related to the load-bearing capacity of the structure, was encoded using the Ordinal Encoding method.

The ‘Year of construction’ feature, although expressed by years in a numerical scale, was divided into categories varying by 5 years. Since time is ordained, the method used was Ordinal Encoding, with “0” corresponding to years until 1954, “1” corresponding to years between 1955 and 1959, until the integer “13” which represents years between 2015 and 2019. The ‘Condition state’ feature, representing the structure condition, is already expressed by ordinal values ranging from 1 to 5, with its scale adjusted to values from 0 to 4 to maintain the scale origin standardized in zero. After all transformation and restructuring, the total number of features in the dataset was 232.

The labels of the dataset, corresponding to each evaluated maintenance service, consisted of continuous numerical data. Although the training and evaluation of the models were conducted independently, with different scales not interfacing with each other, normalization of the labels was applied within the range of 0 to 1. This approach aimed to ensure that the scale of the different labels does not influence the model's performance during training across multiple algorithms.

2.3.3. Null values and outliers handling

An analysis was conducted on the original dataset to determine the presence of null values. As a first analysis, it was decided to ignore and remove entries with null values from the dataset since the imputation by models could add bias to the original information. Considering its low recurrence and low representativeness, entries with constructive systems different from "cast in place" were removed from the dataset.

From the remaining entries, the number and percentage of null values are represented in Table 6. The ‘Standard project load’ and ‘Year of construction’ features, which had the highest missing values percentage, were also highly correlated. The entries frequently had both values missing, requiring their imputation based on lesser correlated features. This aspect of the missing data reinforced the decision to exclude the incomplete entries and avoid the addition of imputation bias in the dataset information. This way, the final dataset was composed of 309 entries without any missing features.

Table 6. Quantity and percentage of null values in features data.

Feature	Standard design load	Year of construction	Condition state
Quantity of null values	107	122	11
Percentage of null values (%)	20.23	23.06	2.08

An analysis to evaluate the presence of outliers in the dataset was conducted. For this analysis, the Local Outlier Factor unsupervised outlier detection was used. The method measures the deviation of the density of a sample from its neighbours, identifying if it is significantly lower and, therefore, an outlier. At first, an analysis of how many entries would remain according to the number of neighbour considered was conducted, and the results are shown in Figure 2.

As illustrated in Figure 2, the number of outliers identified varied significantly within the range of 0 to 15 and 40 to 50 neighbours. Beyond 50 neighbours, the number of remaining samples stabilized at around 230, indicating a well-balanced identification of outliers. Finally, the number of neighbours chosen was 53, resulting in a dataset composed of 232 samples.

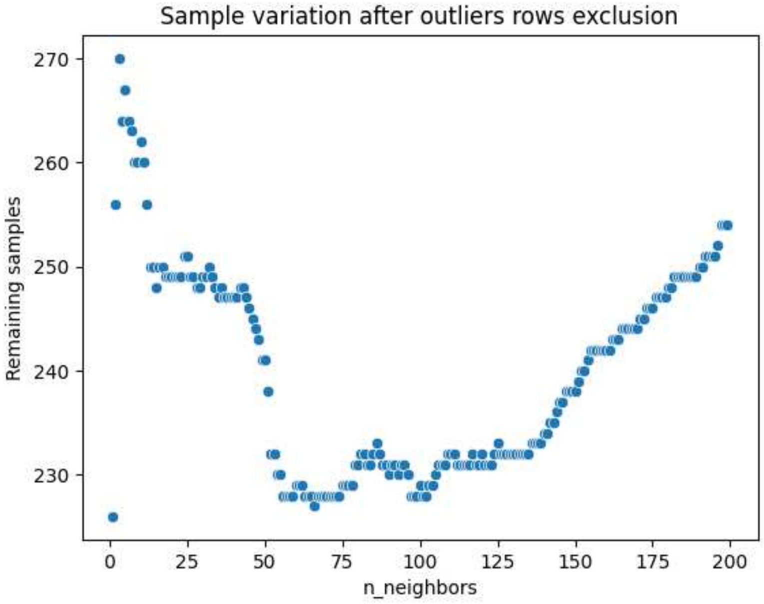


Figure 2. Variation of the number of remaining samples in the dataset according to the number of neighbors considered in the Local Outlier Factor method.

2.4. *Model selection and tuning*

2.4.1. Modeling strategy

In the analysed dataset, after structuring the data, the output of each sample is given by a set of independent labels. It is, therefore, possible to treat the outputs individually, creating a single model for each label, or to treat all label values as a single vector, in which a single model predicts all the values in the vector. However, since the goal is to analyse the characteristics associated with each maintenance service individually, it was decided to create unique models for each label.

Each label, representing the quantities of maintenance services, was composed of continuous numerical data. Since the aim was to predict these quantities, the problem was treated as a regression case. Therefore, for each maintenance service, an individual regression model will be evaluated, employing its best-performing algorithm. It is expected that, if the regression model is good enough, the predicted quantities will be zero or very close to zero in cases where the maintenance service is not employed.

2.4.2. Model evaluation

In the models' evaluation stages, it is necessary to divide the data into distinct groups based on their use in the process, such as training and test datasets. For a single partition of the samples to be representative in expressing the model's generalization error, obtained by comparing predicted labels with true labels not used during training, the total sample size must be sufficiently large [10] since both the sample size and the ratio between training and test sets influence the overall performance of the models [11].

For small datasets, a single, fixed division of the data can generate models that are not very generalized and highly dependent on the samples present in each set. In such cases, an alternative is to employ cross-validation methods, in which the dataset is partitioned several times and the same sample can be used more than once at different stages of the model training and validation process, potentially improving the statistical reliability of the results [12].

Among the various cross-validation methods available, we opted to use the K-fold cross-validation method, which stands out both for its popularity [13] and its speed compared to other methods [12]. In the K-fold cross-validation method, the sample is divided into K different partitions of equal size, and the model is validated for each partition (fold), while the remaining K-1 folds serve as training data. At the end of the process, metrics are obtained for each of the K validations, providing an overview of the performance of the models based on the available data.

According to the literature, varying the value of K, which reflects the number of splits made in the sample, inversely impacts the bias and variance of the results, although exceptions can occur depending on the dataset size [14]. While Jung [15] suggests that the value of K should be approximately $log(n)$, where n is the total number of the sample, other studies use pre-fixed values, typically equal to 2, 5, 10, 20 or directly linked to the total value of the sample, up to a maximum value of $K = n$ [13,16,17]. Considering the size of the sample used, the usual values, and the considerations about the trade-off between bias and variance raised by Raschka [14], it was decided to use $K = 10$. In addition, following the recommendations by Rodríguez [17] and Raschka [14], two cross-validations will be carried out with different random data divisions to increase the reliability of the metrics.

The selection of regression algorithms for evaluation was based on including representatives from different algorithm families, covering a wide range of learning approaches, and using the default hyperparameters. The chosen regressor algorithms were Linear, Poisson, KNeighbors, Support Vector, Random Forest and Multi-layer Perceptron.

Considering the objective of treating each label individually, the algorithm evaluation followed the same principle. With this approach, each label would be predicted based on its better-performing algorithm for its available data. The metric used for the algorithm evaluation was the mean squared error (MSE).

The percentage of labels for which each algorithm performed better is represented in Figure 3. Although the Poisson algorithm performed better in most labels, the Random Forest Regressor had the overall better performance across the labels corresponding to the services with the highest percentage occurrence in the dataset. RFR outperformed the remaining algorithms in 9 of the 11 most recurrent maintenance service labels.

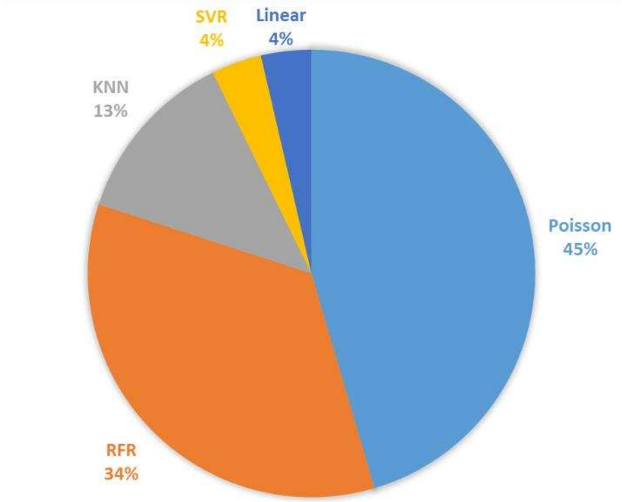


Figure 3. Percentage of the best performing algorithm across the 55 evaluated labels.

2.4.3. Hyperparameter tuning

To explore the capabilities of the chosen algorithms and improve the results obtained, a hyperparameter tuning stage was conducted. The Optuna library was employed to automate hyperparameter search and optimize the algorithm's performance based on the existing data. Considering that each maintenance service has its specific model, based on the better-performing algorithm, the optimization sought to reduce the MSE obtained in the cross-validation by varying the hyperparameters within the specified ranges.

The evaluated hyperparameters and the value ranges considered in the analysis of the five algorithm types employed in the models are shown in Table 7. From the Optuna optimization, the 55 labels had their best-performing hyperparameter combination determined.

Table 7. Hyperparameters and values evaluated on the individual model optmization.

Algorithm	Hyperparameter	Range or values
Linear	Fit intercept	true, false
	Copy x	true, false
Poisson	Alpha	1e-5 to 1e-1
	Maximal iterations	100 to 500
	Tolerance	1e-4 to 1e-2
KNN	Number of neighbors	1 to 30
	Weights function	uniform, distance
	Algorithm	auto, ball_tree, kd_tree, brute
	Leaf size (for BallTree or KDTree)	10 to 50
	Metric	euclidean, manhattan, chebyshev
SVR	C	1e-3 to 1e3
	Epsilon	0.01 to 0.1
	Kernel type	linear, poly, rbf, sigmoid
	Gamma	scale, auto
	Degree (for poly kernel)	2 to 5
RFR	Maximum depth	1 to 20
	Minimum samples to split	2 to 16
	Minimum samples to be at a leaf	1 to 16
	Number of estimators	10 to 100

3. Results

With algorithm and hyperparameters determined for each label series, individual model performance was evaluated by comparing the reference maintenance services quantities with predicted quantities. However, considering the limited number of samples in the dataset, it was expected that a single train/test dataset split could lead to biased models, demanding an alternative approach.

To obtain representative metrics in the final models, 10-fold cross-validation was employed in the training and evaluation of each label. Therefore, for each maintenance service, 10 individual models were trained in distinct partitions of the dataset, and each generated predictions based on the test partitions. With this approach, the number of predictions was equal to the number of samples in the dataset.

For each model, corresponding to a maintenance service, the reference and predicted quantities were plotted on a distribution graph. A linear regression between reference and predicted was also plotted using the *regplot* function from the *seaborn* library. In the *regplot* function, the *robust* parameter was set to True, as it creates a robust regression that de-weight outliers. A dashed red line was added to represent the line where $y = x$ in the graph, facilitating the interpretation of the results.

Based on these settings, Figures 4-8 show the distribution of reference and predicted quantities for the maintenance services evaluated, ordered according to their occurrence frequency. The graph titles express the order, name, and frequency at which each maintenance service appears in the dataset entries. The plotted values were kept normalized to facilitate the visualization of the magnitude.

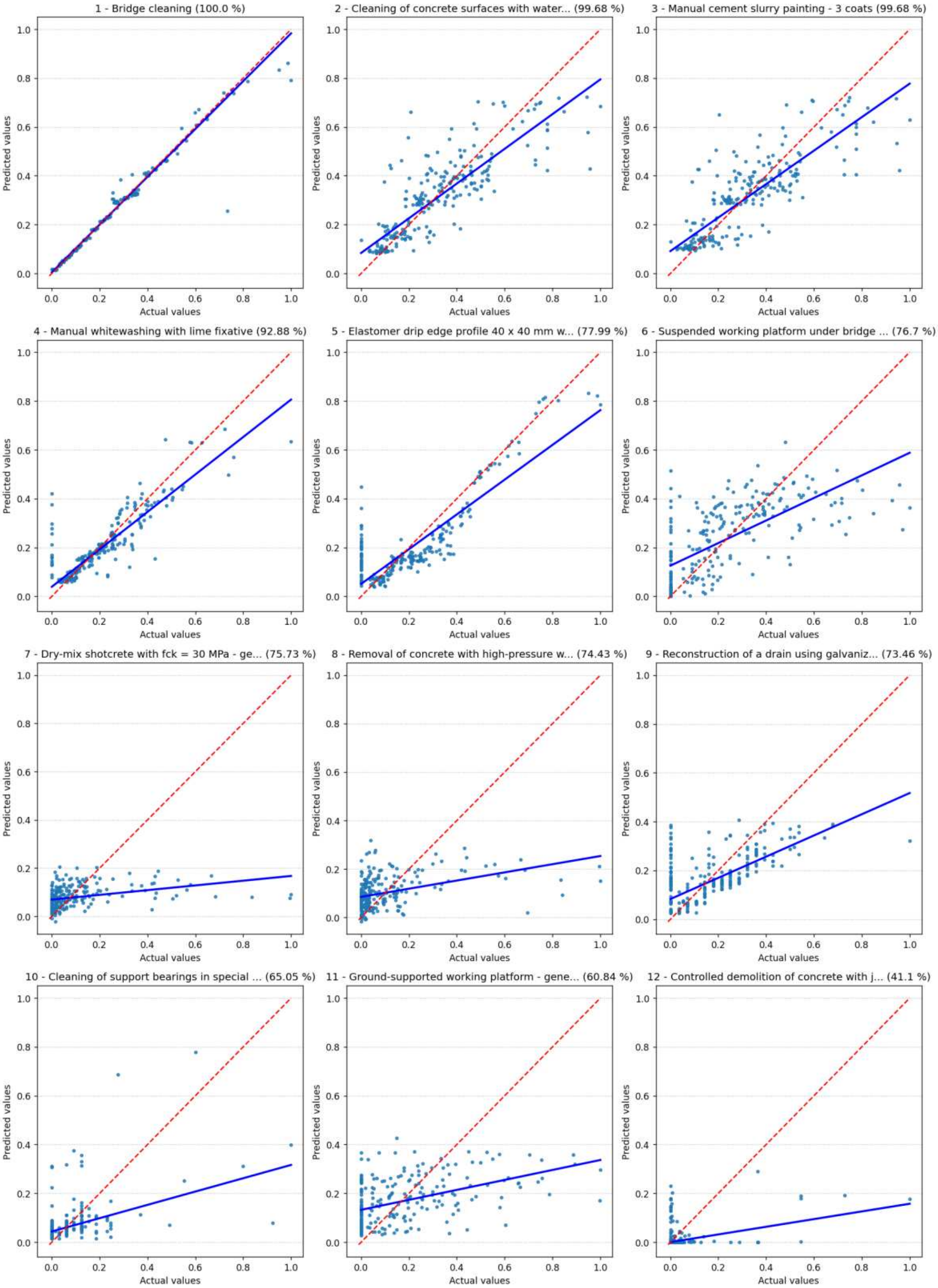
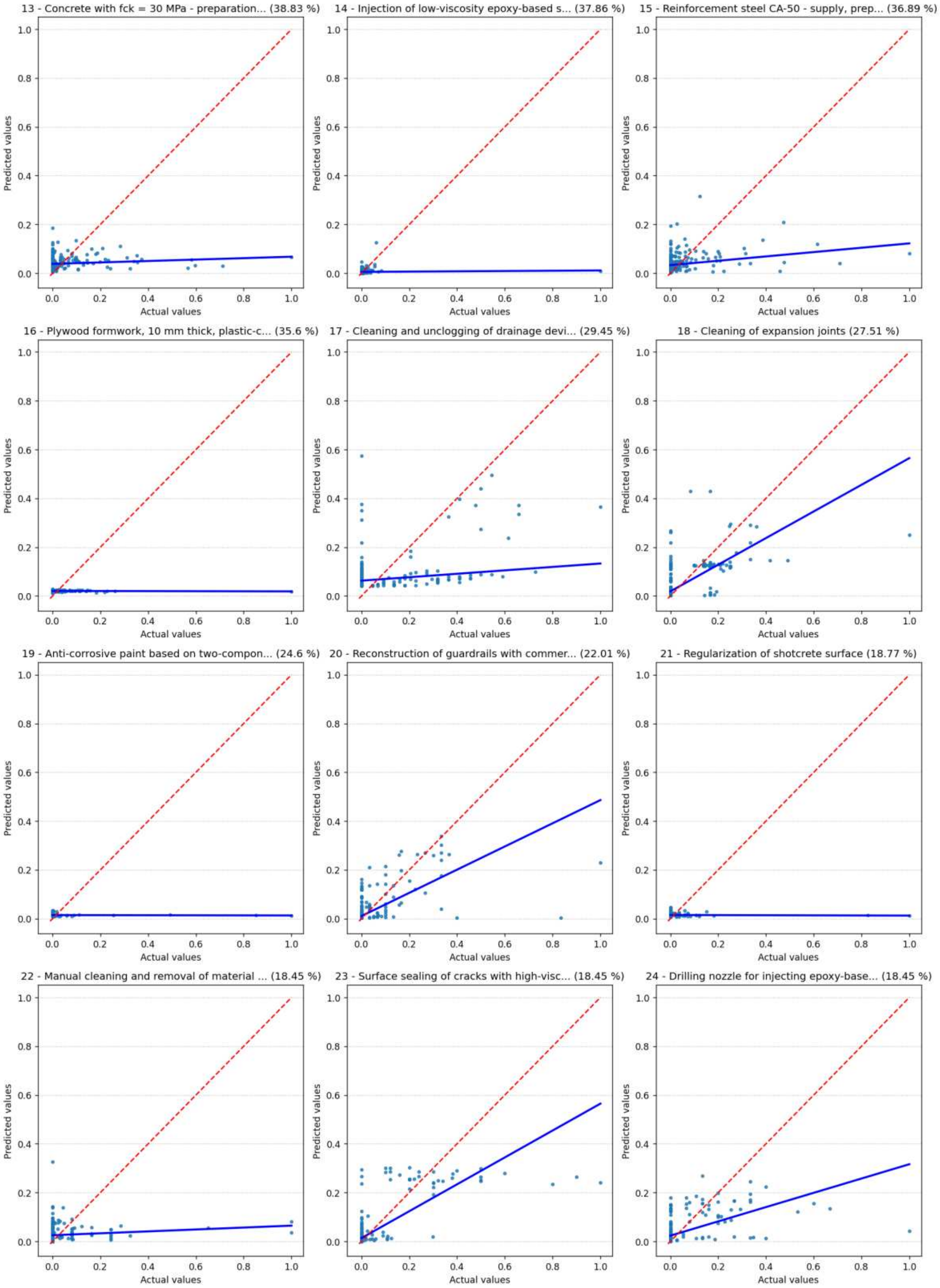


Figure 4. Distribution of reference versus predicted values of individual models, from the 1st to 12th most frequent maintenance services.



13 - Concrete with fck = 30 MPa - preparation... (38.83 %)

14 - Injection of low-viscosity epoxy-based s... (37.86 %)

15 - Reinforcement steel CA-50 - supply, prep... (36.89 %)

16 - Plywood formwork, 10 mm thick, plastic-c... (35.6 %)

17 - Cleaning and unclogging of drainage devi... (29.45 %)

18 - Cleaning of expansion joints (27.51 %)

19 - Anti-corrosive paint based on two-compon... (24.6 %)

20 - Reconstruction of guardrails with commer... (22.01 %)

21 - Regularization of shotcrete surface (18.77 %)

22 - Manual cleaning and removal of material ... (18.45 %)

23 - Surface sealing of cracks with high-visc... (18.45 %)

24 - Drilling nozzle for injecting epoxy-base... (18.45 %)

Figure 5. Distribution of reference versus predicted values of individual models, from the 13th to 24th most frequent maintenance services.

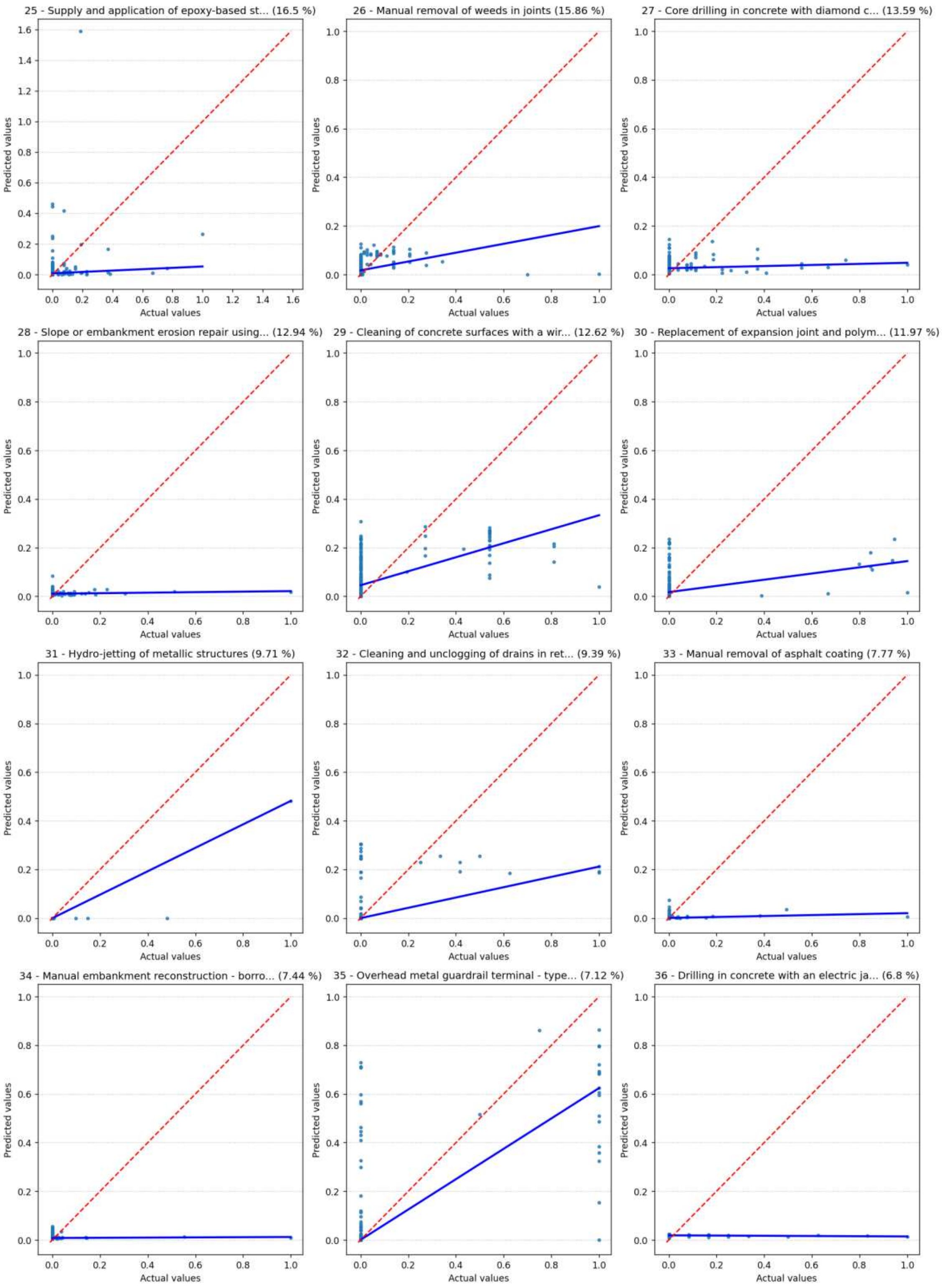


Figure 6. Distribution of reference versus predicted values of individual models, from the 25th to 36th most frequent maintenance services.

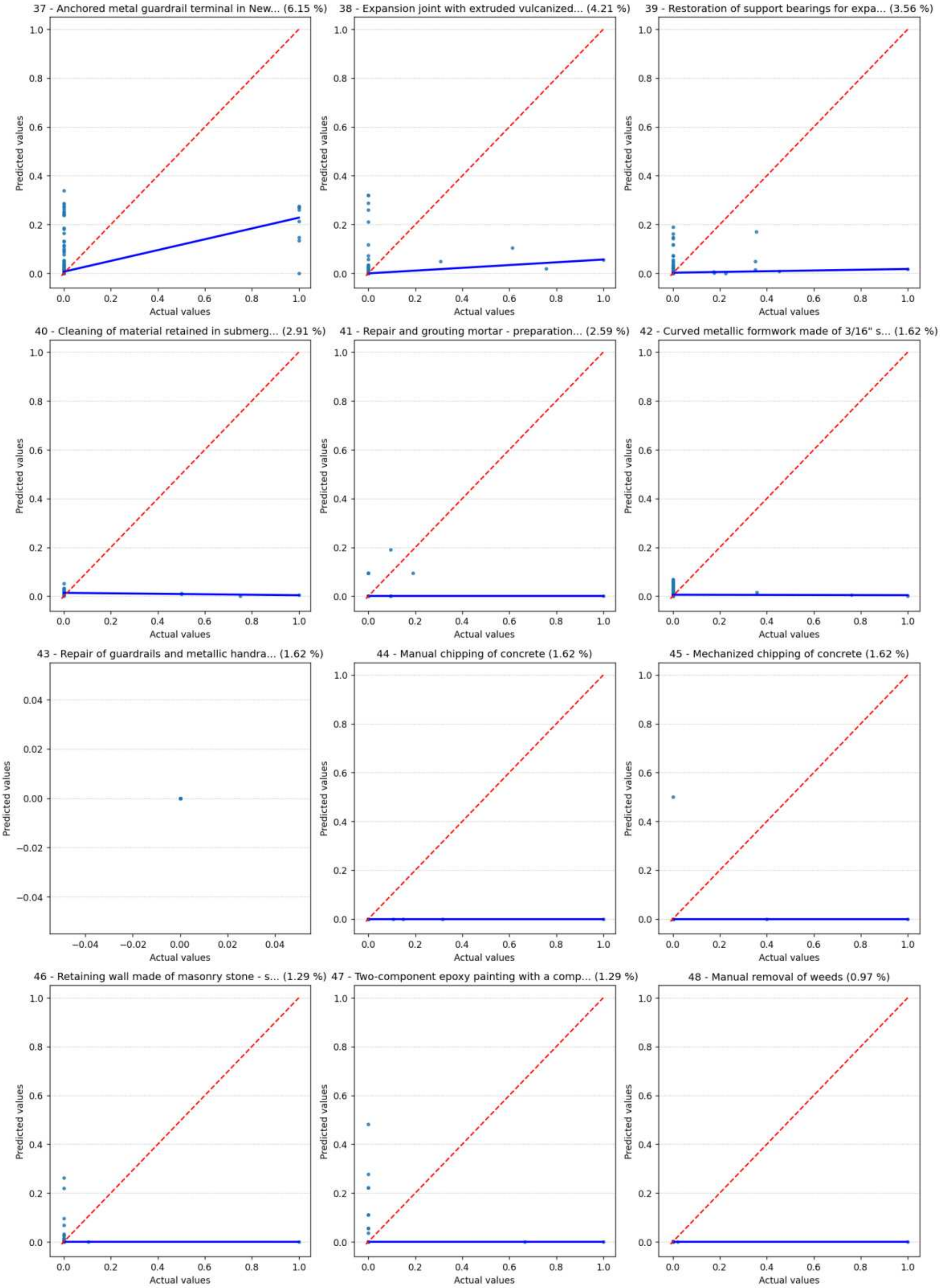


Figure 7. Distribution of reference versus predicted values of individual models, from the 37th to 48th most frequent maintenance services.

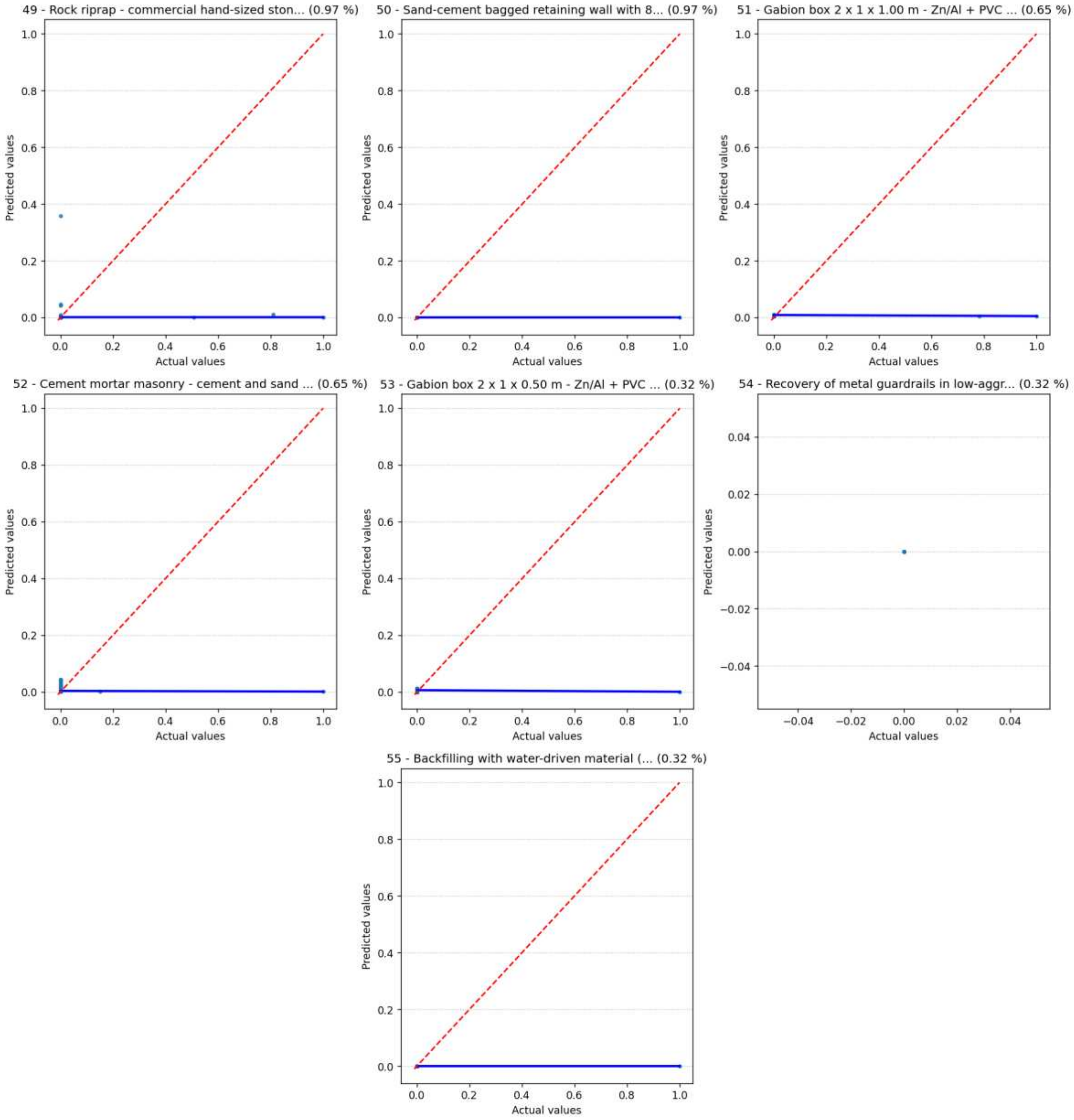


Figure 8. Distribution of reference versus predicted values of individual models, from the 49th to 54th most frequent maintenance services.

4. Discussion

4.1. Overall model performance and feasibility analysis

From the maintenance services evaluated, the first five services with the highest occurrence frequency had the best performance. Not coincidentally, as highlighted in Table 8, all five services are strongly correlated with the bridge’s geometrical characteristics, which are measured data and not susceptible to the subjective interpretation of the inspector. The first four, “Bridge cleaning”, “Cleaning of concrete surfaces with water jetting under pressure”, “Manual cement slurry painting - 3 coats”, and “Manual whitewashing with lime fixative”, are maintenance services usually applied to all structures, and therefore are intrinsically dependent of the length, width, and other measures that were not included in the dataset, such as the girder height.

Table 8. Feature importance factor of the five more frequent maintenance services, considering the data without outliers.

Bridge cleaning		Cleaning of concrete surfaces with water jetting under pressure		Manual cement slurry painting - 3 coats		Manual whitewashing with lime fixative		Elastomer drip edge profile - supply and installation	
Feature	**Impor.**	**Feature**	**Impor.**	**Feature**	**Impor.**	**Feature**	**Impor.**	**Feature**	**Impor.**
Bridge length	0.943	Bridge length	0.835	Bridge length	0.835	Bridge length	0.883	Bridge length	0.854
Humidity stains - Column-type concrete pillar	0.020	Bridge width	0.070	Bridge width	0.069	Humidity stains - Column-type concrete pillar	0.024	Altitude	0.015
Humidity stains - Prestressed concrete box girder	0.007	Altitude	0.018	Altitude	0.017	Longitude	0.012	Latitude	0.012
Leaching and carbonation stain - Reinforced concrete wall column	0.005	Latitude	0.008	Latitude	0.009	Altitude	0.008	Damaged, missing, or expelled joint - Expansion joint	0.012
Humidity stains - Reinforced concrete wall column	0.005	Year of construction	0.007	Year of construction	0.008	Bridge width	0.006	Humidity stains – Reinforced concrete slab	0.010

In the fourth service, “Manual whitewashing with lime fixative”, the recurrence of the service was 92.88 %, leading to multiple non-zero predictions when the reference values were zero. These differing predictions happened even more for the fifth most recurrent maintenance service, “Elastomer drip edge profile 40 x 40 mm with inclined flap, fixed with structural adhesive and pins - supply and installation”. Even though its quantity is directly associated with the bridge’s length, the algorithm could not predict when it would be applied.

The sixth more frequent maintenance service, “Suspended working platform” (abbreviated name), and the eleventh, “Ground-supported working platform – general”, are maintenance services that have a relationship with the bridge’s geometrical characteristics but also depend on multiple parameters not contemplated in the dataset, such as the ground elevation. Even then, the predictions of suspended platforms had a distribution around the reference values. On the other side, the distribution of ground-supported platforms results was very sparse, with many cases where the algorithm failed to determine the absence of the maintenance service in the sample. As seen in Table 9, while the suspended platforms were highly correlated with the bridge length, the ground-supported platform was mistakenly associated with damage as the strongest correlation.

Table 9. Feature importance factor of the two working platform services, considering the data without outliers.

Suspended working platform - preparation, installation, and removal		**Ground-supported working platform - general**	
Feature	**Impor.**	**Feature**	**Impor.**
Bridge length	0.567	Concrete infiltration - Reinforced concrete slab	0.118
Longitude	0.146	Bridge length	0.117
Altitude	0.049	Longitude	0.107
Latitude	0.043	Destroyed guardrail - Reinforced concrete guardrail	0.051
Leaching and carbonation stain - Reinforced concrete slab	0.021	Leaching and carbonation stain – Column-type concrete pillar	0.045

From the seventh most frequent service onwards, the frequency of occurrence quickly diminishes, which impacts the model's capacity to estimate quantities. The reference versus predicted values presented two common behaviours. First, commonly grouped on a vertical line where the reference value is zero, highlighting that the models frequently predict non-zero quantities when they should be zero. Second, the opposite behaviour, with most or even all predictions zero, independently of the reference value. This behaviour was more common in the maintenance services with the lowest occurrence frequency, as there is less non-null reference data to learn from.

Some maintenance services, such as from graphs of numbers 7, 8, 12, 13, 14, 15, 16, 23, 24, 25, and 27, are typically associated with the repair of bridge damages, and a strong correlation between them was expected. To evaluate this correlation, four maintenance services that are employed to repair a wide range of bridge damages were analysed. The ten most important features of “Dry-mix shotcrete with fck = 30 MPa - general application”, “Removal of concrete with high-pressure water jetting”, “Injection of low-viscosity epoxy-based structural adhesive for crack treatment in concrete structures - supply and mechanized application” (posteriorly referenced as “Epoxy injection for crack treatment”), and “Reinforcement steel CA-50 - supply, preparation, and placement” are shown in Table 10.

Table 10. Feature importance factor of maintenance services highly associated with damage repair, considering the data without outliers.

Dry-mix shotcrete with fck = 30 MPa - general application		**Removal of concrete with high-pressure water jetting**		**Epoxy injection for crack treatment**		**Reinforcement steel CA-50 - supply, preparation, and placement**	
Feature	**Impor.**	**Feature**	**Impor.**	**Feature**	**Impor.**	**Feature**	**Impor.**
Disaggregated concrete with exposed and oxidized reinforcement - Reinforced concrete slab	0.127	Disaggregated concrete with exposed and oxidized reinforcement - Reinforced concrete slab	0.166	Deep thin crack - Reinforced concrete slab	0.276	Damaged asphalt pavement - Asphalt pavement	0.103
Concrete delamination with exposed reinforcement - Reinforced concrete guardrail	0.103	Concrete infiltration - Reinforced concrete slab	0.139	Concrete delamination with exposed reinforcement - Old DNER wheel guardrail	0.272	Deep open crack (w > 0.3 mm) - Reinforced concrete curtain wall	0.089
Concrete infiltration - Reinforced concrete slab	0.097	Concrete delamination with exposed reinforcement - Reinforced concrete guardrail	0.086	Leaching and carbonation stain - Reinforced concrete linking transverse beam	0.222	Moisture stains - Reinforced concrete curtain wall	0.072
Concrete infiltration - Reinforced concrete curtain wall	0.067	Reinforcement without coverage - Reinforced concrete T or I beam	0.054	Concrete delamination with exposed reinforcement - New Jersey barrier	0.026	Concrete void (honeycombing) - Reinforced concrete slab	0.060
Concrete infiltration - Abutment - Reinforced concrete front wall	0.049	Concrete infiltration - Reinforced concrete curtain wall	0.050	Superficial crack - Reinforced concrete slab	0.023	Concrete void (honeycombing) - Reinforced concrete T or I beam	0.057
Destroyed guardrail - Reinforced concrete guardrail	0.041	Concrete infiltration - Reinforced concrete T or I beam	0.036	Latitude	0.022	Longitude	0.039
Latitude	0.039	Latitude	0.035	Concrete infiltration - Reinforced concrete curtain wall	0.011	Fire stains - Bracing beam of reinforced concrete column	0.038
Reinforcement without coverage - Reinforced concrete T or I beam	0.035	Longitude	0.032	Reinforcement without coverage - Reinforced concrete T or I beam	0.010	Bridge length	0.036
Concrete delamination with exposed reinforcement - Reinforced concrete slab	0.027	Altitude	0.031	Longitude	0.010	Disaggregated concrete with exposed and oxidized reinforcement - Reinforced concrete T or I beam	0.033
Disaggregated concrete with exposed and oxidized reinforcement - Column-type concrete pillar	0.026	Concrete infiltration - Abutment - Reinforced concrete front wall	0.030	Bridge width	0.009	Fire stains - Reinforced concrete curtain wall	0.030

The five features with higher correlation from both “Dry-mix shotcrete with fck = 30 MPa - general application” and “Removal of concrete with high-pressure water jetting” are very pertinent, as these are damages that generally require concrete removal and replacement. The similarity of the feature’s order and their importance factor is also a good indicator of the correlation of the data with two complementary maintenance services.

In contrast, the maintenance service "Epoxy injection for crack treatment" had only one crack damage featured between the three highest correlation features damages. The second and third most correlated damage features, with an importance factor of the same magnitude as the crack feature, usually do not employ this maintenance service in their repair. Similarly, the "Reinforcement steel CA-50 - supply, preparation, and placement" maintenance service had asphalt damage, crack, and moisture stains, three damages that usually do not require reinforcement steel in their repair, as the most correlated damage features.

Lastly, many of the maintenance services analysed are not directly related to the dataset features. Clear examples are the "Cleaning of support bearings in special structures" and the "Cleaning and unclogging of drainage devices in special structures". The feature importance values shown in Table 11 highlight that these maintenance services are correlated with the bridge length, a logical correlation since longer bridges tend to have more support bearings and drains. However, no feature indicates the actual demand for this type of maintenance service or its quantity.

Table 11. Feature importance factor of services without a clear association with features from the dataset, considering the data without outliers.

Cleaning of support bearings in special structures		**Cleaning and unclogging of drainage devices in special structures**	
Feature	**Impor.**	**Feature**	**Impor.**
Bridge length	0.276	Bridge length	0.453
Longitude	0.171	Slope erosion - Access slope	0.061
Latitude	0.065	Latitude	0.053
Reinforcement without coverage - Bracing beam of reinforced concrete column	0.052	Moisture stains - Reinforced concrete slab	0.043
Deep thin crack - Reinforced concrete slab bridge	0.046	Moisture stains - Reinforced concrete curtain wall	0.029

Considering the results, the primary research question can be answered affirmatively, as the machine learning models trained on raw, tabular inspection records demonstrated predictive capability for maintenance service quantities with an accuracy sufficient to support budgeting processes and provide reliable input for decision-making in bridge maintenance management, provided that sufficient data were available. The models performed satisfactorily for maintenance services with high occurrence frequency, even in an exploratory setting with minimal data intervention. However, the approach adopted in this study is not suitable for services with low occurrence frequency. The observed prediction trends highlight the need for targeted modelling strategies to address these limitations, which are discussed in the following section.

4.2. Limitations, barriers and guidelines for future work

To address the secondary objective of this research, this section identifies the limitations inferred from the results and outlines directions for future work to enhance the operational adoption of ML models as reliable sources of information for decision-making in bridge maintenance management.

The principal limitation of this work was data availability. Due to the difficulty in manually acquiring large datasets, the number of samples was limited, especially considering the complexity of features and labels. Moreover, multiple samples contained missing values and were excluded from the current pipeline, reducing the effective dataset by approximately 40%. These aspect departs from the ideal conditions typically required for robust ML training. Future work should prioritise the acquisition of larger datasets and, where appropriate, apply data imputation techniques (e.g., multiple imputation by chained equations or k-nearest neighbours) to reduce sample loss. Additionally, the inclusion of photographic records processed by computer vision models and unstructured data processed by Large Language Models (LLMs) could significantly enrich the information content and bring the data closer to that used by professional cost estimators.

Regarding data transformation, the approach used to restructure the damage and damaged elements information, although enabling its processing, led to drawbacks in the overall dataset. The transformation yielded 217 unique damage-damaged elements combinations. Along with 15 bridge-level characteristics, this resulted in an input dataset of 232 features for 232 samples. Moreover, this encoding produced a highly sparse input matrix, as illustrated by the binary heatmap of Figure 9. Non-zero values, highlighted in blue, represent only 6.84% of all values related to the damage extension in damaged elements. The distribution histogram in Figure 9 further shows that most damage-damaged element combinations have few occurrences in the available samples: 60% of these features have more than 95% zero values.

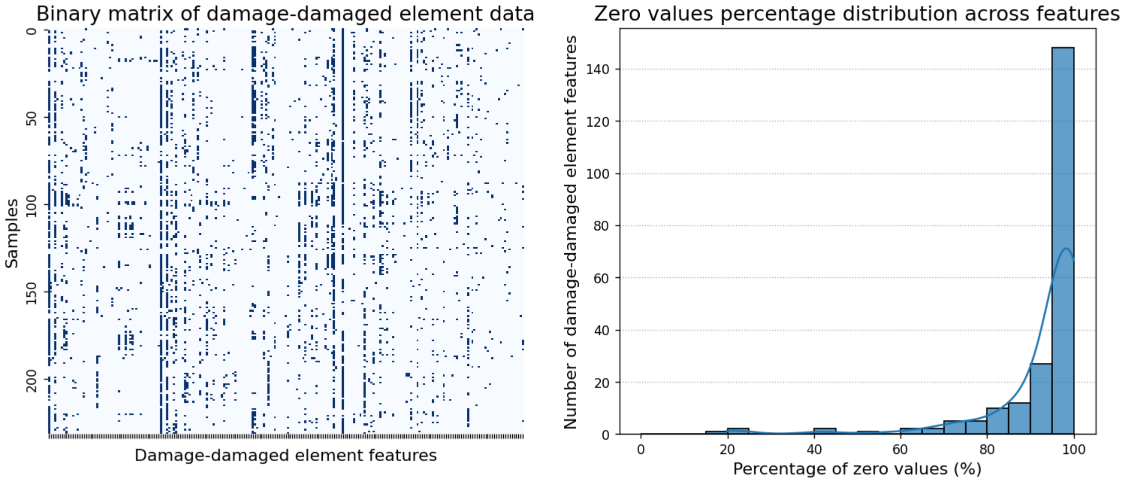


Figure 9. Zero values analysis from the damage-damaged element features.

The high number of features relative to the available samples is, by itself, a concerning characteristic. Considering the 10-fold division for training, the number of features exceeds the number of samples, characterizing a case of the known “curse of dimensionality”. This scenario of a high-dimensional sparse matrix could lead to overfitting, low generalization, and high model variance, and is likely associated with the underperforming results obtained. In this regard, it is recommended to incorporate additional pre-processing steps, such as feature selection (e.g., recursive feature elimination, or mutual information ranking) and dimensionality reduction (e.g., principal component analysis), or to employ alternative feature-structuring strategies (e.g., hierarchical grouping, target encoding or embedding schemes) for the damage-damaged element matrix.

Finally, given the exploratory and generalist approach of this study, along with the large number of labels analysed, the work lacked detailed service model evaluation. Future research should focus on a more comprehensive analysis of each maintenance service’s data and corresponding model, not only to pursue improved predictive performance, but also to provide insights into correlations that could reveal operationally relevant patterns between specific damage types and repair actions.

5. Conclusions

This exploratory study evaluated the application of machine learning models to support decision-making in the bridge maintenance process by automating the quantification of maintenance services from inspection records in a BMS database. To the authors’ knowledge, this work represents one of the first applications of ML to maintenance quantification and budgeting for bridges and viaducts using raw BMS data.

The analysis showed that models performed satisfactorily for maintenance services with high occurrence frequency, where sufficient data allowed correlations consistent with technical knowledge and predictions close to reference values. However, predictions for low-occurrence maintenance services were largely unsatisfactory, with many models either defaulting to near-zero predictions or failing to capture non-zero occurrences. These negative results suggest significant impacts from the limited sample size, sparsity of the damage–damaged element matrix, and imbalance between features and labels.

Answering the primary research question, the results indicate that ML models can predict maintenance service quantities with acceptable accuracy for services supported by sufficient data, but perform poorly for low-occurrence services, requiring additional data and/or alternative modeling approaches.

The study faced several limitations that constrained the results. The dataset was limited and incomplete, with many missing values. Feature dimensionality was disproportionately high compared to the number of samples, and labels with low occurrence frequency had scarce data available. Moreover, important information sources—such as drawings, photographs, and unstructured text—were excluded, considerably limiting the representativeness of the dataset compared to practical budgeting processes. These factors contributed to high variance and explain the underperformance observed for most labels.

Despite these challenges, the study contributes by demonstrating the feasibility of ML applications using basic BMS data, identifying critical barriers, and outlining promising directions for future research. Expanding and enriching datasets, applying advanced pre-processing (e.g., feature selection, dimensionality reduction), and incorporating complementary data sources through computer vision and language models will be crucial to improve predictive performance and establish ML as a reliable tool for bridge maintenance management.

In summary, the results confirm that ML holds potential as a supporting tool for bridge maintenance management, but its adoption at scale depends on addressing the highlighted limitations. This work provides an initial step toward that goal, guiding future research and the evolution of smarter bridge management systems.

6. References

[1] X. Hu, C. Daganzo, S. Madanat, A reliability-based optimization scheme for maintenance management in large-scale bridge networks, Transp Res Part C Emerg Technol 55 (2015) 166–178. https://doi.org/10.1016/j.trc.2015.01.008.

[2] A.P. Chassiakos, P. Vagiotas, D.D. Theodorakopoulos, A knowledge-based system for maintenance planning of highway concrete bridges, Advances in Engineering Software 36 (2005) 740–749. https://doi.org/10.1016/j.advengsoft.2005.03.020.

[3] M.H. Nili, H. Taghaddos, B. Zahraie, Integrating discrete event simulation and genetic algorithm optimization for bridge maintenance planning, Autom Constr 122 (2021). https://doi.org/10.1016/j.autcon.2020.103513.

[4] AASHTO, The manual for bridge evaluation, Washington, DC, 2018. www.transportation.org.

[5] M.A. Hurt, S.D. Schrock, Highway bridge maintenance planning and scheduling, Elsevier, 2016.

[6] M.J. Ryall, Bridge management, Elsevier/Butterworth-Heinemann, 2010.

[7] Y. Jiang, G. Yang, H. Li, T. Zhang, Knowledge driven approach for smart bridge maintenance using big data mining, Autom Constr 146 (2023). https://doi.org/10.1016/j.autcon.2022.104673.

[8] J. Yang, F. Xiang, R. Li, L. Zhang, X. Yang, S. Jiang, H. Zhang, D. Wang, X. Liu, Intelligent bridge management via big data knowledge engineering, Autom Constr 135 (2022). https://doi.org/10.1016/j.autcon.2021.104118.

[9] J. Brownlee, Data Preparation for Machine Learning, 2020.

[10] F. Faber, A. Lindmaa, O.A. Von Lilienfeld, R. Armiento, Crystal structure representations for machine learning models of formation energies, Int J Quantum Chem 115 (2015) 1094–1101. https://doi.org/10.1002/qua.24917.

[11] A. Rácz, D. Bajusz, K. Héberger, Effect of dataset size and train/test split ratios in qsar/qspr multiclass classification, Molecules 26 (2021). https://doi.org/10.3390/molecules26041111.

[12] C.A. Ramezan, T.A. Warner, A.E. Maxwell, Evaluation of sampling and cross-validation tuning strategies for regional-scale machine learning classification, Remote Sens (Basel) 11 (2019). https://doi.org/10.3390/rs11020185.

[13] H.J. Lu, N. Zou, R. Jacobs, B. Afflerbach, X.G. Lu, D. Morgan, Error assessment and optimal cross-validation approaches in machine learning applied to impurity diffusion, Comput Mater Sci 169 (2019). https://doi.org/10.1016/j.commatsci.2019.06.010.

[14] S. Raschka, Model Evaluation, Model Selection, and Algorithm Selection in Machine Learning, 2020. http://arxiv.org/abs/1811.12808.

[15] Y. Jung, Multiple predicting K-fold cross-validation for model selection, J Nonparametr Stat 30 (2018) 197–215. https://doi.org/10.1080/10485252.2017.1404598.

[16] B.G. Marcot, A.M. Hanea, What is an optimal value of k in k-fold cross-validation in discrete Bayesian network analysis?, Comput Stat 36 (2021) 2009–2031. https://doi.org/10.1007/s00180-020-00999-9.

[17] J.D. Rodríguez, A. Pérez, J.A. Lozano, Sensitivity Analysis of k-Fold Cross Validation in Prediction Error Estimation, IEEE Trans Pattern Anal Mach Intell 32 (2010) 569–575. https://doi.org/10.1109/TPAMI.2009.187.

CHAPTER 5 – IFC FRAMEWORK FOR INSPECTION AND MAINTENANCE REPRESENTATION IN FACILITY MANAGEMENT[4]

Abstract

Effectively managing inspection and maintenance data in facility management remains challenging due to the lack of structured and interoperable data representation. This paper explores how the IFC schema can be leveraged to standardize inspection, damage, maintenance, and maintenance cost data representation. To this end, an IFC-based framework was developed to ensure semantic consistency and interoperability in the representation of inspection and maintenance data. The framework was validated through IFC schema verification and semantic evaluation of generated case studies across multiple BIM software, demonstrating its applicability for facility management, maintenance planning, and asset monitoring of buildings, industrial plants, and infrastructure projects. By enabling and standardizing structured information exchange, the proposed framework enhances decision-making in facility management workflows. Future work should focus on extending its application in real-world scenarios, specifically through integration with facility management systems and automated data acquisition technologies.

Keywords: Building Information Modeling (BIM). Industry Foundation Classes (IFC). Facility management. Damage information modeling (DIM). Inspection. Maintenance. Information storage.

---

[4] Original manuscript submitted to *Automation in Construction* in September 2024, accepted in March 2025, and published in April 2025. https://doi.org/10.1016/j.autcon.2025.106157

1. Introduction

Inspection is an essential stage in structure operation, serving to detect and document damage, inform planning and intervention strategies, and build a comprehensive history of the structure condition. However, traditional paper-based documentation often leads to fragmented, limited, and subjective data, making accurate assessments challenging [1–3]. According to Xu et al. [4], a current inspection report includes basic information, identified damage, and assessments by experienced engineers, generating large data volumes over the structure's life cycle. Poor data management can significantly impair the assessment of structural conditions and maintenance decision-making [5,6].

An integrated information repository is essential for managing all databases. Building Information Modeling (BIM) is an efficient methodology for this purpose, digitally representing the physical and functional characteristics of the structure throughout its entire lifecycle [7,8]. Digital models for structures are needed to enable the inspection process digitization [6,9]. The success of BIM in management systems relies on effective communication and interoperability between tools and stakeholders [10–13]. As is well known, interoperability remains a challenge in the information exchange process between different software due to the lack of a standardized neutral format for exchanging information [8,13–15]. OpenBIM is a collaborative project management process that uses BIM based on open standards and workflows, ensuring the accessibility, reliability, management, and sustainability of digital data throughout the structure's lifecycle [16–20].

The IFC (Industry Foundation Classes) data model is an open, neutral, and standardized format developed by BuildingSMART and is widely used for digital data exchange [21]. This model is an object-oriented data architecture for BIM, facilitating the modeling semantics and geometries. Integrating the IFC schema with BIM enhances collaboration and ensures data consistency across design, construction, and facilities management phases. A Damage Information Model (DIM) requires BIM to link damage data to specific elements and materials within a structure, aiding in inspections, simulations, and maintenance planning [9,22]. However, the IFC standard still lacks specific relationships for damage representation, necessitating the development of extensions [9].

This paper presents a methodology based on the IFC workflow to integrate inspection data, damage reports, proposed maintenance services, and costs, emphasizing information flow and data exchange validation. This methodology aims to enhance the management and understanding of the structure's current state and maintenance needs by integrating damage information into the BIM database using the IFC schema.

This approach facilitates interoperability between different software and systems, optimizing the process of documenting and representing information related to inspection, damage, and maintenance interventions in BIM models. The innovation of this methodology lies in its holistic integration of inspection tasks, damage detection, maintenance actions, and cost analysis within the BIM environment. By addressing current gaps in both practice and literature, this framework offers a more efficient, standardized approach to structural information management, ultimately improving decision-making and collaboration among stakeholders.

2. Related Works

In the literature, the use of BIM and IFC in facility management (FM) has been explored in many aspects and contexts throughout the years. Works such as Pishdad-Bozorgi et al. [23], Matarneh et al. [24], and Matarneh et al. [12] address the implementation, exchange, and automation, respectively, of FM information using BIM and IFC. In the mentioned works, the persistent need for a correlational relationship between FM and BIM data representation to standardize the information exchange is highlighted. However, there is still a demand for studies investigating interoperability solutions between FM and BIM systems [24].

The integration of FM and BIM was also studied in specific contexts. Wan et al. [25] developed a Bridge Management System based on BIM using the extensions of the IFC and International Framework for Dictionaries (IFD) standards to store and exchange bridge life-cycle information. Wang et al. [26] and Sharafat et al. [27] utilized BIM in the management of underground utilities, elaborating a mapper between IFC and City Geography Markup Language (CityGML), an open data model for the storage and exchange of 3D city models. A dedicated study case was made by Omayer and Selim [28], emphasizing the need to acknowledge the information exchange procedure and standard, considering the IFC schema and its representation framework.

The use of IFC in representing FM information was also analyzed for specific processes of this context. Focusing on the inspection of infrastructure projects, Ding et al. [29] developed an IFC framework for the inspection process model, extending the existing schema to include quality management representation for real-time monitoring and control of quality. Similarly, Hernández et al. [30] developed an IFC-based framework to enable the interoperability between

Intuitive Self-Inspection Techniques (INSITER) devices and tools, which lacked a common format to combine pertinent data.

In the maintenance process context, Chen et al. [31] focused on automating the scheduling of facility maintenance work orders. An IFC schema extension comprising maintenance process and control entities was proposed, along with a mapping between FM and BIM data. Marmo et al. [32] developed an IFC-based building performance and maintenance information model, elaborating a relational database to support the integration between FM and BIM models with a focus on healthcare facilities. Condotta and Scanagatta [33] proposed a method to promote BIM and Computerized Maintenance Management Systems (CMMS) software integration using a database taxonomy, allowing updates in the BIM models according to the CMMS database.

Still considering maintenance, the damage representation and modeling in BIM and IFC have also been addressed. Processing damage information requires semantic and geometric data, including measurements like width, length, orientation, and element position, as well as textual descriptions such as material specifications [9]. However, the complete integration of inspection and damage data into BIM models remains a challenge, with current methods for linking defects to IFC entities being either inadequate or incomplete [4,34–36]. The principal purpose of a DIM is to address interoperability issues arising from the widespread use of BIM in operation and maintenance. Standardizing damage data can help reduce information loss and costs [9,22,34]. Several studies have proposed solutions for modeling bridges using existing IFC entities or by extending the IFC schema [4,9,34,35,37,38].

Sacks et al. [37] developed SeeBridge, a semantic enrichment method incorporating defect information into BIM, creating relationships between damage and bridge elements. Hüthwohl et al. [34] addressed the lack of standardization in inspection reports, proposing a model to integrate defect data for reinforced concrete bridges. Isailović et al. [35] introduced an IFC-based semantic enrichment framework to align damage features with Bridge Management System classifications. Artus and Koch [9] developed a comprehensive DIM for bridge assessment, incorporating geometric, visual, and semantic damage data. Xu et al. [4] proposed a parametric method for documenting defect geometry, while Shu et al. [38] introduced a framework to model damaged beams and integrate semantic data with FE models. Table 1 summarizes the related work presented and the entities used to represent inspection, damage, and maintenance.

Table 1. Summary table of the proposal, methodology, and entities used to represent inspection, damage, and maintenance.

References	**Purpose**	**Methodology Approach**	**IFC entities**			**IFC relationship entities**		
			Inspection	**Damage**	**Maintenance**	**Damage - inspections**	**Inspection - maintenance**	**Damage - element**
Sacks et al. [37]	Propose the SeeBridge Method for semantically enriching BIM models with information on defects	Developed a schema for defect modeling using UML diagrams; implemented defect modeling using IFC standard; integrated high-resolution images of element defects	*	*IfcElementAssembly* *IfcSurfaceFeature* *IfcImageTexture*	*	*	*	*IfcRelAggregates*
Hüthwohl et al. [34]	Standardize inspection information for reinforced concrete bridges	Proposed an information model for integrating bridge defect information into BIM; identified damage classes and properties; proposed a candidate binding to IFC	*IfcTask*	*IfcElementAssembly* *IfcSurfaceFeature* *IfcPropertySets*	*	*IfcRelDefinesByProperties* *IfcRelAssignToProcess*	*	*IfcRelAggregates*
Isailović et al. [35]	Introduce an IFC semantic enrichment framework for integrating damage features into the existing IFC model	Developed a framework to align damage characteristics with damage classification in BMS; adhered to IFC schema; included semantic data structure	*IfcTask*	*IfcElementAssembly* *IfcSurfaceFeature* *IfcPropertySets*	*	*IfcRelDefinesByProperties* *IfcRelAssignToProcess*	*	*IfcRelVoidsElement*
Artus and Koch [9]	Enhance bridge assessment and structural analysis using a DIM	DIM incorporating geometric, visual, and semantic damage data; explored alternatives for damage modeling; evaluated visualization aspects Implemented IFC concept aligned with IFC 4; evaluated visualization aspects	*	*IfcProxy* *IfcAnnotation* *IfcSurfaceFeature* *IfcVoidingFeature*	*	*	*	*IfcRelAssignsToProduct* *IfcRelAggregates* *IfcRelVoidsElement*
Xu et al. [[4]	Propose an IFC-based method for documenting and representing inspection-related information in bridge BIM	Demonstrated parametric-driven modeling of defect information based on the latest IFC; facilitated an integrated BIM environment for lifecycle management	*IfcTask*	*IfcSurfaceFeature*	*IfcProjectOrder*	*IfcRelAssignsToProduct*	*IcRelAssignsToControl*	*IfcRelAggregates*
Shu et al. [38]	Introduce a framework for semantically modeling damaged RC beams using point clouds	Developed a slice-based method for modeling deformed beams; proposed extending the IFC standard for interoperability with FE models	*	*IfcSurfaceFeature*	*	*	*	*IfcRelAggregates*

Although BIM and the IFC schema usage are becoming commonplace in the management of inspection and maintenance data for structures, there are still significant gaps in the complete integration of damage information into BIM models. As seen in the analysed bibliography, the correct integration between FM and BIM applications and databases is heavily dependent on information exchange standards. In studies that approach a particular context, this need is usually addressed for that individual case, although not enough emphasis is given to the IFC structure. There is no holistic IFC approach that fully integrates inspection data, damage assessment, maintenance actions, and cost analysis within the BIM environment. This gap highlights the need for a methodology that standardizes the representation of facility management entities based on the current version of the IFC schema, ensuring full interoperability in the area.

3. Methodology

The primary objective of this work is to propose a comprehensive framework based on the IFC schema that represents the typical workflow between the inspection and maintenance processes in facility management. This framework includes inspection, damage reporting, proposed maintenance services, and costs, focusing on the information flow structure. The framework's structure follows a general approach that can be adapted to facility management systems, ensuring flexibility and broad applicability. The methodology is structured as follows:

3.1. Understanding and Preparing the IFC Scheme

A comprehensive mapping of the IFC 4.3 ADD2 entities was conducted to identify relevant entities for describing and representing inspection data, damage information, maintenance intervention services, activities quantities and costs, and the relationships between these entities. The mapping' needs could be grouped into three major representation categories: spatial structure, processes, and cost. The spatial structure representation included the physical elements, such as built elements, damages, and the facility. The process representation encompasses all tasks, including both inspection and maintenance activities. The cost representation focused on the maintenance costs but could also include any cost associated with the project.

Only IFC 4.3 ADD2 entities, without any additional extension, were used to elaborate the framework structure and represent the spatial structure, processes, and costs. This approach ensured that the framework's base structure would fully conform to the IFC documentation and requirements, maximizing its interoperability with IFC-compatible software. In specific applications of the framework, extensions of the IFC schema could be employed to satisfy the information representation requirements, as exemplified in the case study.

3.1.1. 3.1.1. Spatial structure representation

The spatial structure representation was intentionally kept general and straightforward to ensure adaptability to various specific cases. Its representation was based on typical schemas found in official examples of buildingSMART IFC, with IfcSite storing the information relative to the asset location and its surroundings and IfcFacility representing a general facility.

The use of IfcFacility guarantees the universality of the facility representation. A more detailed identification of the facility type, most commonly done by replacing IfcFacility with its correspondent subtypes such as IfcBuilding, IfcBridge, IfcRoad, and more, would not demand modifications on the framework structure, since the IfcFacility subtypes also benefit from its attributes and relationships. Moreover, identifying facility types not contemplated in the IfcFacility subtypes set, such as tunnels, dams, and more, could be done by specifying a user-defined type in the *IfcFacility.ObjectType* attribute, not altering the original framework structure.

The facility decomposition, given its specificity, was out of the scope. It is assumed that any physical components of the facility would be represented by IfcElement subtypes, as is highlighted in its definition in the IFC 4.3 ADD2 documentation. Based on this assumption, the physical elements of the facility were generically represented in the structure diagrams, but their relationships with other framework entities are defined considering the inherited attributes from the IfcElement supertype. Regarding the relation between elements and facility, the key relationship inherited is IfcRelContainedInSpatialStructure, which enables the assignment of the IfcElement subtype’s instances to a spatial element, represented in this case by IfcFacility (Figure 1).

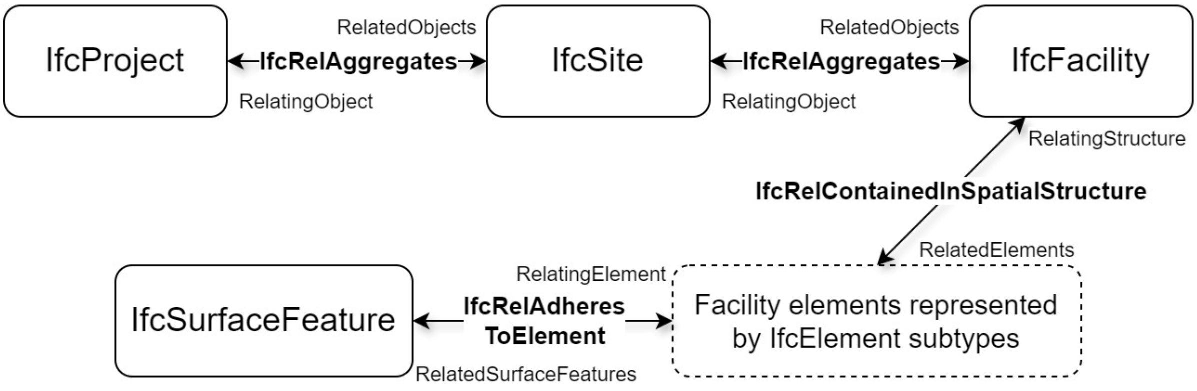


Figure 1. Spatial structure representation.

The remaining physical entity to be represented is the damage itself. Corroborated by many works [4,9,34,35,38,39], the damages were represented using IfcSurfaceFeature, a type of element defined as a "modification at (onto, or into) of the surface of an element". The characterization of the surface feature as damage is made by the PredefinedType attribute with the "DEFECT" value, indicating that it is a "detected defect on the surface of an element, such as corroded or eroded area".

Although the entity that represents the damages is defined as IfcSurfaceFeature, the damage information modeling itself is out of the scope of this study, considering that the damage model can vary considerably according to their purpose. However, independently of the damage modeling approach, the representation of the IfcSurfaceFeature entity and its relationships with the whole framework acts as a placeholder for more detailed representations, ensuring that the proposed workflow would still perform as expected.

Even considering the particularities in damage modeling, the IfcSurfaceFeature documentation provides guidelines on how to represent the required information. Regarding geometrical modeling, multiple alternatives are provided, including even a symbolic representation, particularly useful considering the usual complexity of damaged shapes. Moreover, high-level geometric and non-geometric parameters of the IfcSurfaceFeature entity may be stored in property sets based on the information requirements and agreed upon by convention. This recommendation of the documentation reflects the general nature of the entity, which is employed to model any surface feature and, therefore, is not a bearer of specifically orientated attributes towards the representation of damage information.

Considering the documentation suggestion, property sets could be defined accordingly to the requirements from an application context, encompassing parameters required and/or used by the entire facility management process. In the case study, a basic approach of damage representation is exemplified, including geometrical information and current status of the damage in a property set, while specifying the damage type in the *IfcSurfaceFeature.ObjectType* attribute. The exemplified approach focused only on the minimal information necessary to enable an automated budgeting of maintenance tasks, and can be used as a reference to extend future adaptations. Alternative approaches of damage modeling can be found in the works cited in Table 1.

To the framework structure, an essential damage information is the damaged element. The association of a physical element and a damage instance is established using the objectified relationship IfcRelAdheresToElement, a subtype of IfcRelDecomposes exclusive to the surface feature association. The relationship documentation establishes conditions, such as the dependence of the element's existence on the associated surface feature keep existing, and the hierarchical and non-cyclical nature of the relationship, permitting the association with a single element per instance. The latter condition demands attention in the damage modeling since damages that affect multiple elements should be divided into parts, each exclusive to each affected element.

3.1.2. Process representation

The process representation, the main focus of this work, was entirely based on decompositions using the IfcTask entity. According to the IfcTask documentation, it can describe actions to be performed. Those actions can be subdivided into smaller tasks through aggregation down to the smallest identifiable piece of work, thus forming a task hierarchy. This aggregation of whole-parts of activities that define the different levels of the hierarchy was done using IfcRelNests, as advised by the documentation.

The process decomposition was rooted in a summary task that derived every subtask planned or performed in the project. The summary task, the highest level of the process hierarchy, was directly declared within the IfcProject instance through the IfcRelDeclares relationship and was also used to define a link to the work schedule, as required by the IfcTask documentation. Under the summary task, the processes were divided into the roots of the two main facility management activities addressed: the inspection and the maintenance (Figure 2).

The inspection root task represents the aggregation of all the facility inspections performed in its lifecycle, therefore deriving any inspection-related IfcTask. The inspection root task and its subsequent sub-tasks had their type identified by the IfcTask.PredefinedType attribute, using the enumerated “INSPECTION” value. The inspection root task was decomposed one level further into a set comprising each complete facility inspection performed, as a way to relate each complete facility inspection performed to the damage occurrences reported in it. However, this configuration can be further detailed and even adapted, although maintaining the relationship of the inspection tasks with the damages is strongly advised to preserve the general information flow.

Analogously, the maintenance root task represents the aggregation of all the facility maintenance performed in its lifecycle. The type of the maintenance root task and its sub-tasks were also identified by the IfcTask.PredefinedType attribute, using the enumerated “MAINTENANCE” value. In the proposed framework, the maintenance root task was decomposed into three hierarchical maintenance task levels: facility, damage, and activity. The facility level corresponds to any maintenance intervention targeting the entire facility, usually to repair a range of damages. Besides the relationships that express the decomposition, the distinction between IfcTask instances of different levels was made through the *IfcTask.ObjectType* attribute, whose value provided a level identification.

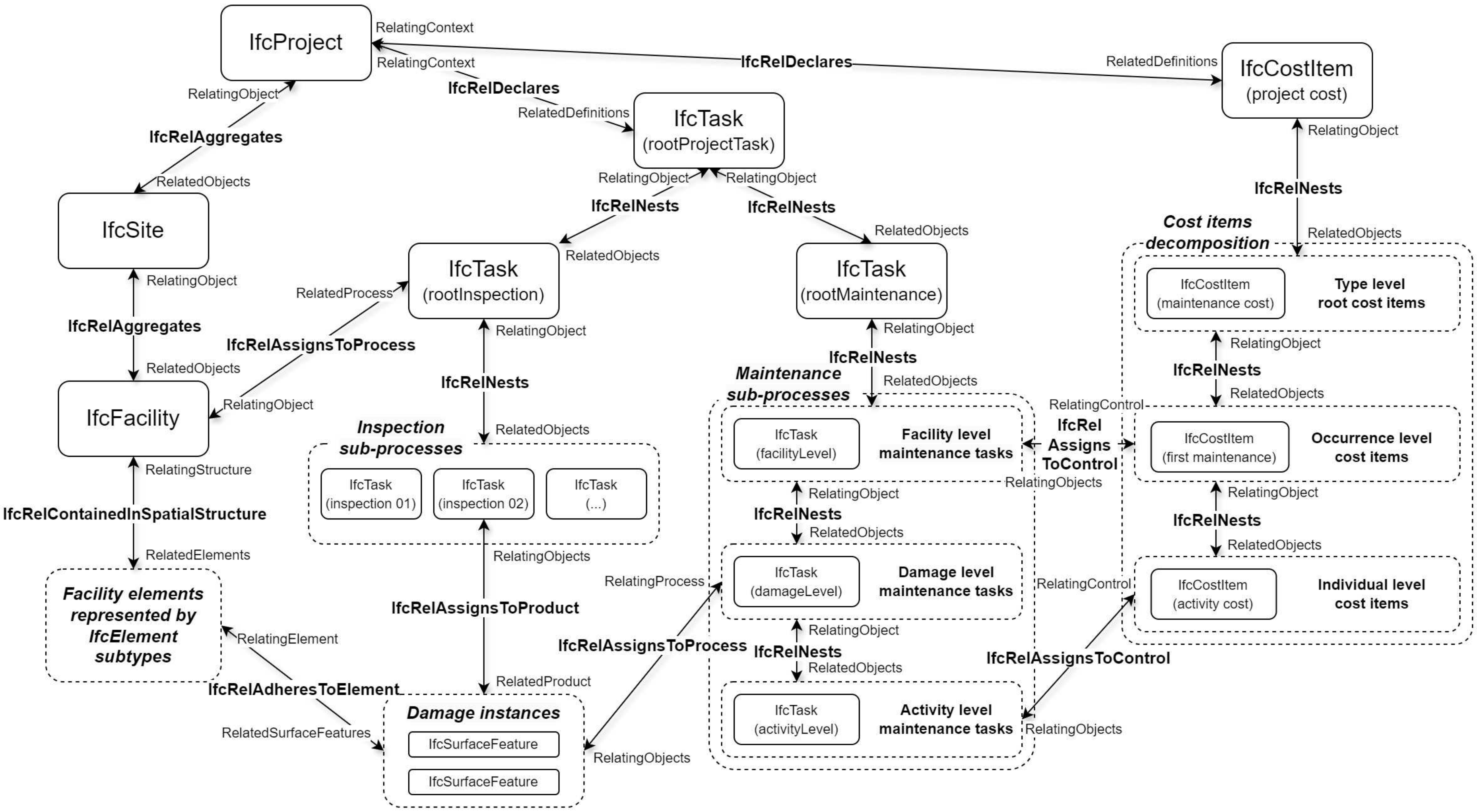


Figure 2. Inspection and maintenance general framework representation.

The damage level is composed of subtasks directly related to the damage instances through the IfcRelAssignsToProcess relationship and symbolizes the grouping of all the activities necessary to perform the repair of that damage type. The activity level represents the actual actions that need to be executed to repair the damage instance, and their quantities and unitary costs can derive the total maintenance cost. Once again, this proposition can be adapted to the most suitable structure for specific cases.

3.1.3. Cost representation

The cost representation was based on the IfcCostItem entity and its decomposition using IfcRelNests. IfcCostItem, as an overall cost description, can be associated with any process. In the framework, the cost items were only associated with the maintenance services, representing the cost of repairing the damages. However, any other cost could be defined, as anticipated in the "type level root cost items" level of the IfcCostItem decomposition in the framework (Figure 3). Through the attributes CostValues, which can reference a list of monetary values using IfcCostValue, and CostQuantities, which can reference physical quantities using subtypes of IfcPhysicalQuantity, the unitary cost, the service quantity, and indirectly the total cost of any maintenance task can be represented.

The IfcCostItem.*CostValues* attribute references an optional list of monetary values represented by IfcCostValue instances. The IfcCostValue entity has several attributes that can be employed to describe monetary values and alter them through arithmetic operators. However, in the simplified representation of this framework, only the name, description, applied value, and category attributes were used. In turn, IfcCostItem.*CostQuantities* attribute references an optional list of IfcPhysicalQuantity subtypes. IfcPhysicalQuantity is an abstract entity that groups simple and complex physical quantity measures, such as length, area, and volume. In the tests and validation, the entities IfcQuantityArea and IfcQuantityVolume were used to represent the typical measures associated with maintenance services, which can be adapted according to the service's measurement unit.

The cost decomposition followed a similar structure to the process decomposition used for inspection and maintenance. The root of the cost decomposition is the project IfcCostItem instance, from which any other cost item will be derived. This summary cost item is directly declared to the project through the IfcRelDeclares relationship, analogously to the summary process declaration. Considering that each monetary value involved in the project is detailed in the IFC file as an IfcCostItem instance, the summary cost item would represent the project' total cost.

Along with the declaration within the project, the summary cost item is also assigned to the control entity IfcCostSchedule. IfcCostSchedule represents a cost schedule that further identifies the cost item instances associated, being specified through an enumerated type, status, and temporal information. In this research, only a general cost schedule associated with the summary cost item was employed, with the main purpose of enabling the whole cost decomposition visualization on the Bonsai extension. However, it can be used inside the cost item decomposition to identify and differentiate the purpose of the costs represented in the same project.

Under the summary cost, the decomposition structure can follow the most appropriate configuration for each case. In the proposed framework, the structure was organized into three levels: type, occurrence, and individual. The cost items at the type level are the roots of the decompositions of each project cost type represented in the IFC file, such as construction, inspection, or maintenance costs. The occurrence level cost items represent the cost of each occurrence of general tasks performed in the project, such as an entire facility inspection or maintenance. The individual level cost items, represented by the lower parts of the cost subdivision, represent each cost individually, such as the cost-derived activity-level maintenance tasks (Figure 3). As the maintenance tasks hierarchical decomposition, the IfcCostItem instance level was differentiated by the decomposition relationships and the *IfcCostItem.ObjectType* attribute.

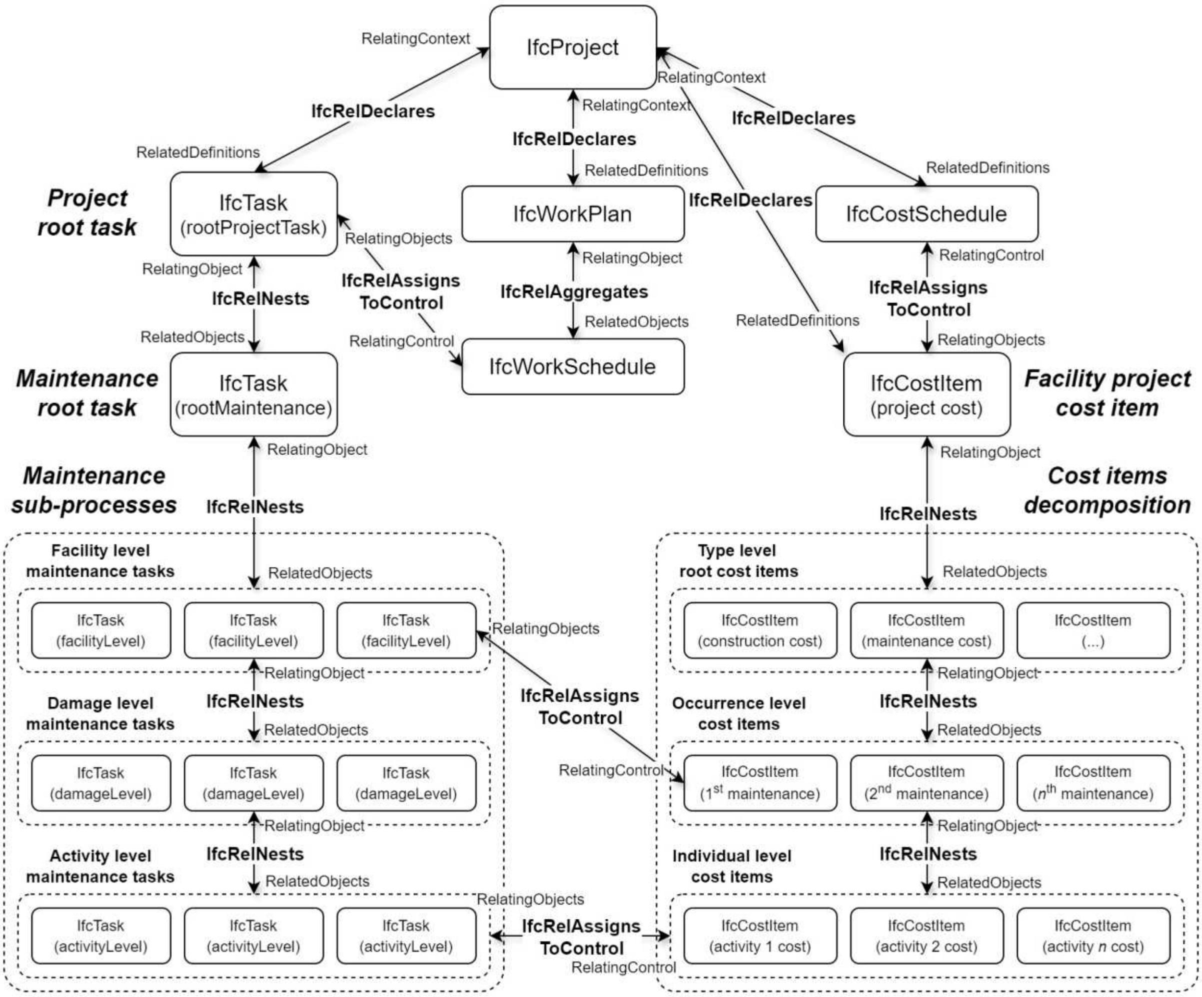


Figure 3. Maintenance and cost general framework representation.

To exemplify, consider the existence of an IfcSurfaceFeature instance that represented "disaggregated concrete" damage. Its instance would be associated with a damage level maintenance task, representing a "disaggregated concrete maintenance" IfcTask. This IfcTask would be decomposed into activity level maintenance tasks, such as "concrete removal with high-pressure water jetting" and "dry-mix shotcrete application", the IfcTask instances that represent the repair activities to be performed. Each activity level maintenance task would be then associated with an individual level cost item, representing individual costs of repair maintenance tasks. The nesting of all the individual level cost items from complete facility maintenance, or in other words, the sum of expenses from all the damage repair activities, represents the total cost of a facility maintenance intervention.

3.2. Information workflow design

Based on the typical workflow of facility inspection and maintenance activities, the relationships in the proposed framework have been structured in such a way as to make it easier to interpret the flow of information, even for an end user who only has access to the IFC file. This flow was described as distinguishing between the “client” and “suppliers” objects done by the IfcRelAssigns relationships. Even with their bi-directional characteristic, the semantic meaning of each IfcRelAssigns subtype and the role performed for each object type in these subtypes is sufficient for assigning proper relations between the IFC instances. A representation of the information flow, its clusters, and relationships is shown in Figure 4.

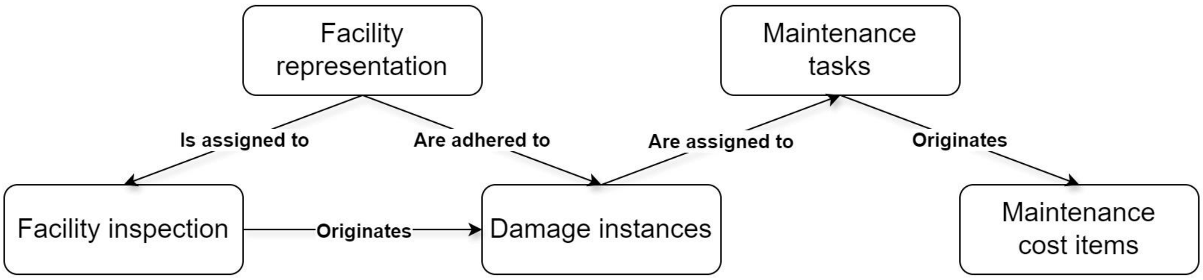


Figure 4. Illustrative representation of the information flow.

Starting from the spatial structure representation, the first relationship that starts the workflow is the assignment of the facility to the summary inspection task through IfcRelAssignsToProcess, with IfcFacility as the *RelatingObjects* and the IfcTask that represents the root inspection task as the *RelatingProcess* (Figure 2). This relationship illustrates that the inspection root task and, by inheritance, its subtasks, act on the installation by default. Particular inspection tasks could be directed to specific spaces or elements of the facility, using a lower hierarchical level IfcRelAssignsToProcess relationship to override the one inherited.

The IfcTask instances that represent each inspection can have diverse relationships, such as the relationship between inspections and the documents they usually derive, expressed either by IfcDocumentReference or IfcDocumentInformation, using the IfcRelAssociatesDocument (Figure 5). However, for the proposed framework, the crucial inspection relationship is IfcRelAssignsToProduct, where the damage instances, represented by the IfcSurfaceFeature entity, are the products of the inspection process. This relationship guarantees that each damage instance is correctly associated with the executed inspection that identified it.

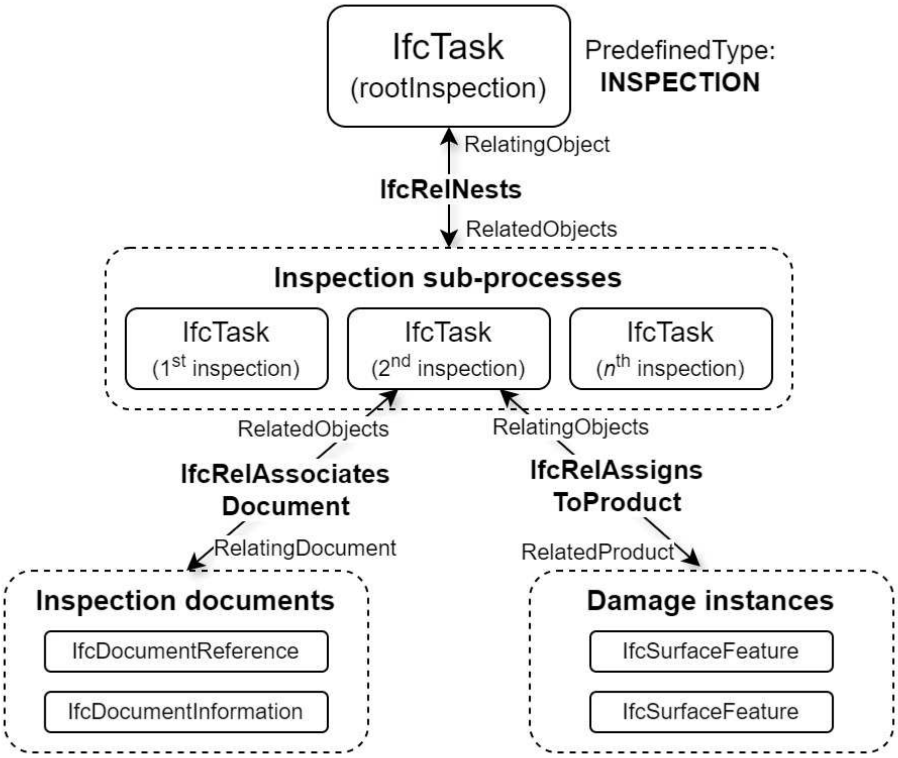


Figure 5. Inspection documents and damages representation.

Once instantiated, it is fundamental that the IfcSurfaceFeature damage instances are associated to the physical elements that they affect through the IfcRelAdheresToElement relationship. Moreover, to continue the workflow, damages should be related to the maintenance tasks when applicable. The relationship between damages and maintenance tasks is expressed through IfcRelAssignsToProcess, with the IfcTask representing the damage level maintenance as the *RelatingProcess*. It is important to emphasize that in the current framework, each damage is assigned to one IfcTask that defines an individual damage repair, as detailed in the maintenance decomposition contextualization.

The damage level maintenance tasks that operate upon the damages are nested by several activity level maintenance tasks that represent the actual performed tasks. These tasks are related to the individual level IfcCostItem instance representing their quantities and costs by the IfcRelAssignsToControl relationship. Each task is individually associated with the corresponding IfcCostItem. The nesting of individual-level cost items under an occurrence-level cost item, representing the total cost of a maintenance intervention, is also associated with the corresponding facility-level maintenance task. With this approach, the total cost of each maintenance is represented, finalizing the workflow.

3.3. Framework implementation

A Python application was developed to automate the implementation of the structure in case studies and validate the proposed scheme. This application was designed to be applied in a general scenario, either creating a complete IFC file from scratch or altering pre-existing facility models. The application used an optional IFC file and a JSON file as input. When provided, the input IFC file would be the basis of the resulting model, with the application retrieving pre-existent information about the facility and its elements to establish relationships with the inspection and maintenance data imported from the JSON file.

In the absence of an input IFC model, the application would use only the information existing in the input JSON file to generate a valid IFC file. To this intent, the JSON input file was structured to gather the most basic necessary information from the facility, elements, inspections, damages, and maintenance interventions, and could easily be adapted for any database or application. Based on these input data, the information would be processed, and the final data would be stored in the output IFC file according to the structure of the proposed framework. An overall illustration of the application workflow is represented in Figure 6.

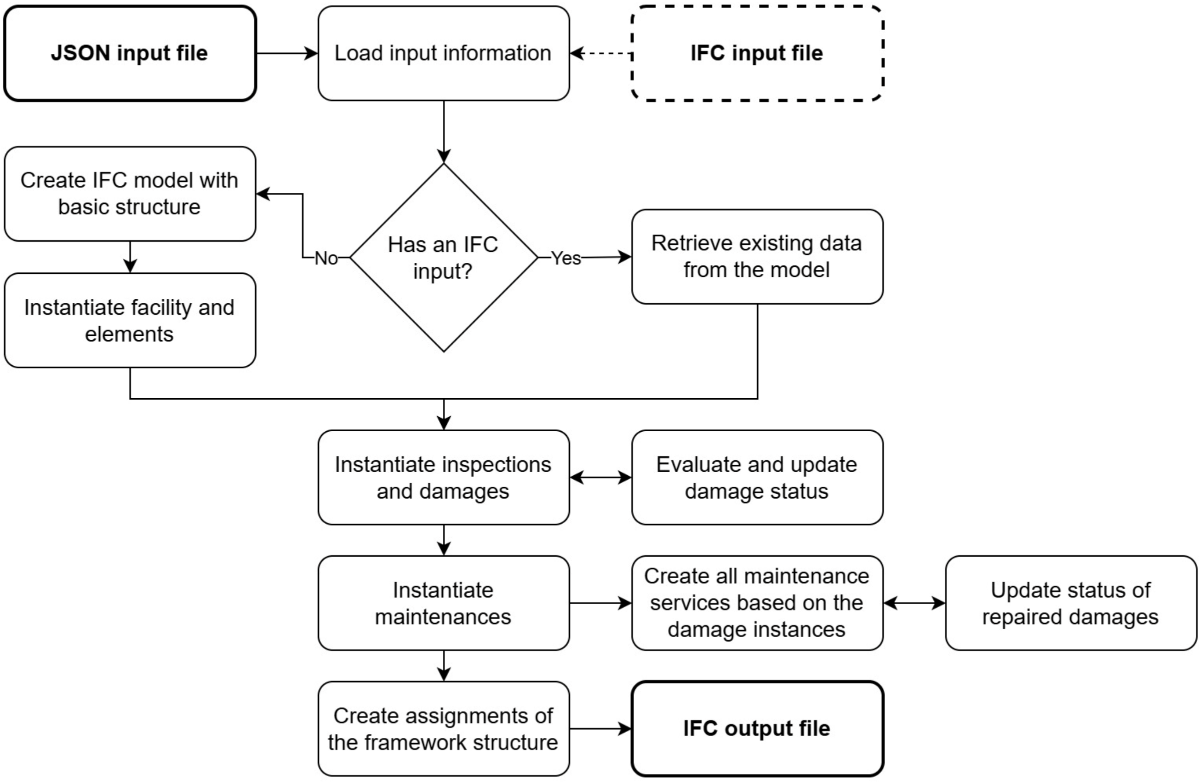


Figure 6. Application workflow diagram.

The process starts by loading information from the input JSON and, if provided, the input IFC file, as illustrated in the application's workflow diagram (Figure 6). The JSON was structured to facilitate the application implementation and to remain simple and easily adaptable to any structured database. Following the JSON structure, the input data were divided into objects, where objects with multiple occurrences were grouped in arrays. Dependent information was grouped using nested objects, such as the information derived from the inspection occurrences. The JSON objects and their data type are presented in Figure 7.

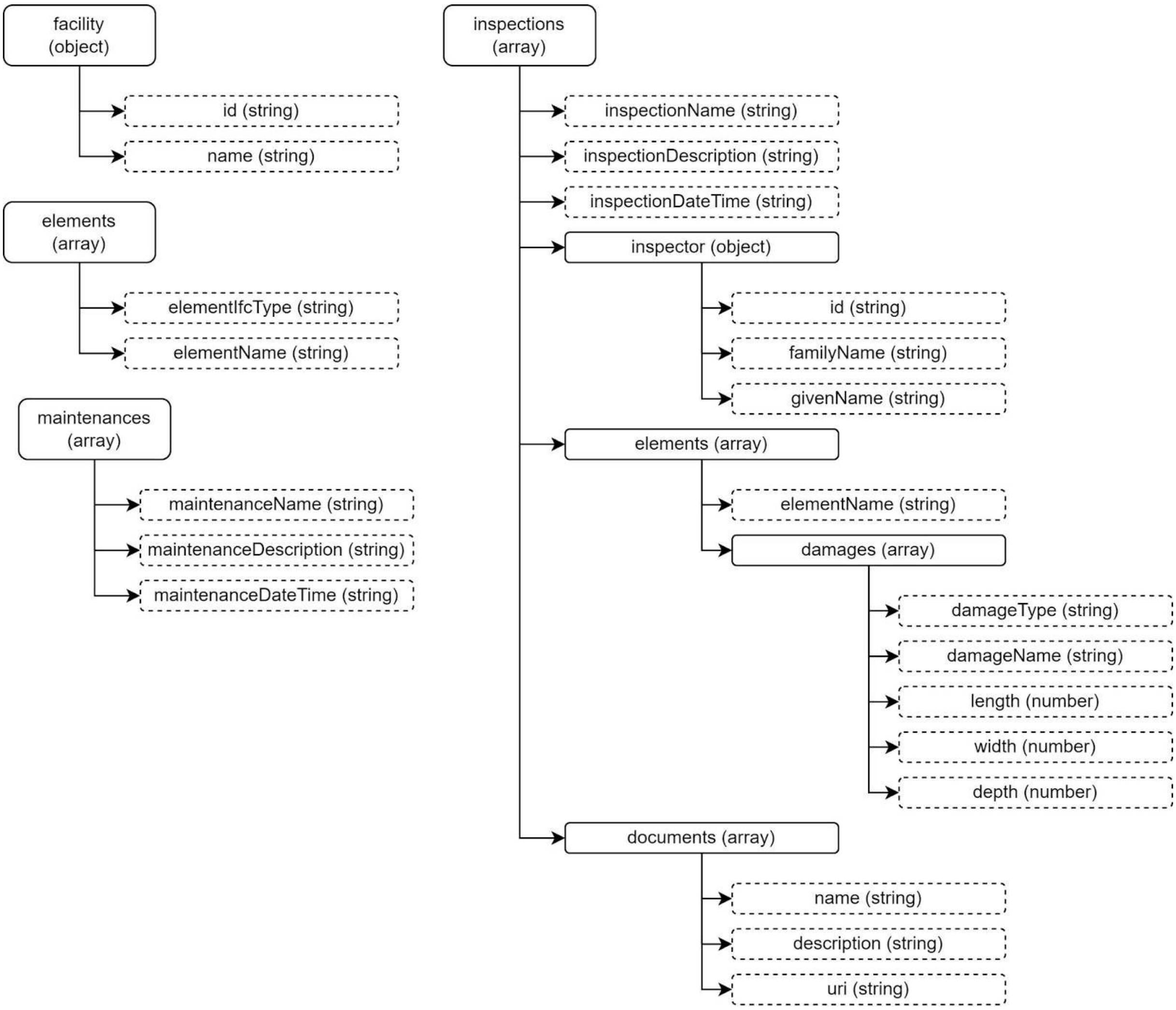


Figure 7. Input data in JSON structure.

The input data structured in the JSON was separated into facility, elements, inspections, and maintenance. The facility object stores basic information to identify the facility in the IFC file. The elements array carries the name and IFC type of all physical elements associated with the facility, damaged or not. The inspection array stores the inspection basic information, the inspector identification, the damaged elements and their damages, and any document generated during the inspection. The maintenance array has primary information for identifying the date and time of its execution.

When starting, the application verifies the input provided. If only the JSON file is passed as input, the JSON information is loaded, and the basic structure of the framework is created in an IFC 4.3.2.0 file instance using the IfcOpenShell library. The information of the base file structure includes the IfcOwnerHistory with the user, organization, application information, the project definition through IfcProject, the primary spatial structure decomposition, and the relationships between them.

After establishing the basic structure, the facility and its elements are instantiated based on the “facility” and “elements” objects from the JSON. Since the IFC file is generated from scratch, any element can be defined within the “elements” array. This approach was developed independently of the inspection damaged elements, allowing users to declare all facility elements without relying on inspection data. However, it is crucial to declare at least the damaged elements, as they are necessary to establish the relationship between elements and the associated damages. If these elements are not declared beforehand, they will be instantiated as generic IfcBuiltElement entities during the inspection processing.

On the other hand, in cases where the JSON and the IFC file are passed as input, besides the JSON data, the existing data from the IFC model is also loaded and used as the basis for the resulting file. Entities of interest, such as the project definition, the facility, or its physical elements, are stored in variables for future assignment. The only entity created at this point is a new owner history to keep track of any modification in the model. From this point forward, the approach for cases with or without an existing IFC model remains mostly the same.

The inspection instantiation starts with the information storage in the IfcTask entity that represents inspection as a whole. Then, the data of the responsible inspector is stored in the IfcPerson and IfcActor entities, added as complements of the original framework. The inspection is assigned to the IfcActor instance using the IfcRelAssignsToActor objectified relationship. The damage information was structured in the input JSON nested in the damaged elements to facilitate the implementation of their relationship. Therefore, for each damaged element of the inspection, the corresponding damages are instantiated in IfcSurfaceFeature instances and then are related to it. The element, already instantiated in both cases, is filtered and selected by the elementName property provided in the inspection data. The documents are also allocated in IfcDocumentReferences and associated with the inspection IfcTask instance.

In the damage representation, an extension of the framework and the IFC schema was made. As advised in the IfcSurfaceFeature documentation, a property set was used to store additional damage information and meet the implementation requirements. The additional information was represented as single-value properties using the IfcPropertySingleValue entity. Those properties were then grouped in a property set, defined by the IfcPropertySet entity, and were related to the damage instances using the IfcRelDefinesByProperties relationship. The damage properties created were composed of measure values needed to calculate the maintenance task quantities and status used to track the damage's current state.

A crucial aspect of the implementation was the damage processing across different inspections. If a damage occurrence was reported in only one inspection or was the most recent report of that occurrence, its status property was considered "active"; older damage occurrences preceding the "active" one was labeled "outdated". This convention was adopted in this implementation as a simplification to support the automation of the maintenance processing. The status evaluation and update were executed in every inspection instantiation, which was ordered based on the date and time of its execution. Then, when parsed, only the most recent and "active" occurrences of singular damage were automatically assigned to maintenance tasks.

Based on the "*maintenances*" object declared in the input data, the maintenance instantiation initially creates a facility level IfcTask that stores the basic maintenance information. Subsequently, the inspection data is parsed, assigning all the damage instances with the "active" status created in inspections with execution date and time prior to the maintenance execution to maintenance processing. In the maintenance processing, a parametric model automatically determines and instantiates the damage level maintenance tasks based on each damage type and its measures.

In the parametrical model, each damage level maintenance task instance was automatically decomposed into its correspondent activity level IfcTask instances, based on the premise that each damage type would derive a set of repair activities. After the activity level IfcTask instances are created, their quantities are calculated and stored in the corresponding IfcCostItem instances with the task unitary cost. After each instantiation, the relationships between instances are created according to the framework.

Similarly to the inspections, the damage status is also evaluated after any maintenance. In the current example, it was assumed that any damage reported prior to a maintenance intervention was repaired. Consequently, the damage status of all damage instances created in inspections before the maintenance is labeled “repaired”. In any posterior maintenance, new evaluations of “active” status damages will be performed, determining the damages to be repaired while disregarding the “repaired” damages. This simplified approach was adopted for this implementation and case study and can be freely adapted.

At the end of the application's workflow, the remaining relationships between the instantiated entities are created according to the framework structure. After the structure is completed and the IFC file has its final form, it is submitted through validation using the IfcOpenShell data validation module. After the validation, the IFC file created in the Python application is stored locally in an .ifc file and can be used independently from the application.

3.4. Validation of data exchange

The validity of the proposed schema was checked in two distinct steps of validation of the generated file. First, the file was automatically validated using the built-in IfcOpenShell validation module embedded into the application workflow. This validation generated logs with the errors caught in the file. However, as stated by the IfcOpenShell documentation, not all possible errors are caught by the validate function (ifcopenshell.validate - IfcOpenShell 0.7.11 documentation).

Then, the IFC file was validated using the official buildingSMART IFC Validation Service (https://validate.buildingsmart.org/), the utmost reference in IFC validation. The IFC Validation Service is a free, open-source online platform, developed and managed by buildingSMART International, for checking IFC files against the IFC standard. When IFC files are uploaded, their content is tested for conformity against four criteria: STEP syntax, IFC schema, normative IFC rules, and industry practices.

The first three criteria are based on defined normative rules and must be met for the IFC file to comply with the IFC standard (ISO 16739:1) and be considered valid. The STEP Physical File syntax verification analyses if the file structure obeys the ISO 10303-21 definitions, the international standard that specifies the STEP format syntax. The IFC schema verification evaluates if the formal propositions and rules, such as inverse attributes, attribute types, cardinalities, "where" rules, and function constraints defined in the EXPRESS language, are met. The normative IFC rules verification checks additional rules of the IFC specification, such as implementer agreements and informal propositions, which are not defined explicitly in EXPRESS language but are still mandated in the IFC specification.

The remaining criteria is based on non-normative evaluations. In the industry practices verification, the file is checked against common practices and sensible defaults from the industry. Any issue found in the industry practices verification does not invalidate the IFC file but generates a warning highlighting which part of the content should be revised and, where needed, adapted to industry practices.

When uploading a file, the STEP syntax is the first criterion verified. In case of disapproval, the verification is interrupted and finished since an invalid syntax impedes the application from correctly reading and evaluating the file. In the case of a compliant syntax, the remaining criteria are evaluated. Any IFC schema and normative IFC rules error will invalidate the file, indicating that its content contradicts propositions of the IFC specification, the reference that ensures the IFC standardization. The approval of these three criteria ensures that the file is valid from both STEP syntax and IFC specification viewpoints. Warnings found in the industry practices verification will only complement the verification, indicating points for improvement.

4. Framework application

Two practical applications with different approaches were structured to evaluate the framework, each focusing on specific aspects. First, a case study that creates an IFC file from scratch was created, emulating cases where 3D facility models are unavailable. Although populated with the essential facility information and the entire framework, this file did not contain any spatial representation and, therefore, did not have a 3D visualization available. However, considering the IFC file creation only for this purpose, without any third-party data, it ensures that the validation via the buildingSMART Validation Service will essentially evaluate the proposed framework structure.

In the second case study, the workflow considered the availability of a facility 3D model, aiming to replicate a typical BIM workflow. From a starting as-built 3D model, the inspection and maintenance data, structured as idealized in the proposed framework, were incorporated into the existing IFC file. Congruently with the approach, a 3D representation of the damage was also included, ensuring its visualization. Then, all the information was evaluated in a wide range of IFC-compatible software. This approach aimed to assess the practical application of the framework and analyse the performance of typical software in correctly interpreting and presenting the information stored in the IFC file.

As follows, the methodology and results of the two case study approaches were detailed:

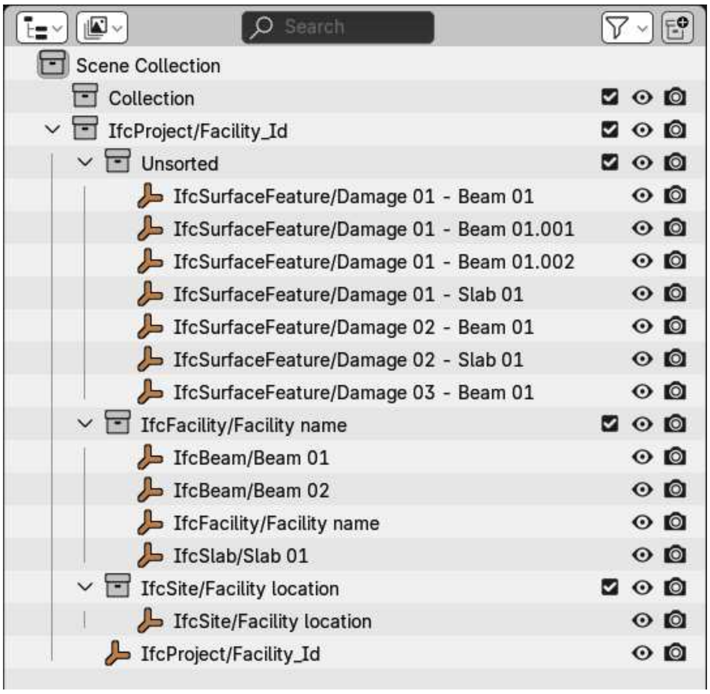
4.1. First case study – validation of the framework

In the first approach, a generic case study was designed to create an IFC file based on the proposed structure and its implementation. Since the main focus of this approach was to evaluate the generated IFC file qualitatively, both the input data and the implementation's parametric processing were kept general, with generic damages and maintenance tasks. However, it was ensured that each framework entity was employed to attest its validity. The input was structured to explore the implementation capabilities, such as the damage status update. The graphical visualization of the information generated in the IFC file was conducted using the open-source software Blender, along with the Bonsai (formerly blenderBIM) extension.

The case study structure was compatible with the simplest scenario where the framework could be applied. In such a scenario, it was considered that the facility management database would have only basic damage information without any pre-existing model of the damage or even of the facility itself. With this approach, the case study aims to evaluate the framework's applicability in an information-restricted context, exploring its capacity to build a fully functional IFC facility maintenance model from scratch.

The case study was structured in two stages. In the first stage, no maintenance processes were included in the input data to assess the damage status during the inspection period. Subsequently, in the second stage, maintenance will occur after all the declared inspections, indicating that all the active damages should be repaired. The difference in the input data from these two cases will be just the absence of maintenance in the "*maintenances*" JSON object in the first case. The second case, which comprises all the structures proposed in the framework, will be validated. In both stages, three elements were defined in the input data, and two were associated with damage in the inspection instantiation. Three inspections were declared, and the dimensions of one of the damage instances increased progressively throughout the inspections. An external document reference was included in the first inspection.

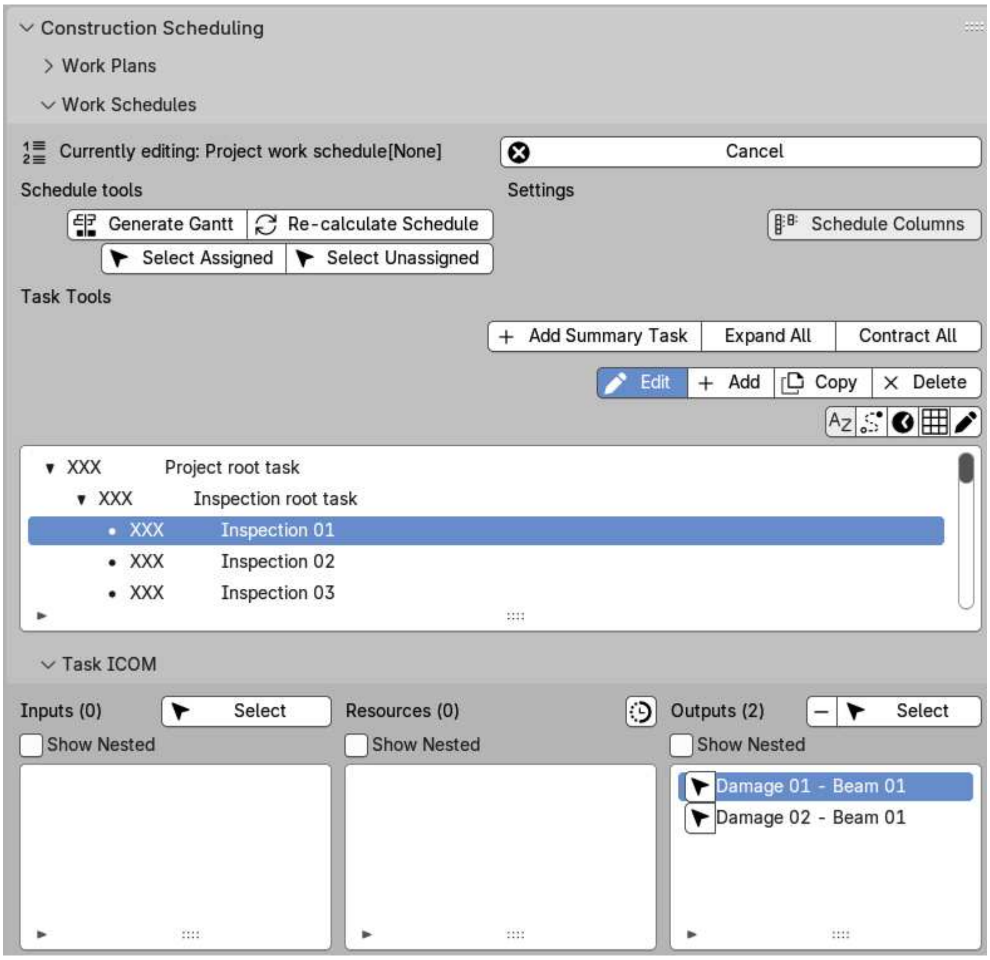
After importing the IFC file from the first stage in Bonsai, the element tree already provides an information visualization of all the physical entities instantiated, even without a graphical 3D representation. In Figure 8, the entities that represent the project, facility site, facility, facility elements, and damages were correctly identified. The damages, separated by the element, are all represented independently from their status. Particularly in the damage named "Damage 01 - Beam 01", which instances have the same name across the three inspections, the Bonsai automatically displayed unique names in the tree visualization. However, this differentiation is only visual and does not interfere with the IFC file.



- Scene Collection
  - Collection
  - IfcProject/Facility_Id
    - Unsorted
      - IfcSurfaceFeature/Damage 01 - Beam 01
      - IfcSurfaceFeature/Damage 01 - Beam 01.001
      - IfcSurfaceFeature/Damage 01 - Beam 01.002
      - IfcSurfaceFeature/Damage 01 - Slab 01
      - IfcSurfaceFeature/Damage 02 - Beam 01
      - IfcSurfaceFeature/Damage 02 - Slab 01
      - IfcSurfaceFeature/Damage 03 - Beam 01
    - IfcFacility/Facility name
      - IfcBeam/Beam 01
      - IfcBeam/Beam 02
      - IfcFacility/Facility name
      - IfcSlab/Slab 01
    - IfcSite/Facility location
      - IfcSite/Facility location
    - IfcProject/Facility_Id

Figure 8. Tree representation of the spatial structure decomposition in Bonsai.

The IFC process decompositions can be visualized in a tree representation inside the “Costing and Scheduling” section of the Bonsai extension. The first stage of the case study (Figure 9) exhibits only the inspection decompositions, as maintenance instances were included only in the second stage. This representation clarifies the hierarchical nesting decomposition that originates in the project root task, which nests the inspection root task that, in turn, comprises all the individual inspections executed in the project. The window, presented in the example of Figure 9, also shows the relationships between the processes and other objects. When selecting the “Inspection 01” inspection process, the two object outputs highlighted, “Damage 01 - Beam 01” and “Damage 02 - Beam 01”, are the IfcSurfaceFeature instances that originated in the inspection.



Currently editing: Project work schedule[None]

XXX	Project root task
XXX	Inspection root task
XXX	Inspection 01
XXX	Inspection 02
XXX	Inspection 03

Damage 01 - Beam 01
Damage 02 - Beam 01

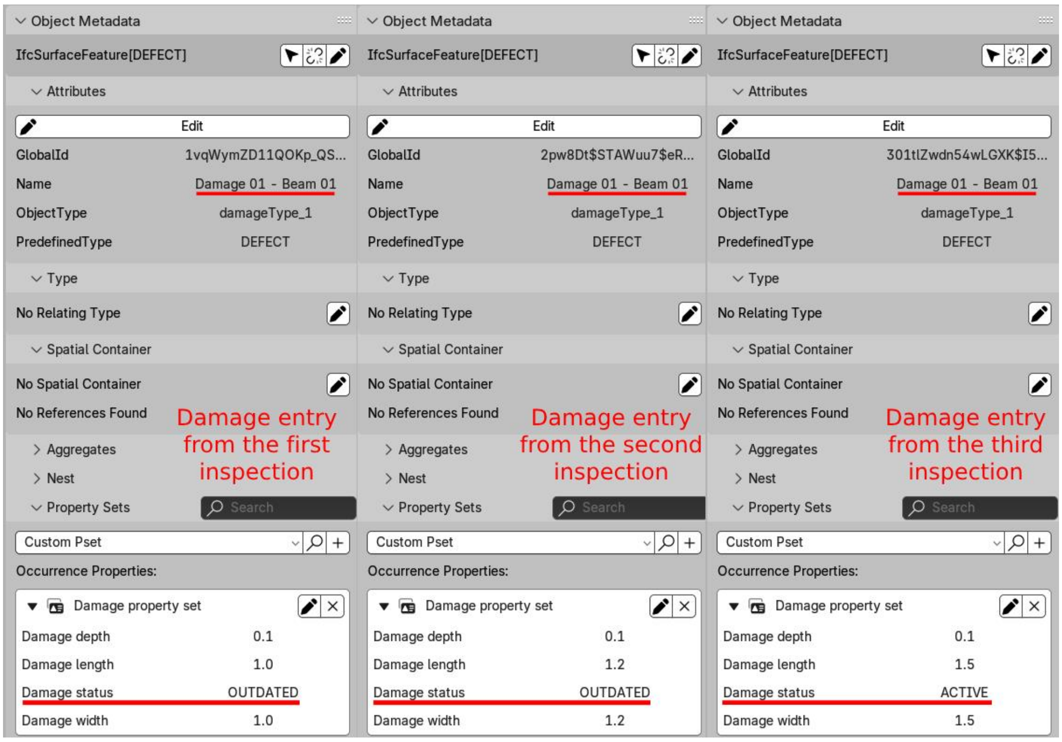
Figure 9. Task decomposition visualization in Bonsai.

For a deeper understanding of the IFC structure of an inspection, the section of the IFC file generated on the first stage of the case study comprising “Inspection 01” is represented in Figure 10. In this section file, the inspection task, the inspector, the external document, the damages, and the properties of the damages are instantiated. Moreover, the relationships between the instances are created.

```
...
#25=IFCBEAM('0iLsEGJzjCMPGLQMY1IIj$',#6,'Beam 01',$,$,$,$,$,$);
...
#29=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-01-10T08:00:00',$,$,$);
#30=IFCTASK('01aUj6WFD0HgPxJEblMu9T',#6,'Inspection 01','Description of the
inspection 01',$,$,$,$,$,.F.,$,#29,.INSPECTION.);
#31=IFCPERSON('Inspector_01_Id','Inspector 01 Family Name','Inspector 01 Given
Name',$,$,$,$,$);
#32=IFCACTOR('275tOiLhP3aPF1v_IOc0iF',#6,'Responsible Inspector','Inspector
responsible for the inspection',$,#31);
#33=IFCRELASSIGNSTOACTOR('3mODW3se5Fn97zNzSqLuoN',#6,'Inspector
assignment','Assignment of an inspector to an inspection',(#30),$,#32,$);
#34=IFCDOCUMENTREFERENCE('https://standards.buildingsmart.org/IFC/RELEASE/
IFC4_3/HTML/lexical/IfcDocumentReference.htm',$,'Document name','Document
description',$);
#35=IFCRELASSOCIATESDOCUMENT('0V8zjDZvr0POjoXouekXSj',#6,'Document
association','Association of a document to the inspection',(#30),#34);
#36=IFCSURFACEFEATURE('3ZooB06Az4RP4sI4dtyYX7',#6,'Damage 01 - Beam
01',$,'damageType_1',$,$,$,.DEFECT.);
#37=IFCPROPERTYSINGLEVALUE('Damage length',$,IFCLENGTHMEASURE(1.),$);
#38=IFCPROPERTYSINGLEVALUE('Damage width',$,IFCLENGTHMEASURE(1.),$);
#39=IFCPROPERTYSINGLEVALUE('Damage depth',$,IFCLENGTHMEASURE(0.1),$);
#40=IFCPROPERTYSINGLEVALUE('Damage status',$,IFCLABEL('OUTDATED'),$);
#41=IFCPROPERTYSET('2iQTYX_zPBLOYyTJtgjZMr',#6,'Damage property set','Property
set of additional information of the damages',(#37,#38,#39,#40));
#42=IFCRELDEFINESBYPROPERTIES('34dMr_zir02h3$jInmlYWL',#6,'Damage pset
relationship','Assignment of a property set to a damage',(#36),#41);
#43=IFCRELASSIGNSTOPRODUCT('1n$dNg8E9DlR6PI$JxLNQW',#6,'Damage
origin','Relationship from the inspection that originated the damage instance (as a
product)',(#30),$,#36);
#44=IFCSURFACEFEATURE('0WOgTp6359seQv1F8_e0O2',#6,'Damage 02 - Beam
01',$,'damageType_2',$,$,$,.DEFECT.);
#45=IFCPROPERTYSINGLEVALUE('Damage length',$,IFCLENGTHMEASURE(1.),$);
#46=IFCPROPERTYSINGLEVALUE('Damage width',$,IFCLENGTHMEASURE(0.5),$);
#47=IFCPROPERTYSINGLEVALUE('Damage depth',$,IFCLENGTHMEASURE(0.05),$);
#48=IFCPROPERTYSINGLEVALUE('Damage status',$,IFCLABEL('ACTIVE'),$);
#49=IFCPROPERTYSET('1a6oBYto10Q9JH1ey7FxrY',#6,'Damage property
set','Property set of additional information of the damages',(#45,#46,#47,#48));
#50=IFCRELDEFINESBYPROPERTIES('3X3pXOlG15EuixWM8mgflD',#6,'Damage pset
relationship','Assignment of a property set to a damage',(#44),#49);
#51=IFCRELASSIGNSTOPRODUCT('22gmJYV1bCM96XoRH5vmb9',#6,'Damage
origin','Relationship from the inspection that originated the damage instance (as a
product)',(#30),$,#44);
#52=IFCRELADHERESTOELEMENT('0c2oYY5Vf4VR8OBQZZrYgQ',#6,'Damage
aggregation','Aggregation between the damage and the damaged
element.',#25,(#36,#44));
...
```

Figure 10. Section of the IFC file exemplifying the inspection and damage instantiation.

In the raw IFC file section of Figure 10, the property set and the properties proposed for the damages were highlighted. Those properties store the damage dimensions and the damage status. The first damage, named "Damage 01 - Beam 01", has the 'OUTDATED' status, indicating that a newer damage instance with the same name was reported in a newer inspection. This damage was reported in all three inspections, with only the most recent instance classified as 'ACTIVE', as illustrated in the "Object Information" window of Bonsai for the three damage instances with the same name, as illustrated in Figure 11. As seen in this comparison, the dimensions of the damage grew progressively, with only the more recent data being used to calculate services, quantities, and costs. Ultimately, the inspections reported seven damage entries: two outdated and five active.



GlobalId	1vqWymZD11QOKp_QS...	2pw8Dt$STAWuu7$eR...	301tlZwdn54wLGXK$I5...
Name	Damage 01 - Beam 01	Damage 01 - Beam 01	Damage 01 - Beam 01
ObjectType	damageType_1	damageType_1	damageType_1
PredefinedType	DEFECT	DEFECT	DEFECT
Damage depth	0.1	0.1	0.1
Damage length	1.0	1.2	1.5
Damage status	OUTDATED	OUTDATED	ACTIVE
Damage width	1.0	1.2	1.5

Damage entry from the first inspection

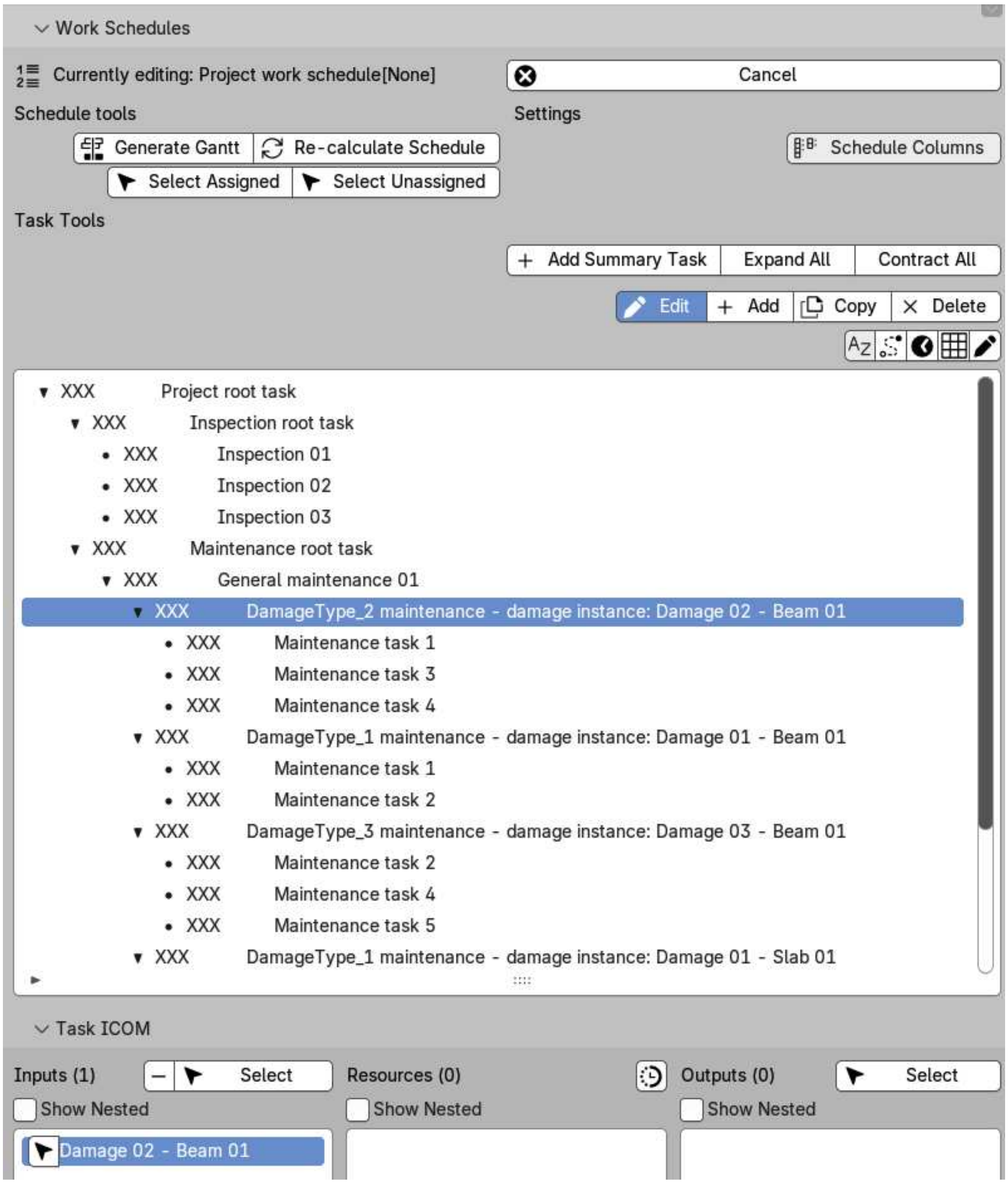
Damage entry from the second inspection

Damage entry from the third inspection

Figure 11. Damage status update across different inspections.

In the second stage of the case study, maintenance was added to the input data. Since no physical object was added, the object tree from Figure 8 remained unchanged. In contrast, the “Cost and Scheduling” window had the addition of all the maintenance processes and costs, as shown in Figure 12. In the second stage, the process nesting also has a maintenance summary task that includes all the facility level maintenance, represented in this example by the “General maintenance 01” instance. In turn, the “General maintenance 01” nests all the damage level maintenance tasks created for each active damage.

To facilitate the visualization, the name of damage level maintenance tasks also included a reference to the damage instance’ name that it intends to repair. However, this relationship can be visualized directly in Bonsai in the “inputs” of the process. For example, in Figure 12, the “Damage 02 - Beam 01” is highlighted when the first damage level maintenance task is selected.



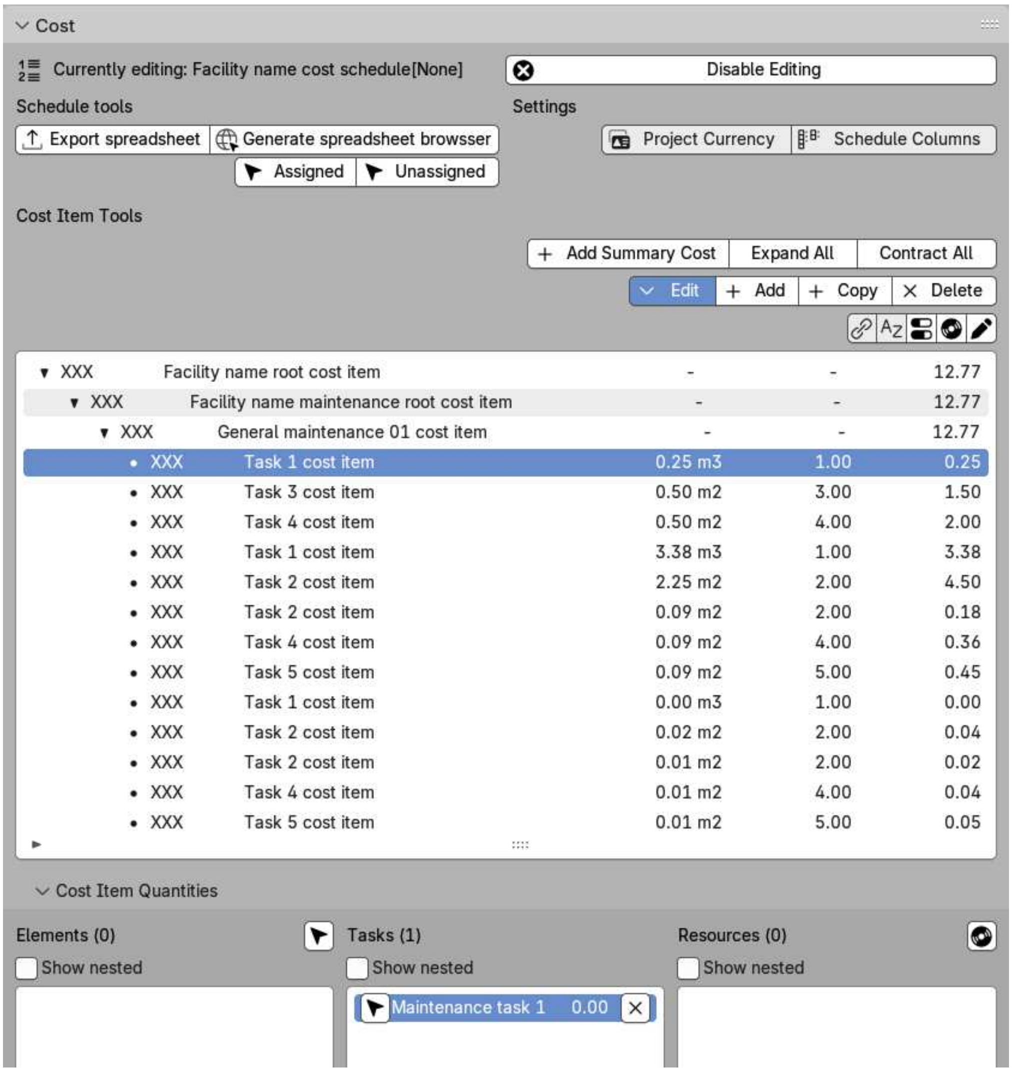
Currently editing: Project work schedule[None]

- XXX Project root task
  - XXX Inspection root task
    - XXX Inspection 01
    - XXX Inspection 02
    - XXX Inspection 03
  - XXX Maintenance root task
    - XXX General maintenance 01
      - XXX DamageType_2 maintenance - damage instance: Damage 02 - Beam 01
        - XXX Maintenance task 1
        - XXX Maintenance task 3
        - XXX Maintenance task 4
      - XXX DamageType_1 maintenance - damage instance: Damage 01 - Beam 01
        - XXX Maintenance task 1
        - XXX Maintenance task 2
      - XXX DamageType_3 maintenance - damage instance: Damage 03 - Beam 01
        - XXX Maintenance task 2
        - XXX Maintenance task 4
        - XXX Maintenance task 5
      - XXX DamageType_1 maintenance - damage instance: Damage 01 - Slab 01

Damage 02 - Beam 01

Figure 12. Task decomposition visualization including the maintenance tasks.

The maintenance process decomposition shown in Figure 12 also illustrates the activity level maintenance tasks. Those tasks were automatically assigned based on the damage type, simulating a defined service package for each damage. Moreover, for each activity automatically created, a cost item was also derived, including the activity quantity and unitary cost. In the “Cost” window in Figure 13, the cost item decomposition of the project is represented, with each cost item derived from the activity IfcTask instances. When selecting a cost item, the corresponding task is shown in the “Tasks” window. The nested cost items can represent the total cost from each maintenance occurrence, from all maintenance, or even from all the processes in the project if declared. In Figure 14, a section of the .ifc file containing maintenance tasks and cost items exemplifies how these entities are created and related.



Currently editing: Facility name cost schedule[None]

▾ XXX	Facility name root cost item	-	-	12.77
▾ XXX	Facility name maintenance root cost item	-	-	12.77
▾ XXX	General maintenance 01 cost item	-	-	12.77
• XXX	Task 1 cost item	0.25 m3	1.00	0.25
• XXX	Task 3 cost item	0.50 m2	3.00	1.50
• XXX	Task 4 cost item	0.50 m2	4.00	2.00
• XXX	Task 1 cost item	3.38 m3	1.00	3.38
• XXX	Task 2 cost item	2.25 m2	2.00	4.50
• XXX	Task 2 cost item	0.09 m2	2.00	0.18
• XXX	Task 4 cost item	0.09 m2	4.00	0.36
• XXX	Task 5 cost item	0.09 m2	5.00	0.45
• XXX	Task 1 cost item	0.00 m3	1.00	0.00
• XXX	Task 2 cost item	0.02 m2	2.00	0.04
• XXX	Task 2 cost item	0.01 m2	2.00	0.02
• XXX	Task 4 cost item	0.01 m2	4.00	0.04
• XXX	Task 5 cost item	0.01 m2	5.00	0.05

Elements (0)

Tasks (1)

Maintenance task 1 0.00

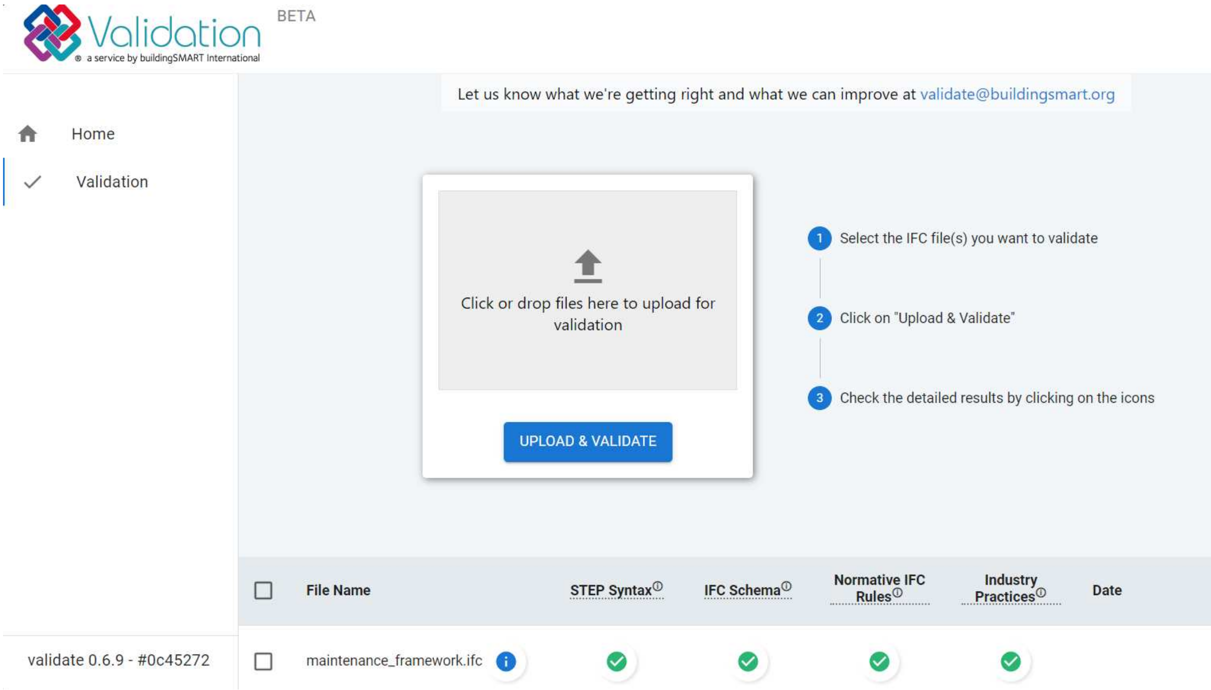
Resources (0)

Figure 13. Cost item decomposition visualization in Bonsai.

```
...
#105=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2024-01-20T08:00:00',$,$,$);
#106=IFCTASK('2UV0WbQgj0gPJqkDsz32NA',#6,'General maintenance 01','Maintenance of
all active damages in the
facility','facilityLevelMaintenance',$,$,$,$,.F.,$,#105,.MAINTENANCE.);
#107=IFCTASK('1JDC4vA15CuQQ0gh5FGIHD',#6,'DamageType_2 maintenance - damage
instance: Damage 02 - Beam 01','General maintenance for damages of type 2, applied in
the damage Damage 02 - Beam 01
instance.','damageLevelMaintenance',$,$,$,$,.F.,$,$,.MAINTENANCE.);
#108=IFCRELASSIGNSTOPROCESS('06EboHr25AbBsVAr8utGpq',#6,'Maintenance process
relationship','Relationship of the damage and the maintenance process',(#44),$,#107,$);
#109=IFCTASK('1wPB0kff54kQy9TgyMR_9O',#6,'Maintenance task 1','Maintenance task of
type 1','activityLevelMaintenance',$,$,$,$,.F.,$,$,.MAINTENANCE.);
#110=IFCCOSTVALUE('Task 1 unitary cost','Unitary cost of the maintenance task of type
1',IFCMONETARYMEASURE(1.),$,$,$,'Maintenance',$,$,$);
#111=IFCQUANTITYVOLUME('Task volume','Quantity, in volume, of the task to be
performed',$,0.25,$);
#112=IFCCOSTITEM('1ZwOq5CrPB8AFQqBuFRcE_',#6,'Task 1 cost item','Cost item entity
with the quantity and unitary cost of the maintenance task of type 1',$,$,$,(#110),(#111));
#113=IFCRELASSIGNSTOCONTROL('27$0en2jv08hmnwIVtxRMp',#6,'Maintenance task
quantities and cost relationship','Assignment of a cost item to a maintenance
task.',(#109),$,#112);
#114=IFCTASK('1D_wkczT1DePOuA$i4stbp',#6,'Maintenance task 3','Maintenance task of
type 3','activityLevelMaintenance',$,$,$,$,.F.,$,$,.MAINTENANCE.);
#115=IFCCOSTVALUE('Task 3 unitary cost','Unitary cost of the maintenance task of type
3',IFCMONETARYMEASURE(3.),$,$,$,'Maintenance',$,$,$);
#116=IFCQUANTITYAREA('Task area','Quantity, in area, of the task to be
performed',$,0.5,$);
#117=IFCCOSTITEM('3il9feVeDCUxpaQ5qCq__z',#6,'Task 3 cost item','Cost item entity with
the quantity and unitary cost of the maintenance task of type 3',$,$,$,(#115),(#116));
#118=IFCRELASSIGNSTOCONTROL('0f3gpvbWTDhRGTqS18MVoK',#6,'Maintenance task
quantities and cost relationship','Assignment of a cost item to a maintenance
task.',(#114),$,#117);
#119=IFCTASK('0OjfCBOr97VRVSHsW94KLd',#6,'Maintenance task 4','Maintenance task of
type 4','activityLevelMaintenance',$,$,$,$,.F.,$,$,.MAINTENANCE.);
#120=IFCCOSTVALUE('Task 4 unitary cost','Unitary cost of the maintenance task of type
4',IFCMONETARYMEASURE(4.),$,$,$,'Maintenance',$,$,$);
#121=IFCQUANTITYAREA('Task area','Quantity, in area, of the task to be
performed',$,0.5,$);
#122=IFCCOSTITEM('1r5MIbW0H3U9Hq$O28Aska',#6,'Task 4 cost item','Cost item entity
with the quantity and unitary cost of the maintenance task of type 4',$,$,$,(#120),(#121));
#123=IFCRELASSIGNSTOCONTROL('36D12iIDr6vgRISclkkryv',#6,'Maintenance task
quantities and cost relationship','Assignment of a cost item to a maintenance
task.',(#119),$,#122);
#124=IFCRELNESTS('1GU75BUavAgwXKig4YgVqz',#6,'Maintenance tasks nesting','Nesting
of all the tasks needed to perform the maintenance of the given
damage.',#107,(#109,#114,#119));
...
```

Figure 14. Section of the IFC file exemplifying the maintenance tasks and cost item instantiation.

After checking all the displayed data, the .ifc file created for the second stage of the case study, containing all the structures proposed in the framework, was validated in the IFC Validation Service from buildingSMART. The maintenance_framework.ifc file was approved in all the categories evaluated (Figure 15).



Let us know what we're getting right and what we can improve at validate@buildingsmart.org

1. Select the IFC file(s) you want to validate
2. Click on "Upload & Validate"
3. Check the detailed results by clicking on the icons

☐	File Name	STEP Syntax	IFC Schema	Normative IFC Rules	Industry Practices	Date
☐	maintenance_framework.ifc	✓	✓	✓	✓	

Figure 15. Validation results of the generated file in buildingSMART IFC Validation Service.

4.2. Second case study – applicability of the framework

In the second approach, the case study structuration aimed to apply actual data from an inspection database in a facility model based on the proposed framework. The facility selected for the case study was the Coimbra I bridge from Minas Gerais, Brazil. The bridge was chosen due to its as-built BIM model existence, created from a laser-scanning point cloud. The bridge was modelled on the commercial software Autodesk Revit and was available in its proprietary file format.

The inspection data was ceded by the Departamento Nacional de Infraestrutura de Transportes (DNIT), the Brazilian federal department responsible for transportation infrastructure management. The DNIT bridge database stores information relative to all bridges and viaducts of federal highways managed, including the data from the Coimbra I bridge. The inspection data stored in the DNIT database comprises extensive information, including damage data, condition state, structural insufficiencies, photographic records, and others. For this case study, the data of interest was the damage instances' structured information, damaged elements, and damage extensions. The inspection data acquired and employed in the study case was structured as shown in Table 2:

Table 2. Actual inspection data acquired from the DNIT database and applied in the second case study.

Instance	Damage type	Extension	Unit	Damaged element
1	Crack	1.00	m	Slab - 518725
2	Water leakage	0.25	m²	
3	Efflorescence	0.20	m²	
4	Fire action	0.40	m²	
5	Fire action	0.20	m²	Beam 35 x 170 cm - 461753
6	Efflorescence	0.05	m²	Beam 20 x 150 cm - 529766
7	Fire action	0.30	m²	
8	Efflorescence	0.05	m²	Beam 20 x 115 cm - 525442
9	Concrete spalling	0.05	m²	Column 30 x 45 cm - 573901
10	Damaged concrete pavement	10.00	m²	Pavement - 557027

From the original Autodesk Revit proprietary format, the bridge model was exported to IFC STEP files to be processed by the Python script. To this objective, the IFC4 version, which presented better compatibility in preliminary tests, and the IFC4.3 ADD2 version, compatible with the version in which the framework was idealized, were employed. With models based on different IFC schemas, the impact of IFC versions on the information exchange could also be assessed. The differences between the two versions that impacted the original framework structure were the absence of the IfcRelAdheresToElement relationship, replaced by IfcRelAggregates, the mandatory usage of IfcBuilding as the only facility available, and the lack of some entity predefined types, such as “INSPECTION” for IfcTask and “DEFECT” for IfcSurfaceFeature.

When applying the script to the original IFC file, the framework entities that already existed in the file remained unchanged. Integrating these entities, such as the project, the facility, its physical elements, and the new inspection and maintenance data, was made through relationships that do not modify the existing file structure. After reading the data from the IFC file, all the data from Table 2, loaded into the Python application through the JSON input file, was incorporated into the model, following the workflow described in Figure 6. Each damage instance was graphically represented with a generic cubic geometry, assigning the red colour to its surface to facilitate its visualization, as illustrated in Figure 16.

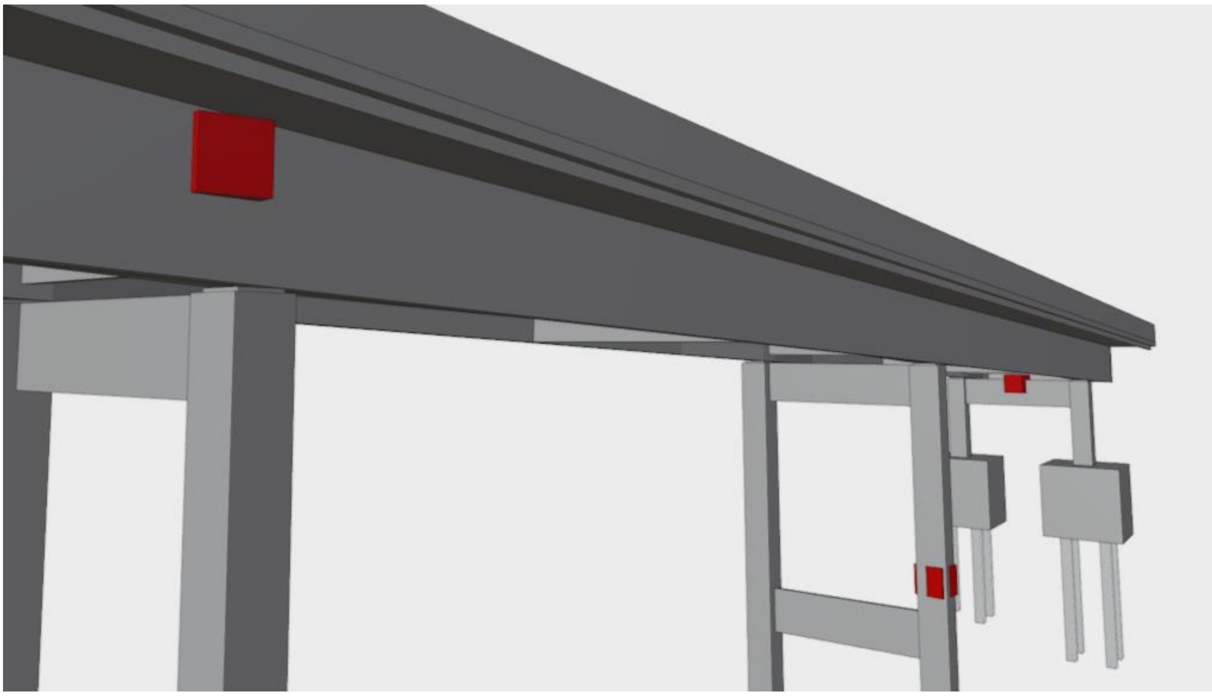


Figure 16. Generic damage geometrical representation identified by red cubes located in the damaged element's centroid.

As in the first study case, parametric relationships between the inspection damage types and their typical maintenance services were established to support the workflow. Based on these relationships, each damage instance will derive a set of related maintenance services, and each maintenance service will be associated with its unitary and total costs, as idealized in the framework structure. At the end of the scripted process, the resulting file contained all the original information, including the damage representation, the inspection and maintenance process instances, and the costs related to the maintenance tasks.

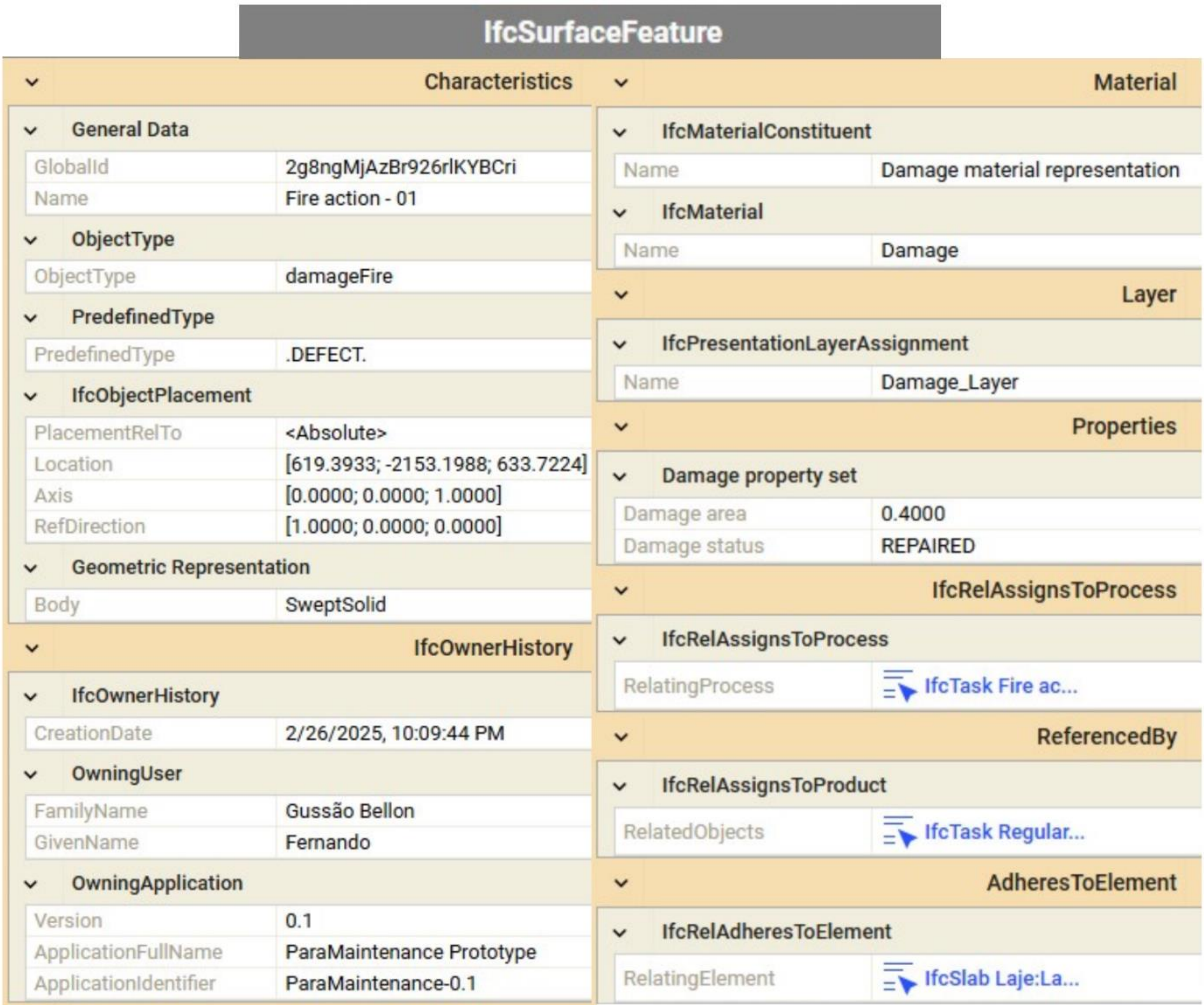
For a broader assessment, the resulting IFC file was imported and visualized in a wide range of IFC-compatible software, commercial and open-source. The evaluation included known software of the AEC industry to emulate a typical workflow of information exchange. We prioritized software focused on budgeting and planning, considering their higher probability of importing and interpreting correctly the process and cost IFC entities. In each software, the information evaluated according to its correct interpretation and visualization included the tridimensional model of the facility, the geometrical IfcSurfaceFeature damage representation, the aggregation relationship between damages and damaged elements, the damage data (type, extension, and status), the relationships of assignment of damages to maintenance, the maintenance processes, and the maintenance costs. The evaluations of the resulting IFC4 and IFC4.3 ADD2 files are summarized in Table 3:

Table 3. Comparison of the evaluation of the framework information interpreted and displayed in different software using IFC4 and IFC4.3 models.

	Evaluated software															
	BimCollab ZOOM		**Bonsai**		**KITModel Viewer**		**Navisworks Manage**		**Primus**		**Solibri Anywhere**		**Trimble Connect**		**usBIM browser**	
IFC version	4	4.3	4	4.3	4	4.3	4	4.3	4	4.3	4	4.3	4	4.3	4	4.3
Facility model	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Damage 3D representation	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✗	✓	✓
Relationship between damages and elements	✓	✗	✓	✓	✓	✓	✓	✗	✓	✗	✓	✗	✓	✗	✓	✓
Damage information	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✗	✓	✓
Relationships between damages and maintenances	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓
Maintenance processes representation	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗*	✗*
Costs representation	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗*	✗*

The Navisworks Manage and the Trimble Connect software have successfully interpreted and displayed the information from the facility, the damage representation, its relationship with the damaged element, and its properties and property sets when evaluating the model based on IFC4. However, when importing the IFC4.3 model, only the facility was correctly recognized. No reference to any other framework entity was found in the interactive software interface. While showing the same results as the previous software when assessing the IFC4 model, BimCollab ZOOM, ACCA Primus, and Solibri Anywhere showed better compatibility with the IFC4.3-based model. The geometrical representation of the damage and its properties were correctly interpreted and displayed in the software interface. However, none of the software recognized the IfcRelAdheresToElement objectified aggregation relationship, considering the IfcSurfaceFeature damage instances as elements apart from the facility. The remaining framework entities were also not recognized.

The ACCA usBIM.browser software showed equal compatibility with IFC4 and IFC4.3 versions of the model generated. In addition to the correct interpretation of the model, the damage representation and properties, and the damage decomposition relationship, it also displayed the inverse relationships of physical entities within the model. This made it possible to verify the relationships between damage instances, their originating inspection process, and the damage-level maintenance tasks, as shown in Figure 17. Although visible and recognized, these process data were unavailable for direct visualization in version 3.3.5, employed in this evaluation. The software has an additional functionality focused on planning and costs, usBIM.gantt, that demanded a subscription and could not be verified.



IfcSurfaceFeature

Characteristics

General Data

GlobalId	2g8ngMjAzBr926rlKYBCri
Name	Fire action - 01

ObjectType

ObjectType	damageFire

PredefinedType

PredefinedType	.DEFECT.

IfcObjectPlacement

PlacementRelTo	<Absolute>
Location	[619.3933; -2153.1988; 633.7224]
Axis	[0.0000; 0.0000; 1.0000]
RefDirection	[1.0000; 0.0000; 0.0000]

Geometric Representation

Body	SweptSolid

IfcOwnerHistory

IfcOwnerHistory

CreationDate	2/26/2025, 10:09:44 PM

OwningUser

FamilyName	Gussão Bellon
GivenName	Fernando

OwningApplication

Version	0.1
ApplicationFullName	ParaMaintenance Prototype
ApplicationIdentifier	ParaMaintenance-0.1

Material

IfcMaterialConstituent

Name	Damage material representation

IfcMaterial

Name	Damage

Layer

IfcPresentationLayerAssignment

Name	Damage_Layer

Properties

Damage property set

Damage area	0.4000
Damage status	REPAIRED

IfcRelAssignsToProcess

IfcRelAssignsToProcess

RelatingProcess	IfcTask Fire ac...

ReferencedBy

IfcRelAssignsToProduct

RelatedObjects	IfcTask Regular...

AdheresToElement

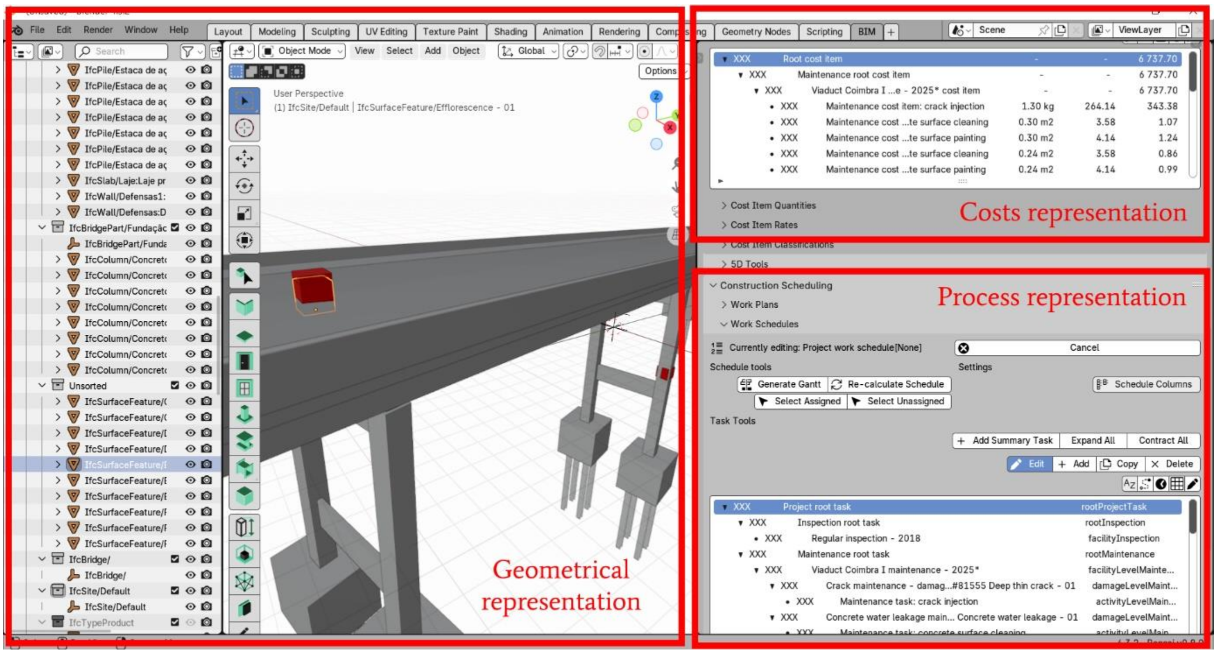
IfcRelAdheresToElement

RelatingElement	IfcSlab Laje:La...

Figure 17. Visualization of the damage properties, property sets and inverse relationships in ACCA usBIM.browser.

The Bonsai add-on for Blender and the KITModelViewer showed maximum compatibility with the resulting IFC file, enabling the visualization of the geometrical representation, processes, and cost data in both IFC4 and IFC4.3 versions. The Bonsai add-on, as already presented in the previous study case, successfully imported and interpreted the information inserted in the model, representing both processes and costs in the user interface. The only exception was the IfcRelAdheresToElement that, although correctly identified, was not considered a type of aggregation, which resulted in representing damages as “Unsorted” elements. Further information on the instance, such as their relationships, could be inspected in the debug panel.

A general visualization of the bridge model with the damage representation, along with the processes and costs in Bonsai, is shown in Figure 18.



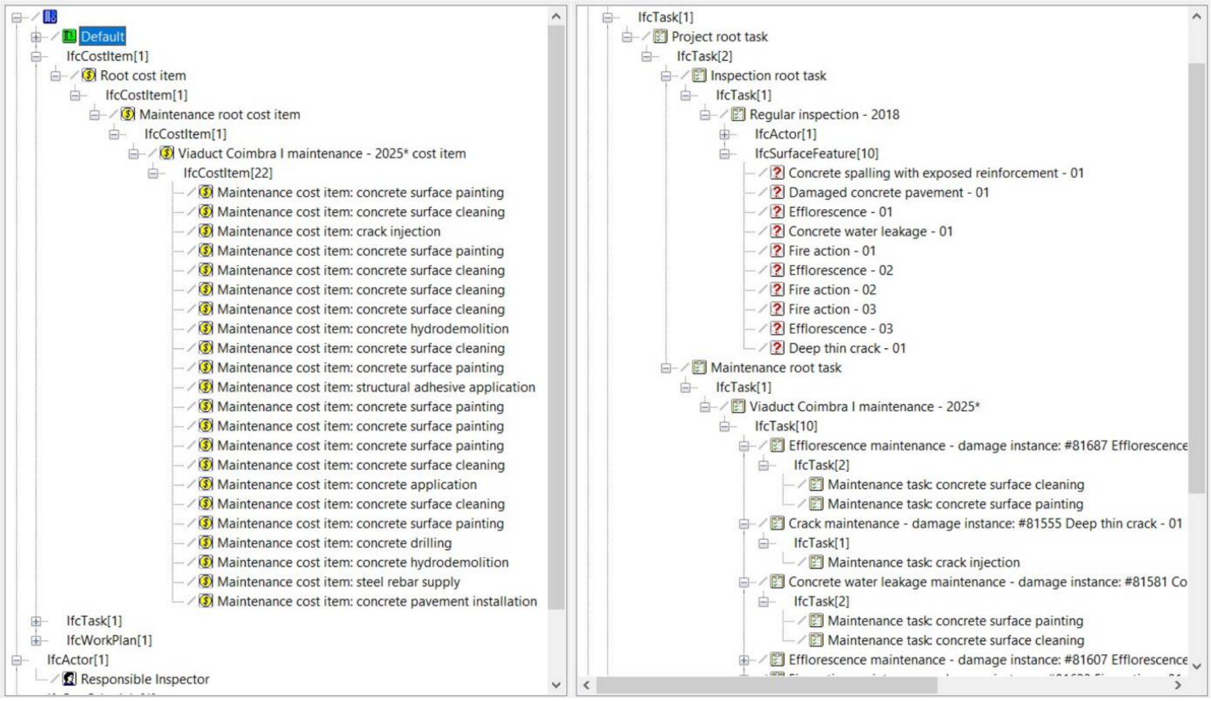
Currently editing: Project work schedule[None]

▾ XXX	Root cost item	-	-	6 737.70
▾ XXX	Maintenance root cost item	-	-	6 737.70
▾ XXX	Viaduct Coimbra I ...e - 2025* cost item	-	-	6 737.70
• XXX	Maintenance cost item: crack injection	1.30 kg	264.14	343.38
• XXX	Maintenance cost ...te surface cleaning	0.30 m2	3.58	1.07
• XXX	Maintenance cost ...te surface painting	0.30 m2	4.14	1.24
• XXX	Maintenance cost ...te surface cleaning	0.24 m2	3.58	0.86
• XXX	Maintenance cost ...te surface painting	0.24 m2	4.14	0.99

▾ XXX	Project root task	rootProjectTask
▾ XXX	Inspection root task	rootInspection
• XXX	Regular inspection - 2018	facilityInspection
▾ XXX	Maintenance root task	rootMaintenance
▾ XXX	Viaduct Coimbra I maintenance - 2025*	facilityLevelMainte...
▾ XXX	Crack maintenance - damag...#81555 Deep thin crack - 01	damageLevelMaint...
• XXX	Maintenance task: crack injection	activityLevelMain...
▾ XXX	Concrete water leakage main... Concrete water leakage - 01	damageLevelMaint...

Figure 18. Visualization of the damage geometric representation, maintenance costs, and inspection and maintenance processes in Blender Bonsai.

The KITModelViewer, freeware software provided by the Karlsruhe Institute of Technology, also presented a complete visualization of the framework information. The instances declared to the project and their aggregates could be explored from the browser toolbar. As depicted in the framework representation of Figure 2, the 'Project root task' is decomposed by the inspection and maintenance tasks. Although similar to Bonsai, the tree representation of the KITModelViewer also presented some of the task associations, such as actors and derived products. The cost items, rooted in an IfcCostItem instance declared in the project, could also be accessed in the browser toolbar in a decomposition tree structure. The visualization of existing processes and costs in the resulting file is shown in Figure 19.

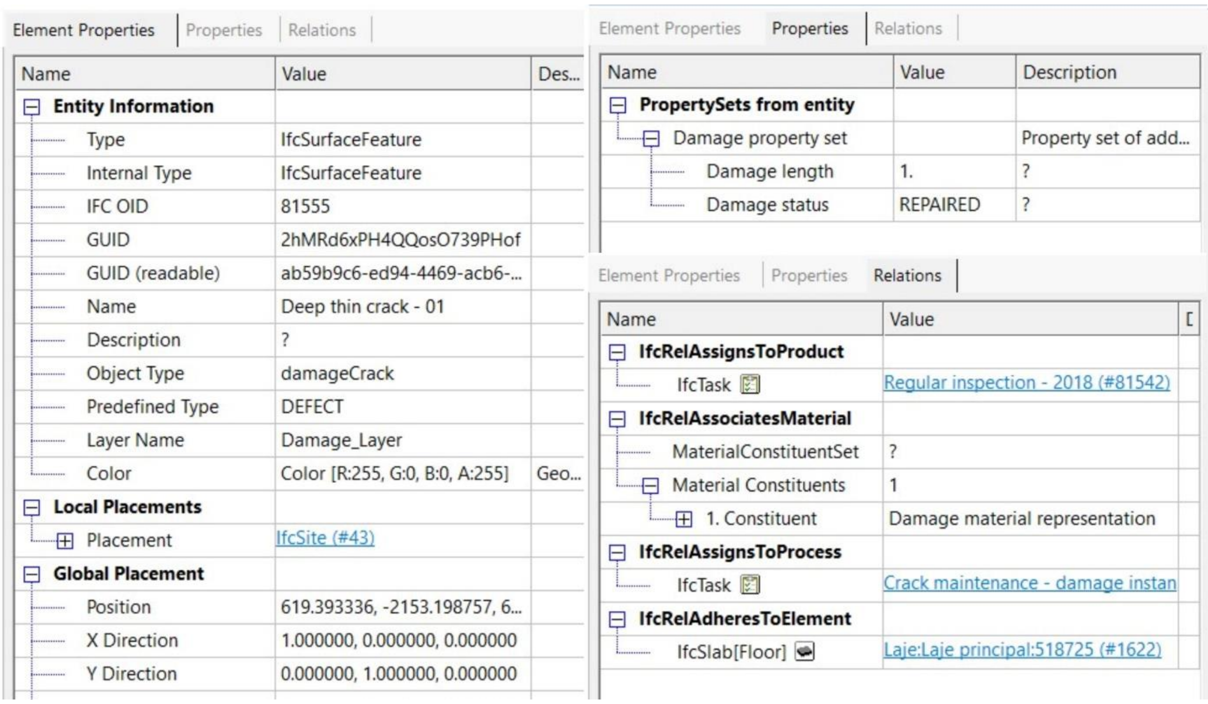


```
Default
IfcCostItem[1]
  Root cost item
    IfcCostItem[1]
      Maintenance root cost item
        IfcCostItem[1]
          Viaduct Coimbra I maintenance - 2025* cost item
            IfcCostItem[22]
              Maintenance cost item: concrete surface painting
              Maintenance cost item: concrete surface cleaning
              Maintenance cost item: crack injection
              Maintenance cost item: concrete surface painting
              Maintenance cost item: concrete surface cleaning
              Maintenance cost item: concrete surface cleaning
              Maintenance cost item: concrete surface cleaning
              Maintenance cost item: concrete hydrodemolition
              Maintenance cost item: concrete surface cleaning
              Maintenance cost item: concrete surface painting
              Maintenance cost item: structural adhesive application
              Maintenance cost item: concrete surface painting
              Maintenance cost item: concrete surface painting
              Maintenance cost item: concrete surface painting
              Maintenance cost item: concrete surface cleaning
              Maintenance cost item: concrete application
              Maintenance cost item: concrete surface cleaning
              Maintenance cost item: concrete surface painting
              Maintenance cost item: concrete drilling
              Maintenance cost item: concrete hydrodemolition
              Maintenance cost item: steel rebar supply
              Maintenance cost item: concrete pavement installation
IfcTask[1]
IfcWorkPlan[1]
IfcActor[1]
  Responsible Inspector
```

```
IfcTask[1]
  Project root task
    IfcTask[2]
      Inspection root task
        IfcTask[1]
          Regular inspection - 2018
            IfcActor[1]
            IfcSurfaceFeature[10]
              Concrete spalling with exposed reinforcement - 01
              Damaged concrete pavement - 01
              Efflorescence - 01
              Concrete water leakage - 01
              Fire action - 01
              Efflorescence - 02
              Fire action - 02
              Fire action - 03
              Efflorescence - 03
              Deep thin crack - 01
      Maintenance root task
        IfcTask[1]
          Viaduct Coimbra I maintenance - 2025*
            IfcTask[10]
              Efflorescence maintenance - damage instance: #81687 Efflorescence
                IfcTask[2]
                  Maintenance task: concrete surface cleaning
                  Maintenance task: concrete surface painting
              Crack maintenance - damage instance: #81555 Deep thin crack - 01
                IfcTask[1]
                  Maintenance task: crack injection
              Concrete water leakage maintenance - damage instance: #81581 Co
                IfcTask[2]
                  Maintenance task: concrete surface painting
                  Maintenance task: concrete surface cleaning
              Efflorescence maintenance - damage instance: #81607 Efflorescence
```

Figure 19. Cost items and tasks decomposition visualized in KITModelViewer interface.

Similar to Bonsai, KITModelViewer provided an in-depth instance data visualization. For any selected instance, its attributes, property sets, and relationships could be explored in the property toolbar. The information displayed in the property toolbar when selecting an IfcSurfaceFeature damage instance is exemplified in Figure 20. In this example, it is relevant to emphasize the correct interpretation of the relationships of the damage instance with the damaged element, originating inspection, and damage-level maintenance.



Name	Value	Des...
Entity Information		
Type	IfcSurfaceFeature	
Internal Type	IfcSurfaceFeature	
IFC OID	81555	
GUID	2hMRd6xPH4QQosO739PHof	
GUID (readable)	ab59b9c6-ed94-4469-acb6-...	
Name	Deep thin crack - 01	
Description	?	
Object Type	damageCrack	
Predefined Type	DEFECT	
Layer Name	Damage_Layer	
Color	Color [R:255, G:0, B:0, A:255]	Geo...
Local Placements		
Placement	IfcSite (#43)	
Global Placement		
Position	619.393336, -2153.198757, 6...	
X Direction	1.000000, 0.000000, 0.000000	
Y Direction	0.000000, 1.000000, 0.000000	

Name	Value	Description
PropertySets from entity		
Damage property set		Property set of add...
Damage length	1.	?
Damage status	REPAIRED	?

Name	Value
IfcRelAssignsToProduct	
IfcTask	Regular inspection - 2018 (#81542)
IfcRelAssociatesMaterial	
MaterialConstituentSet	?
Material Constituents	1
1. Constituent	Damage material representation
IfcRelAssignsToProcess	
IfcTask	Crack maintenance - damage instan
IfcRelAdheresToElement	
IfcSlab[Floor]	Laje:Laje principal:518725 (#1622)

Figure 20. Damage instance properties, property sets, and relationships visualized in KITModelViewer interface.

5. Discussion

Maintaining a general structure to enable future adaptation was beneficial in the framework structuring, keeping the approach straightforward and avoiding IFC extension demands. The spatial structure, process, and cost decompositions were entirely based on official IFC 4.3.2.0 entities, ensuring that future adaptations would be grounded in a standard and valid structure. Even the detailing of decomposition levels, the most particular sections of the framework, were created without extending the IFC schema.

The implementation, although focused on the generation and extension of .ifc files based on the proposed framework, showed the framework's capabilities to be extended and applied in real-world cases. The adaptations employed to address implementation needs also relied solely on standard IFC entities and had no influence over the general semantics of the proposed structure. With a neutral data format as input, the information could be easily exchanged with structured management system databases. For more complex databases, the framework and the input data could be adapted to generate semantically richer IFC files, expanding the scope of the existing application.

Even though the implemented application already automatically processes inspection and damage information to generate maintenance tasks according to each damage type, this processing serves as an example to illustrate its potential. Real-life applications would require the inclusion of data-based parametric models that relate each damage type and its dimensions to appropriate maintenance services.

Additionally, associating the maintenance parametric model with cost and labor databases could significantly expand the application and the completeness of the IFC generated, leveraging the advantages of the IfcProcess entity capabilities for planning purposes. By incorporating temporal information, maintenance tasks could be automatically scheduled and sequenced using the IfcRelSequence relationship. Furthermore, this database integration could also include resource information within the IFC, expanding beyond the scope of the proposed framework.

In visualizing and evaluating in Blender and the Bonsai add-on the IFC files generated in the first study case by the implemented application, the interface captures from Figure 8 to Figure 13 demonstrate that the information was not only written in the file but also successfully interpreted semantically by popular open-source software. All visualizations were generated without direct intervention in Bonsai, except for the cost items visualization in Figure 13. In that case, the total costs of the nested cost items were added in Bonsai, as this value was not directly exported when the IFC file was generated. The visualization in Bonsai also served as a validation of the framework and the implementation since both entities and relationships could be viewed and evaluated.

When evaluating the practical application of the framework using actual data, the information structure and the implementation adaptation showed distinct results across software and IFC versions. At first, the basic bridge inspection structured data acquired from the DNIT bridge management system database was sufficient to generate a generic 3D damage representation. The damage metadata provided enough information to enable the information structuration according to the proposed framework into the resulting IFC file. The presence of the inspection and maintenance data in the model was verified through the evaluation in the Bonsai add-on for Blender and the KITModelViewer, software that presented full compatibility with the information structure.

However, for most of the software evaluated, the inspection and maintenance data inserted in the model was only partially interpreted and displayed on the interface. While the damage data was generally correctly interpreted, the software failed to recognize all information related to maintenance services and costs, even in tools specifically designed for planning and budgeting.

This lack of compatibility with typical openBIM software and the generated file raised concerns about the availability of the information to the user. Considering that most of the evaluated software is proprietary, the source code could not be examined to determine the reasons for the absence of process and cost representations.

The most critical cases, where not even the damage representation was correctly interpreted, may be explained by the differences between the IFC4 and IFC4.3 schema. As previously stated, the structural differences between the original framework and its adaption for the IFC4 schema were minimal. The only significant adjustment that could influence the damage representation was the IfcRelAdheresToElement objectified relationship replacement by the equivalent IfcRelAggregates relationship. With the IfcRelAdheresToElement relationship not being correctly interpreted, the damage instances were not included in any decomposition directly associated with the IfcProject. Without the IfcRelAdheresToElement recognition as an aggregation objectified relationship, the damage instances cannot be considered part of the IfcProject and may be ignored when importing and displaying the model information.

The built-in validation implemented in the application, using the validate module of the IfcOpenShell library, was particularly useful in the early stages of the implementation, highlighting errors in the IFC file associated with the application code. However, for final validation, the IFC Validation Service from buildingSMART was used, and confirmed that the IFC file based on the proposed framework passed all verifications performed.

6. Conclusion

This paper proposed a comprehensive IFC framework for representing inspection and maintenance processes within facility management workflow. The framework was entirely based on the entities from IFC 4.3.2.0 (IFC4.3 ADD2), the latest official release from buildingSMART. The proposed structure was adapted, implemented, and tested using a generic study case, focused on exploring all framework entities and validating the overall structure, and a practical study case, focused on the framework's practical adaptability to typical real-life scenarios. The IFC file in the generic case study was evaluated through information visualization using open-source compatible software and was validated using the official IFC Validation Service from buildingSMART.

The positive results from the adaptation and evaluation of the framework application on the first study case with a restricted amount of data, compatible with simple facility management databases, support the capacity of the general approach to represent the most simple facility maintenance data using the IFC schema. The adaptation capabilities of the framework were further explored in the second case study, where data from an actual facility management system database was effectively represented and stored in an IFC model. In cases with more available data and a broader range of entities to be characterized, the framework is expected to be adapted accordingly, with the additional data incorporated into the base structure.

However, some limitations can be drawn in this study, providing guidelines for future research. It is still necessary to evaluate the framework application in a significant amount of real-world cases with comprehensive datasets, preferably associated with consolidated facility management systems from different regions, to confirm the adaptation capabilities of the framework. Similarly, it is needed to explore its integration with automated data acquisition technologies, such as Internet of Things (IoT) and Digital Twins, that could significantly expand its capabilities and application scenarios. The absence of process and cost information representation, which occurred in most IFC-compatible software tested, must be further investigated to determine the causes of this issue. The distinct levels of information interpreted when varying the IFC schema between two similar versions evidenced the necessity to assess a more comprehensive range of practical cases, including models originating from different software and distinct IFC releases, and to map the needed adaptions to adequate the framework to these scenarios.

Even considering future developments, the proposed framework contributes to facility management by providing researchers, implementers, and users with a straightforward data structure for representing damages, inspection and maintenance processes, costs, and their interconnected relationships in IFC. This proposition fills an existing gap in the literature, establishing a standardized representation framework that supports data exchange and could potentially favor the employment of IFC and openBIM initiatives in facility management, maintenance planning, and asset monitoring of buildings, industrial plants, and infrastructure projects.

The IFC usage, as introduced, offers well-known advantages within the A&C industry and BIM application. Beyond that, IFC usage enables detailed information sharing with semantic richness between stakeholders without giving access to private databases, particularly useful in government tenders and general third-party contracts. Considering that facility management and maintenance are commonly performed by different parties, the IFC schema - and consequently, the proposed framework - can be widely used as a standard for sharing inspection and maintenance information, adaptable to the context needs.

7. References

[1] V. Kasireddy, B. Akinci, Towards the Integration of Inspection Data with Bridge Information Models to Support Visual Condition Assessment, Computing in Civil Engineering (2015) 644–651. https://doi.org/https://doi.org/10.1061/9780784479247.08.

[2] M. Mohammadi, M. Rashidi, Y. Yu, 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 147 (2023). https://doi.org/10.1016/j.compind.2023.103881.

[3] A.C.P. Martins, J.M. Franco de Carvalho, M.C.S. Alvarenga, D.S. de Oliveira, K.M.L. César Júnior, J.C.L. Ribeiro, G.S. Santos, R.C. Verly, Detecting, monitoring and modeling damage within the decision-making process in the context of managing bridges: a review, Structure and Infrastructure Engineering (2024) 1–23. https://doi.org/10.1080/15732479.2024.2331103.

[4] S. Xu, J. Wang, X. Wang, P. Wu, W. Shou, C. Liu, A Parameter-Driven Method for Modeling Bridge Defects through IFC, Journal of Computing in Civil Engineering 36 (2022) 04022015. https://doi.org/10.1061/(asce)cp.1943-5487.0001026.

[5] D.-C. Nguyen, T.-Q. Nguyen, R. Jin, C.-H. Jeon, C.-S. Shim, BIM-based mixed-reality application for bridge inspection and maintenance, Construction Innovation 22 (2022) 487–503. https://doi.org/10.1108/CI-04-2021-0069.

[6] A.C.P. Martins, I.R. Castellano, K.M. Lenz César Júnior, J.M. Franco de Carvalho, F.G. Bellon, D.S. de Oliveira, J.C.L. Ribeiro, BIM-based mixed reality application for bridge inspection, Autom Constr 168 (2024) 1–14. https://doi.org/10.1016/j.autcon.2024.105775.

[7] H.Y. Chong, R. Lopez, J. Wang, X. Wang, Z. Zhao, Comparative Analysis on the Adoption and Use of BIM in Road Infrastructure Projects, Journal of Management in Engineering 32 (2016) 05016021. https://doi.org/10.1061/(asce)me.1943-5479.0000460.

[8] A. Costin, A. Adibfar, H. Hu, S.S. Chen, Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and

recommendations, Autom Constr 94 (2018) 257–281. https://doi.org/10.1016/j.autcon.2018.07.001.

[9] M. Artus, C. Koch, Object-Oriented Damage Information Modeling Concepts and Implementation for Bridge Inspection, Journal of Computing in Civil Engineering 36 (2022) 04022029. https://doi.org/10.1061/(ASCE).

[10] G.S. Floros, C. Ellul, LOSS of INFORMATION during DESIGN & CONSTRUCTION for HIGHWAYS ASSET MANAGEMENT: A GEOBIM PERSPECTIVE, in: ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Copernicus GmbH, 2021: pp. 83–90. https://doi.org/10.5194/isprs-annals-VIII-4-W2-2021-83-2021.

[11] R. Hajdin, V. Samec, BIM and BMS: Current Status and Challenges, in: IABSE Symposium Prague, 2022: Challenges for Existing and Oncoming Structures - Report, International Association for Bridge and Structural Engineering (IABSE), 2022: pp. 710–715. https://doi.org/10.2749/prague.2022.0710.

[12] S. Matarneh, F. Elghaish, F.P. Rahimian, N. Dawood, D. Edwards, Automated and interconnected facility management system: An open IFC cloud-based BIM solution, Autom Constr 143 (2022). https://doi.org/10.1016/j.autcon.2022.104569.

[13] M.L.R. Antunes, K.M. Lenz César Júnior, J.C.L. Ribeiro, D.S. de Oliveira, J.M. Franco de Carvalho, Analysis of IFC interoperability data schema for project representation, Autom Constr 166 (2024). https://doi.org/10.1016/j.autcon.2024.105650.

[14] A. Jiménez Rios, V. Plevris, M. Nogal, Bridge management through digital twin-based anomaly detection systems: A systematic review, Front Built Environ 9 (2023) 1–18. https://doi.org/10.3389/fbuil.2023.1176621.

[15] N. Ali, S. Chen, R. Srikonda, H. Hu, Development of concrete bridge data schema for interoperability, Transp Res Rec (2014) 87–97. https://doi.org/10.3141/2406-10.

[16] S. Ait-Lamallam, R. Yaagoubi, I. Sebari, O. Doukari, Extending the IFC Standard to Enable Road Operation and Maintenance Management through OpenBIM, ISPRS Int J Geoinf 10 (2021). https://doi.org/10.3390/ijgi10080496.

[17] A. Ciccone, S. Di Stasio, D. Asprone, A. Salzano, M. Nicolella, Application of openBIM for the Management of Existing Railway Infrastructure: Case Study of the Cancello–Benevento Railway Line, Sustainability (Switzerland) 14 (2022). https://doi.org/10.3390/su14042283.

[18] S. Jiang, L. Jiang, Y. Han, Z. Wu, N. Wang, OpenBIM: An enabling solution for information interoperability, Applied Sciences (Switzerland) 9 (2019). https://doi.org/10.3390/app9245358.

[19] N. Moretti, X. Xie, J. Merino, J. Brazauskas, A.K. Parlikad, An openbim approach to iot integration with incomplete as-built data, Applied Sciences (Switzerland) 10 (2020) 1–17. https://doi.org/10.3390/app10228287.

[20] F. Pour Rahimian, V. Chavdarova, S. Oliver, F. Chamo, OpenBIM-Tango integrated virtual showroom for offsite manufactured production of self-build housing, Autom Constr 102 (2019) 1–16. https://doi.org/10.1016/j.autcon.2019.02.009.

[21] International Organization for Standardization, ISO 16739-1:2018 Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries – Part 1: Data Schema, International Organization for Standardization, Geneva, Switzerland, 2018. https://www.iso.org/standard/70303.html.

[22] M. Artus, C. Koch, State of the art in damage information modeling for RC bridges – A literature review, Advanced Engineering Informatics 46 (2020) 101171. https://doi.org/10.1016/j.aei.2020.101171.

[23] P. Pishdad-Bozorgi, X. Gao, C. Eastman, A.P. Self, Planning and developing facility management-enabled building information model (FM-enabled BIM), Autom Constr 87 (2018) 22–38. https://doi.org/10.1016/j.autcon.2017.12.004.

[24] S. Matarneh, M. Danso-Amoako, S. Al-Bizri, M. Gaterell, R. Matarneh, BIM-based facilities information: streamlining the information exchange process, Journal of Engineering, Design and Technology 17 (2019) 1304–1322. https://doi.org/10.1108/JEDT-02-2019-0048.

[25] C. Wan, Z. Zhou, S. Li, Y. Ding, Z. Xu, Z. Yang, Y. Xia, F. Yin, Development of a bridge management system based on the building information modeling technology, Sustainability (Switzerland) 11 (2019) 1–17. https://doi.org/10.3390/su11174583.

[26] M. Wang, Y. Deng, J. Won, J.C.P. Cheng, An integrated underground utility management and decision support based on BIM and GIS, Autom Constr 107 (2019). https://doi.org/10.1016/j.autcon.2019.102931.

[27] A. Sharafat, M.S. Khan, K. Latif, W.A. Tanoli, W. Park, J. Seo, Bim-gis-based integrated framework for underground utility management system for earthwork operations, Applied Sciences (Switzerland) 11 (2021). https://doi.org/10.3390/app11125721.

[28] H.M. Omayer, O. Selim, The interaction of BIM And FM through sport projects life cycle (case study: Sailia training site in Qatar), HBRC Journal 18 (2022) 31–51. https://doi.org/10.1080/16874048.2021.2018170.

[29] L. Ding, K. Li, Y. Zhou, P.E.D. Love, An IFC-inspection process model for infrastructure projects: Enabling real-time quality monitoring and control, Autom Constr 84 (2017) 96–110. https://doi.org/10.1016/j.autcon.2017.08.029.

[30] J.L. Hernández, P.M. Lerones, P. Bonsma, A. van Delft, R. Deighton, J.D. Braun, An IFC interoperability framework for self-inspection process in buildings, Buildings 8 (2018). https://doi.org/10.3390/buildings8020032.

[31] W. Chen, K. Chen, J.C.P. Cheng, Q. Wang, V.J.L. Gan, BIM-based framework for automatic scheduling of facility maintenance work orders, Autom Constr 91 (2018) 15–30. https://doi.org/10.1016/j.autcon.2018.03.007.

[32] R. Marmo, F. Polverino, M. Nicolella, A. Tibaut, Building performance and maintenance information model based on IFC schema, Autom Constr 118 (2020). https://doi.org/10.1016/j.autcon.2020.103275.

[33] M. Condotta, C. Scanagatta, BIM-based method to inform operation and maintenance phases through a simplified procedure, Journal of Building Engineering 65 (2023). https://doi.org/10.1016/j.jobe.2022.105730.

[34] P. Hüthwohl, I. Brilakis, A. Borrmann, R. Sacks, Integrating RC Bridge Defect Information into BIM Models, Journal of Computing in Civil Engineering 32 (2018) 04018013. https://doi.org/10.1061/(asce)cp.1943-5487.0000744.

[35] D. Isailović, V. Stojanovic, M. Trapp, R. Richter, R. Hajdin, J. Döllner, Bridge damage: Detection, IFC-based semantic enrichment and visualization, Autom Constr 112 (2020) 103088. https://doi.org/10.1016/j.autcon.2020.103088.

[36] F. Tanaka, M. Hori, M. Onosato, H. Date, S. Kanai, Bridge Information Model Based on IFC Standards and Web Content Providing System for Supporting an Inspection Process, Proc. in International Conference on Computing in Civil and Building Engineering (ICCCBE) (2016) 1140–1147. http://www.see.eng.osaka-u.ac.jp/seeit/icccbe2016/Proceedings/Full_Papers/144-301.pdf.

[37] R. Sacks, A. Kedar, A. Borrmann, L. Ma, I. Brilakis, P. Hüthwohl, S. Daum, U. Kattel, R. Yosef, T. Liebich, B.E. Barutcu, S. Muhic, SeeBridge as next generation bridge inspection: Overview, Information Delivery Manual and Model View Definition, Autom Constr 90 (2018) 134–145. https://doi.org/10.1016/j.autcon.2018.02.033.

[38] J. Shu, C. Zhang, K. Yu, M. Shooshtarian, P. Liang, IFC-based semantic modeling of damaged RC beams using 3D point clouds, Structural Concrete 24 (2023) 389–410. https://doi.org/10.1002/suco.202200273.

[39] R. Sacks, A. Kedar, A. Borrmann, L. Ma, D. Singer, U. Kattel, SeeBridge information delivery manual (IDM) for next generation bridge inspection, ISARC 2016 - 33rd International Symposium on Automation and Robotics in Construction (2016) 826–834. https://doi.org/10.22260/isarc2016/0100.

CHAPTER 6 – CONCLUDING REMARKS

Abstract

This chapter presents the concluding remarks of the thesis, compiling insights for future works.

1. General conclusions

This thesis explores and proposes solutions for the digitalization and automation of bridge and viaduct maintenance quantification and budgeting. Supported by an extensive literature review and an analysis of contextual demands, this research introduces a parametric model for the design and budgeting of maintenance work platforms, a machine learning application for predicting maintenance quantities based on inspection data, and an IFC-based framework for structuring inspection and maintenance data.

Each proposed approach advances the bridge maintenance field. The literature review compiles the most recent developments in BIM applications for bridge management, identifying existing gaps and guiding future research. The parametric model for maintenance work platforms addresses the need for standardization and automation in their design and quantification, particularly within the Brazilian federal context. The machine learning application represents a pioneering effort in data-driven bridge maintenance quantification, demonstrating its potential and outlining directions for improvement. Finally, the IFC-based framework integrates inspection, maintenance, damage, and cost representation into a standardized data structure, ensuring interoperability within facility management systems.

In summary, this research contributes to the advancement of bridge management by demonstrating the feasibility and applicability of digital, automated, and data-driven methodologies. The proposed solutions provide a foundation for improving existing bridge management systems, enhancing decision-making processes, and facilitating the transition toward a more structured, automated, and interoperable maintenance workflow. By filling key gaps in digitalization and automation, this study reinforces the importance of data integration in the future of bridge management.

2. Future works

The pioneering nature of the studies presented in this thesis opens up several possibilities for further research and future practical developments.

The parametric model for designing and budgeting working platforms for maintenance was intended to be adaptable to systems with limited data. Future studies could expand the methodology by incorporating a broader range of parameters. Additional optimization criteria should be explored according to the analyzed context, which could lead to more accurate results.

The methodology should be employed in larger datasets for a more comprehensive evaluation of its performance in diverse scenarios, helping to identify potential improvements.

The machine learning application for maintenance services quantification based on inspection data, as an exploratory study, leaves significant room for improvement. The analysis could improve significantly with additional pre-processing techniques and individual hyperparameter optimization. Employing computer vision and large language models would enable the inclusion of complementary data, such as photographic records and unstructured text. Expanding the dataset would diminish the feature-to-sample ratio, potentially reducing overfitting and increasing model accuracy.

The IFC-based framework for structuring inspection and maintenance data was evaluated in test study cases with limited data. Applying the framework with actual facility management data could provide insights into areas for refinement and potential improvements. Future work could extend the framework to include a broader range of management processes and costs. Further studies should evaluate the compatibility of the data structure across multiple IFC versions and IFC-compatible software, ensuring broader interoperability.