Univerza *v Ljubljani*
Fakulteta *za gradbeništvo*
in geodezijo

PAULA REBELLO BENDER

APPLICATION OF BIM FOR BRIDGE MONITORING

MASTER THESIS

SECOND CYCLE MASTER STUDY PROGRAMME BUILDING INFORMATION MODELLING – BIM A+

Ljubljana, 2023

Univerza v *Ljubljani*
Fakulteta *za gradbeništvo in geodezijo*

PAULA REBELLO BENDER

APPLICATION OF BIM FOR BRIDGE MONITORING

UPORABA BIM ZA NADZOR MOSTOV

BIM A+ European Master in Building Information Modelling

Master thesis No.:

Supervisor:
Prof. Vlatko Bosiljkov, Ph.D.

Co-Supervisor:
Ass. Prof. Tomo Cerovšek, Ph.D.

Committee members:

Ljubljana, 2023

Co-funded by the Erasmus+ Programme of the European Union

ERRATA

Page	Line	Error	Correction

»This page is intentionally blank«

BIBLIOGRAFSKO – DOKUMENTACIJSKA STRAN IN IZVLEČEK

UDK:	004.057.8:694.21-021.131(043.3)
Avtor:	Paula Rebello Bender
Mentor:	Prof. dr. Vlatko Bosiljkov
So-mentor:	doc. dr. Tomo Cerovšek
Naslov:	Uporaba BIM za nadzor mostov
Tip dokumenta:	Magistrisko delo
Obseg in oprema:	49 str., 36 sl., 1 preg.
Ključne besede:	BIM- informacijsko modeliranje zgradb, nadzor mostov, Infraworks, Dalux, upravljanje mostov

Izvleček:

Aplikacija in integracija informacijskega modeliranja stavb (BIM) na področje nadzora mostov predstavlja pomemben napredek pri upravljanju infrastrukture. Diplomsko delo raziskuje večplastno implementacijo tehnologij BIM pri nadzoru in vzdrževanju mostu. Raziskuje, kako lahko integracija tehnologij BIM, zlasti prek programske opreme Dalux, izboljša način spremljanja, upravljanja in vzdrževanja mostne infrastrukture.

Magistrska naloga se teoretično poglobi v zapletenost nadzora mostov z uporabo BIM, vključno z vidiki integracije podatkov, analitike v realnem času in podpore pri odločanju. Naloga osvetljuje transformativni učinek modelne predstavitve, vizualizacije podatkov in protokolov za izmenjavo informacij na področju upravljanja mostov. Poleg tega raziskava obravnava praktične vidike uvajanja senzorjev, integracije podatkov in vizualizacije v okolju Dalux. Okolje Dalux nudi uporabniku prijazen vmesnik, ki omogoča vsem deležnikom enostavno komunikacija in interakcijo s 3D modeli mostov in obravnava tudi sodelovalni potencial Daluxa, s poudarkom na njegovi vlogi pri premoščanju vrzeli med načrtovanjem, gradnjo in tekočim upravljanjem mostov.

Pričujoča naloga služi kot vodnik za aplikacijo BIM pri nadzoru mostov. Zagotavlja praktične vpoglede, metodologije in priporočila za praktike, inženirje in zainteresirane strani na tem področju ter zagovarja široko sprejetje tega celostnega pristopa za zagotovitev dolgoživosti, varnosti in odpornosti kritične mostne infrastrukture.

»This page is intentionally blank«

BIBLIOGRAPHIC– DOCUMENTALISTIC INFORMATION AND ABSTRACT

UDC:	004.057.8:694.21-021.131(043.3)
Author:	Paula Rebello Bender
Supervisor:	Prof. Vlatko Bosiljkov, Ph.D.
Co-supervisor:	Ass. Prof. Tomo Cerovšek, Ph.D.
Title:	Application of BIM for bridge monitoring
Document type:	Master Thesis
Scope and tools:	49 p., 41 fig., 1 tab.
Keywords:	BIM, bridge monitoring, Infraworks, Dalux, bridge management

Abstract:

The application and integration of Building Information Modeling (BIM) into the realm of bridge monitoring represents a significant advancement in infrastructure management. This thesis explores the multifaceted implementation of BIM technologies for the purpose of monitoring and maintenance of bridges. It investigates how the integration of BIM technologies, specifically through the Dalux, can improve the way we monitor, manage, and maintain bridge infrastructure.

The thesis delves into the intricacies of BIM-enabled bridge monitoring, including coverage of aspects of data integration, real-time analytics, and decision support. It uncovers the transformative impact of 3D modeling, data visualization, and information exchange protocols in the realm of bridge management. Moreover, the research investigates into practical aspects of sensor deployment, data integration, and visualization within the Dalux platform. It explores how Dalux's user friendly interface empowers stakeholders to interact with 3D bridge models and it also addresses the collaborative potential of Dalux, emphasizing its role in bridging the gap between design, construction, and ongoing bridge management.

In conclusion, this thesis serves as a comprehensive guide to harnessing the power of BIM in bridge monitoring. It can be used by other professionals involved in bridge maintenance and management, such as engineers and stakeholders, contributing with methodologies and advocating for the adoption of GIS (Geographic Information System) technologies in BIM integration.

»This page is intentionally blank«

ACKNOWLEDGEMENTS

I would like to thank my supervisor Vlatko Bosiljkov and the coordinator of the course – co-supervisor Tomo Cerovšek for their guidance and knowledge shared during the period of this dissertation. The support from Družba za avtoceste v Republiki Sloveniji, d.d. (Motorway Company in the Republic of Slovenia) DARS d.d that provides project documentation is gratefully acknowledged.

To all my friends from the masters, I appreciate the moments we shared. I would like to thank Mohamad Chaaban, Fabrizia Della Penna, Joe Buckets, Minja Radenkovic and Gabriel Veloso for making this period a bit lighter and fun.

Lastly, I would like to express gratitude to my family for always believing in me and supporting my goals. Thank you for the unconditional love.

»This page is intentionally blank«

TABLE OF CONTENTS

INDEX OF FIGURES

INDEX OF TABLE

LIST OF ACRONYMS AND ABBREVIATIONS

BIM	Building Information Modelling
3D	3 Dimensions
IFC	Industry Foundation Classes
SHM	Structural Health Monitoring
NDT	Non-Destructive Testing
SDT	Semi- Destructive Testing
UAV	Aerial Vehicles Equipped
WSNs	Wireless Sensor Networks
WIM	Weigh-In-Motion
GIS	Geographic Information System
RFID	Radio Frequency Identification Devices
RADAR	Radio Detection and Ranging
VC	Vision Cameras
UWB	Ultra-Wide-Band

1 INTRODUCTION

Bridge, as components of transportation infrastructure, serve as lifelines for the efficient movement of people and goods, fostering economic development and connectivity. Over time, bridges are exposed to various environmental factors, dynamic loads, and the relentless passage of time itself, leading to gradual deterioration and structural damages.

The safety and longevity of these critical structures demand continuous and precise monitoring to detect anomalies, assess structural health, and plan maintenance effectively. In this context, Building Information Modeling (BIM) emerges as transformative technology, offering new dimensions to bridge monitoring.

BIM, initially embraced in the architectural a construction sectors, has proven its capacity to optimize design, and manage build assets. Its fundamental principles of digital representation, information integration, and collaborative workflows have extended the realm of possibilities to structural engineering, infrastructure management, and beyond. Through a case of study of a real bridge going through deterioration process this research will show how the principles and tools of BIM can be harnessed to enhance the assessment, visualization, and management of bridge's structural health.

Across a comprehensive exploration of BIM's capabilities, this research seeks to elucidate the challenges of traditional approaches in bridge monitoring systems and evaluate the potential in that BIM can have offering predictive maintenance and efficient decision-making. The foundation of this work lies in the premise that BIM, with its ability to create a digital twin of a physical bridge, can serve as a dynamic platform for the assimilation of diverse data sources, from sensors and remote monitoring to historical records of bridge's condition, enabling engineers and asset managers to make informed decisions with unprecedent precision and foresight.

The ensuing chapters of this thesis delve into various aspects of this evolving field. It will be explored the efficiency of currently used monitoring system and the possibility of integrating with BIM, investigate data, analyze the visualization of structural health, and propose optimized maintenance strategies.

1.1 Objectives

In order to better understand bridge monitoring system work, it is presented the different approaches commonly used and their challenges. The main objective of this dissertation is to simulate how would work a BIM approach for monitoring and management to an existent bridge and the benefits of using a collaboration between the monitoring systems. This will be achieved through an integration between the documentation of the bridge, visual inspection and the 3D model created through a software platform specialized in digital solutions for construction and facility management.

1.2 Partnership for the dissertation

This work was developed based on the data provided by Družba za avtoceste v Republiki Sloveniji, d.d. (Motorway Company in the Republic of Slovenia) DARS d.d that provided project documentation designed by GRADIS d.o.o., Maribor, a civil engineering company based in Maribor – Slovenia, present at key projects of the national road infrastructure, for new constructions and reconstructions and renovations of the existing road network in Slovenia, as well as in the wider region. The documentation provided by the company was an important asset to this research, improving and facilitating the BIM implementation proposed.

1.3 Structure of dissertation

This dissertation is organized into six sections. In the first two chapters, the base for the work is established. The first chapter aims to introduce the topic, present work motivations and a general panorama of the important of an effective bridge monitoring systems and procedures. Also, it exposes the objectives and goals of this research. The second chapter comprehends a literature review about the essential topics to support the development of the work, mainly involving bridge monitoring systems. Within common procedures to monitor bridges were present along, visual inspections, structural health monitoring and BIM implementation and standardization for bridge monitoring were reviewed. On the monitoring systems review, concepts, advantages and difficulties of each were presented. The third chapter of this work focuses on explaining the methodology used for the development of the proposed BIM implementation.

The last two chapters concern the development and validation of the work. Chapter four the development of the case of study and inspection that was made, along with the considerations on the work are presented and explained. This chapter displays the 3D model and simulations of the work, along with the possibilities that could be reach through the BIM implementation. The last chapter presents the conclusions of the work and suggestions for future development.

2 LITERATURE REVIEW

2.1 General overview

Bridges are one of the oldest infrastructures that humans have used to improve their transportation routes. These structures may have a usable life of many decades, depending on the location and materials employed (Zinno, Haghshenas, Guido in VItale, 2022). With the passage of time, they suffer with the aging process and frequently exceed their design life (*THE IABMAS BRIDGE MANAGEMENT COMMITTEE OVERVIEW OF EXISTING BRIDGE MANAGEMENT SYSTEMS 2014*, 2014).

Bridges conditions deteriorate progressively over time due to factors such as creep, corrosion, cyclic loads, and various other influences. The degradation process can be characterized as a composition of all degradation mechanism that act simultaneously affecting the examined structure (Board, of Sciences Engineering in Medicine, 2012; Estes in Frangopol, 2001; Greco, Lonetti in Zinno, 2002). The mechanism of degradation can be divided in long-term nature such as corrosion or a short-term form like overloading during collision (Bień, Kużawa in Kamiński, 2020).

Two basic types of bridge inspection techniques are currently employed: the interval-based inspection technique, which is more common and used to evaluate the condition of bridges, and the condition-based technique (Liu, Hauser, Chen in Haywood, b. d.). The interval-based technique is divided in two types: routine visual inspection and the non-destructive inspection technique (Lea in Middleton, 2002).

Condition-based inspection also known as Structural Health Monitoring or SHM by the engineering community, involves the ongoing monitoring of specific response characteristics of a bridge, such as vibration responses, operational deflection shape and strain measurements (Boller, 2000). This type of monitoring can minimize maintenance expenses through its ability to provide advanced warnings and detect potential damages that can occur to railway infrastructures (Farrar in Worden, 2007).

The detection of structural problems in bridges has grown and the reason is strongly related to the roads and trains growing outdated and no longer being able to handle the traffic volume that they were originally designed for (Casas in Moughty, 2017). To assure the safety of structures is required ongoing maintenance and repair efforts (Dessi in Camerlengo, 2015).

Procedures of Bridge Health Monitoring can be divided into two main categories:

- Load-independent procedures, comprising of regular as well as irregular (special), these inspections rely on visual examination and data from of the non-destructive testing (NDT) and/or semi-destructive testing (SDT).
- Load-dependent procedures, that includes tests under controlled loads as well as short- and long-term monitoring under normal traffic and environmental loads (wind, earthquake, etc.). In such instances, bridges structures experience a variety of dynamic loads, including moving live loads and time varying wind loads. Dynamic effects are considered in bridge design and hold a significant role as performance indicators during the bridge's lifetime.

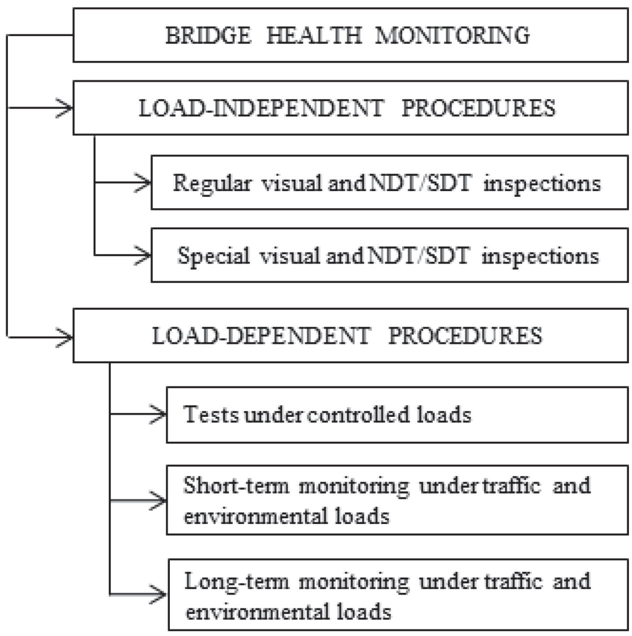


Figure 1: Basic procedures in Bridge Health Monitoring.

Scheduled dynamic tests under controlled loads are commonly administered before opening a new bridge structure for traffic or after completing significant rehabilitation projects. The short and long-term monitoring occurs under the influence of routine traffic loads and environmental impacts during operation of a bridge. Short-term monitoring and the scheduled dynamic tests typically require placed sensors, while the long-term monitoring necessitates a permanently installed system (Bien in Kużawa, 2020).

2.2 Visual inspections

In Bridge Management System, the initial stage usually relies on visual inspection techniques. During this phase, each bridge is visually evaluated and receives a pre-defined condition rating, providing a condition evaluation for the designated inventory of bridges (Adu-Gyamfi, Chase, Aktan in Minaie, 2016). Visual inspection can be divided into six main phases (Nepomuceno, Bennetts, Pregnolato, Tryfonas in Vardanega, 2022):

(1) preparation and planning,
(2) image/data acquisition,
(3) detection of defects,
(4) assessment of defect severity,
(5) analysis of changes over time and
(6) decision making regarding maintenance.

It is essential to establish solid criteria to evaluate the overall condition of the chosen bridge, offering specific guidelines for documenting conditions, like deformations and vibrations as well as significant damage indicators, including environmental factors, traffic impact and routine maintenance (Tenzera, Puz in Radić, 2012). With well-defined performance standards it is possible to have comprehensive descriptions of both global and localized damage with deterioration rated it, to prioritize maintenance tasks and to do projections regarding future deterioration (Gattulli in Chiaramonte, 2005).

The inspection of crucial structure elements and challenging-to-access areas is typically carried out by trained staff or with large under bridge unites, such as elevating platforms or other specialized equipment. Often special equipment and specially trained staff are required, such as unmanned Aerial Vehicles Equipped (UAV) with high-definition cameras (Hallermann in Morgenthal, 2014). UAVs and 360° cameras offer the potential to reduce on-site time and, in certain instances, mitigate safety concerns for inspector while minimizing disruption to the traffic network. For instance, 360 cameras can swiftly capture images of the undersides of highway bridges from a slow-moving vehicle, eliminating the need to close traffic lanes (Nepomuceno, Vardanega, idr., 2022).

While visual inspection methods have historically been used as the common approach for monitoring buildings over long periods, its effectiveness is limited primarily to simple structures (Dessi in Camerlengo, 2015). Given its strong dependence on human assessment, there is a significant possibility of same conditions state being rated differently by inspectors (Adu-Gyamfi idr., 2016).

2.3 SHM

In the current scenario a discipline growing in the construction field is the automatic observation of the structural behaviour of a building, named Structural Health Monitoring (SHM). It consists in a non-destructive, on-site monitoring system that enables real-time control of the condition of the analyzed structure by measuring physical–mechanical parameters (Zinno Raffaeleand Artese, 2019).

Structural Health Monitoring system has been represented as the process of traditional inspections to inspections achieved through data acquisition and damage evaluation and it has evolved into an approach that integrates non-destructive testing and structural analysis to detect changes in structural response (Comisu, Taranu, Boaca in Scutaru, 2017).

Figure 2 shows an overview of the performance monitoring procedure applied to bridges equipped with the SHM system:

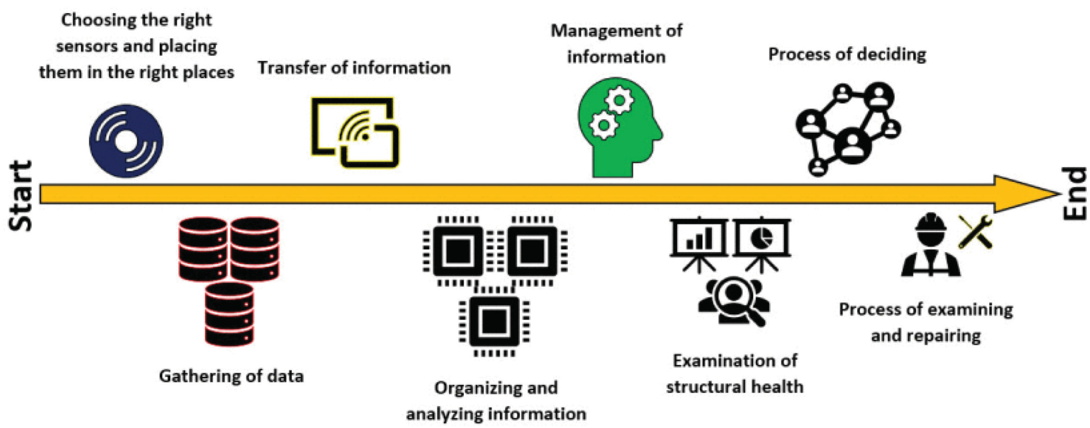


Figure 2: Overview of the performance monitoring process of bridges with the SHM system (Zinno idr., 2022).

The choice of sensors is significantly related to the specific application and the structure under surveillance. To measure the level of vibration an accelerometer can be employed aiming to comprehend the overall performance the structure, particularly the changes in modal frequencies that can serve as indicators of potential damage. When considering strain sensors (like strain gauges or fiber optic sensors) or ultrasonic transducers, the emphasis shifts toward localized assessments of potential damage within the structure (Mustapha, Lu, Ng in Malinowski, 2021).

The SHM process involves the observation of a structure or mechanical system over time using periodically spaced measurements, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of system health. One of the most frequently employed approach for feature extraction is based is establishing correlations between measured system response quantities, like vibration amplitude or frequency, and direct observation of the degrading system (Farrar in Worden, 2007).

A complete SHM system can be divided in four stages, also known as statistical pattern recognition paradigm:

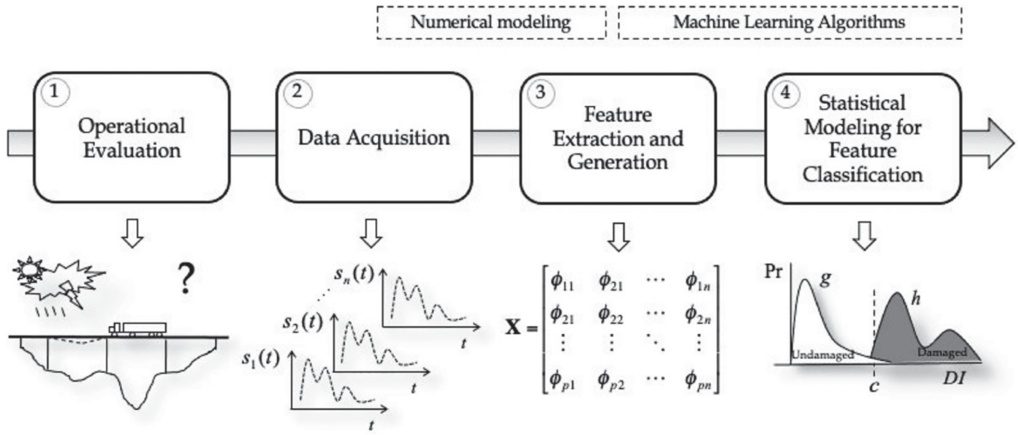


Figure 3: The SHM process for bridges based on a four-stage SPT paradigm (Figueiredo in Brownjohn, 2022).

The primary goal of the stages is to distinguish patterns or structural alterariong linked to the undamaged structural condition under operational and environmental variability from patterns erlated to damaged states. This is achieved by initiating the process with sensor data from the monitored structure and concluding with damage identification to accurately assess the structural condition (Figueiredo in Brownjohn, 2022).

In the operational evaluation stage, the purpose is to compile extensive pre-existing data about the structure to assess the viability of introducing the SHM system. This evaluation typically focuses on four key criteria: the type and severity of damage, the operational and environmental conditions of the road, the limitations on data collection due to the operational and environmental conditions and the economic and safety feasibility of implementing an SHM system. (Khan, Atamturktur, Chowdhury in Rahman, 2016)

The data acquisition, feature extraction and statistical modeling stages are processes like data normalization, cleansing, fusion and compression (Farrar in Worden, 2007). Data acquisition involves selecting the type of sensor, numbers and location, data storage/processing/transmittal hardware and the excitation methods (Figueiredo in Brownjohn, 2022). The selection and placement of the sensors is a vital part to obtain accurate measurements (Nassif, Gindy in Davis, 2005).

Sensors should be installed to be able to measure different parameters, including vehicle loads, wind speed and direction, environmental temperature and humidity, vibrations, structural temperature, strain, deflection of the main beam, displacement of bearing, and cable tension force (Li in Ou, 2016). To track changes in wind speed and wind direction bridge sites frequently utilize mechanical and utrasonic anemometers. For collecting data on vehicle loads, traffic flow, vehicle speeds, individual acle weights and the quatity of axles, weigh-in-motion WIM systems are commonly used (Chen, Zhou, Wang, Dong in Qian, 2017). In sequence the data cleansing process is employed to remove data that has been compromised or had become unreliable as a result of the data acquisition procedure (Khan idr., 2016).

Gathering real-time information of facilities, structures, and various construction-related domains proves to be a valuable method for efficiently overseeing construction operations. This data can be readily obtained through sensor technologies. Wireless Sensor Networks (WSNs) emerge as a viable and practical technology for remote sensing applications, particularly for monitoring inherent or environmental conditions such as temperature and humidity. WSNs are well suited for long-term management, even in scenarios where structural elements are not the primary focus or where maintenance is challenging, making them a versatile choice compared to stationary monitoring system (Cheung, Lin in Lin, 2018). This important type of sensors in this category are global positioning system (GPS), encoder sensors, laser technology, Radio Frequency Identification Devices (RFID), Audio Technology, Radio Detection and Ranging (RADAR), magnetic sensors, Vision Cameras (VC) and Ultra-Wide Band (UWB) (Panah in Kioumarsi, 2021). The effectiveness of sensing technologies is contingent on their intended application in monitoring and maintenance. Researchers extensively explore these technologies, weighing their advantages and drawbacks, to enhance equipment navigation and bolster construction safety (Dong, Li in Yin, 2018).

Feature extraction is the procedure of extracting damage-related information from the measured data. (Overbey, 2008) Comparing the features makes it possible to differentiate between the damaged and the undamaged structural states. By comparing the features, it becomes possible to distinguish between the structural states that have incurred damage and those that remain undamaged (Sohn, Farrar, Hemez in Czarnecki, 2002).

The last stage, statistical modeling for feature classification, has the purpose of recognizing shifts and patterns in a structure's response. In the context of detecting changes in bridge behavior, these models refer to algorithms that utilize the damage-sensitive features obtained in the previous stage to evaluate the structural condition (Farrar in Worden, 2007).

Currently, the International Association for Bridge and Structural Engineering (IABSE) has Task Groups focused on the studies of BIM in Structure Management, to connect Bridge Management System with existing BIM solutions, and Task Groups focused on the latest findings in the field of remote inspections of bridges (International Association for Bridge and Structural Engineering (IABSE) 2020).

2.4 Limitations in Bridge Monitoring Systems

One of the fundamental challenges in Structural Health Monitoring is the precise and suitable selection, installation, and initiation of sensors. Sensors employed, particularly if it is for long-term monitoring, must exhibit resilience to external factors that can impact their functionality, such as temperature variations, humidity levels and corrosive substances. Many sensors commonly used necessitate an external power source, causing difficulties to set up and maintain the system. Furthermore, this arrangement can influence on project costs, potentially necessitating structural modifications to accommodate these sensors networks and leading to increase project expenses (Deivasigamani, Daliri, Wang in John, 2013).

Sensors often have their own limitations, for instance vibration-based approaches are commonly used, but often lack in providing a qualitative assessment of the structural health (Runcie, Mustapha in Rakotoarivelo, 2014). In the other hand fiber-optic sensors are ideal for high-resolution monitoring, like strains and temperatures, but have some logistical limitations to their routine installation during the construction process, some precautions are needed to prevent fiber damage in the construction environments (Figueiredo in Brownjohn, 2022).

Another approach using artificial intelligence, like artificial neural networks, has been successfully applied for damage detection, however the network susceptibility to alterations in input data is still a concern. This method may not exhibit the same level of effectiveness in setting such as bridges, where environmental conditions are frequently volatile and noise levels are substantial (Zinno idr., 2022).

When it comes to an effective Structural Health Monitoring implementation, sensor reliability plays a crucial role and can serve as a complement to annual inspections. Over time, as sensors age along with the structure they are monitoring, they may encounter a phenomenon known as drift. Drift manifests as a gradual decline in accuracy, often following a linear or exponential patttern, and can sometimes go undetected if not closely monitored. If the sensors reach a significant loss in their accuracy, it can lead to undesirable outcomes such as false positives or false negatives. False positives alarms need on-site inspections and verification. The worst-case scenario would be a false negative, where critical damage remanis unnoticed until the next bridge inspection cycle (Rizzo in Enshaeian, 2021).

2.5 Building Information Modelling in Bridge Monitoring

BIM technology employs object-based 3D information models, offering a groundbreaking departure from conventional and less effective 2D methods in the planning, design, construction, and maintenance of infrastructure. Initially, BIM technology found its beginnings in building designs characterized by standardized components, serving as a means to effectively oversee and exchange information throughout the entire lifecycle of a building, all grounded in the principles of 3D information modeling (Byun, Han, Kwon in Kang, 2021).

Several research studies have explored the application of BIM models in the health monitoring and maintenance of bridges by using BIM models. The integration of BIM with complementary software like GIS enhances the monitoring process and facilitates the assessment of risks and damage (Panah in Kioumarsi, 2021). The utilization of advanced BIM capabilities, such as 6D modeling, which incorporates 3D model data along with cost, time, and environmental impact analysis, has improved the decision-making process for maintenance activities, especially for conventional bridges (Kaewunruen, Sresakoolchai in Zhou, 2020).

Maintenance has an extremely important role in the transportation infrastructure like highways, roads, airports, and tunnels. The effectiveness of maintenance efforts can be extended by employing specialized software packages in conjunction with BIM (Panah in Kioumarsi, 2021). Integrating BIM and Wireless Sensor Networks enhances the precision of monitoring hazards and energy consumptions, addressing critical challenges in life-cycle management and ensuring human safety (Zhao in Liang, 2015). The primary objective of these tools is to improve the accuracy of decision-making by collecting and processing data, with a particular focus on reducing the maintenance costs associated with smart buildings (Ibanez, Fitz in Smarsly, b. d.).

The Industry Foundation Classes (IFC) open data model represents an international open standard developed by buildingSMART and is commonly used for data exchange (Byun idr., 2021). IFC supports platform-independent or open BIM, and it furnishes a collection of categories, functions, and guidelines designed to effectively acquire pertinent information in specific domains, such as structural engineering procedures (Theiler in Smarsly, 2018).

The advantages of employing BIM in Structural Health Monitoring (SHM) includes efficient management and oversight of SHM data, improved interpretation by linking real-time data with BIM models, and the establishment of a reliable database to support diverse projects (Panah in Kioumarsi, 2021).

3 METHODS

In this chapter it is presented the procedure and factors considered during the development of the proposed work. Initially, it is provided a concise overview of the thesis primary subject area. Subsequently, it is presented the dissertation's methodology. At last, it is explained the aspects related to the creation of the 3D model and the software chosen to help in the BIM implementation and maintenance of the bridge.

Incorporating BIM into bridge monitoring systems enhances the ability to proactively manage and maintain bridge, ensuring their safety, longevity, and optimal performance. BIM provides a centralized repository for all bridge-related data, from design information to all the documentation related to the bridge, facilitating collaboration, and making easier to track any changes and improvements over time. Visualization in 3D and 4D of the bridge's conditions also facilitate better decision-making, and it is particularly useful for understanding complex structures. In summary BIM provides a comprehensive platform for bridge monitoring and management, offering benefits such as real-time monitoring, predictive maintenance, risk assessment, cost control and improved collaboration.

This study seeks to show the benefits of BIM implementation on bridge monitoring. Through a case of study, BIM was implemented in an existent bridge with objective of improving bridge maintenance and centralizing the bridge data. As a methodology:

- The study investigates the data provided of the bridge, 2D drawings and inspections made along the years.
- To improve visualization a 3D model of the bridge was created.
- In order to add and connect data to the 3D and location of the model on a software platform named Dalux about the current conditions a visual inspection was made with a normal and a 360° camera.
- Dalux was used to integrate the real data and the 3D model.
- As a result, the benefits of BIM implementation in bridge maintenance and monitoring are demonstrated through the software platform and a procedure created for the inspections.

4 CASE OF STUDY

For this proposal, it was considered essential to develop three sections: the information provided of the bridge, the 3D modelling and visual inspection and the integration between all these stages. The understanding of these parts can help to improve the management and monitoring system of different types of structures, also providing a strategic view on how to implement BIM in existing structures.

4.1 Bridge Data

The bridge chosen as case of study is located in Slovenia, was built in 1981, based on project n. 1247 from 1980 made by GIP GRADIS. The bridge is divided in two: viaduct A and viaduct B, each has eight pillars, respective length of 344,36m and 319,36m and both share the same width of 14,95m. In the figure 4 and 5 it is possible to see the viaducts cross sections:

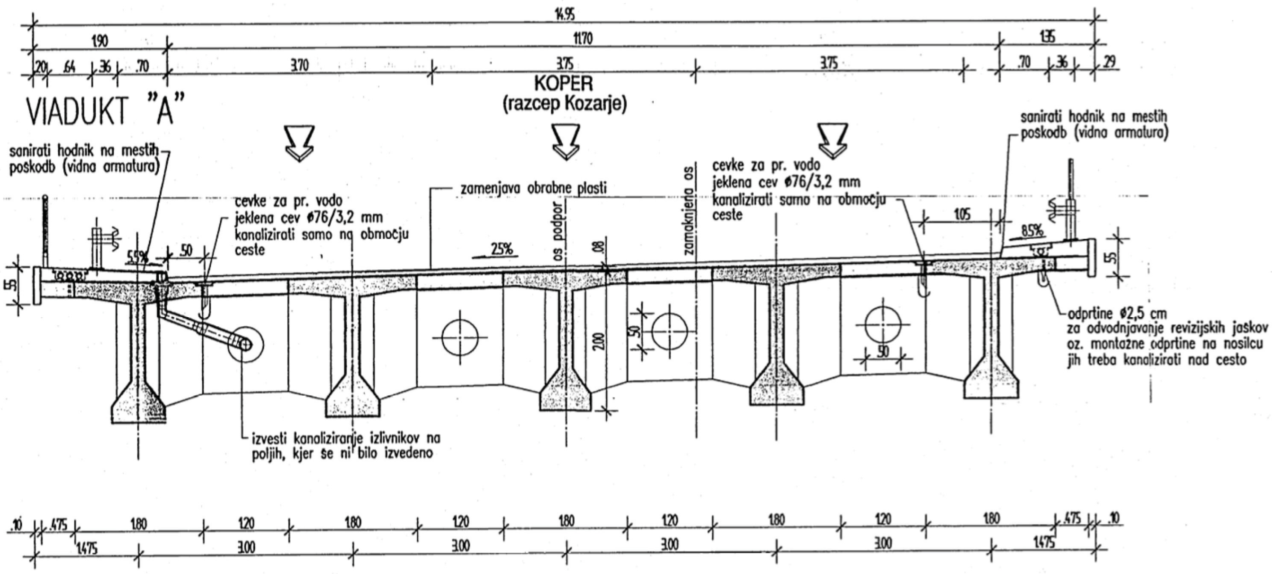


Figure 4: Cross section Viaduct A.(GRADIS BP Maribor d.o.o., 2001)

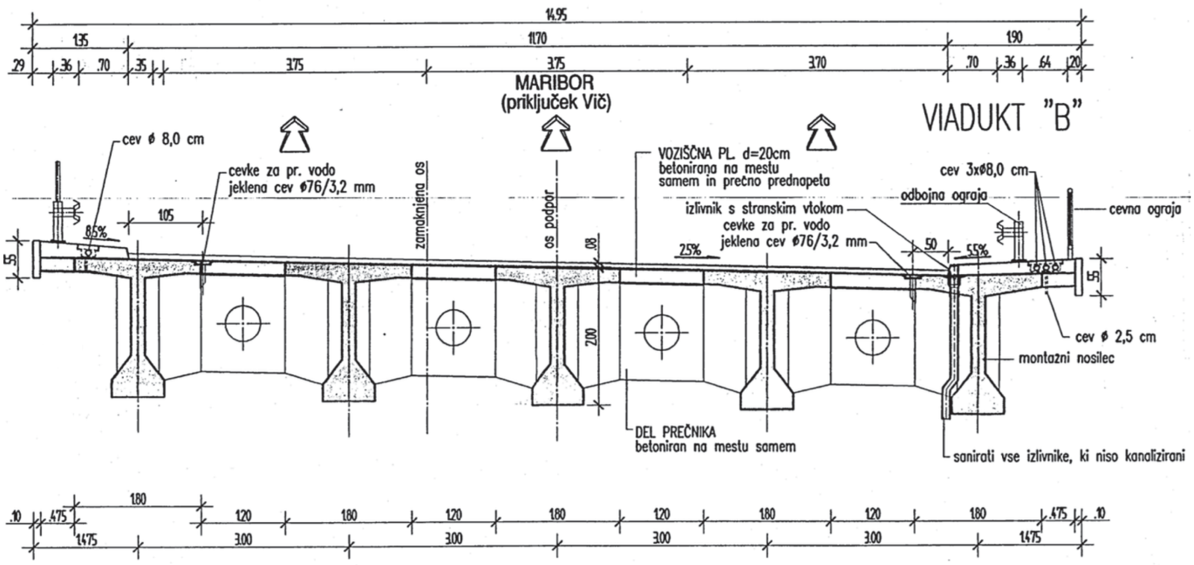


Figure 5: Cross section Viaduct B.(GRADIS BP Maribor d.o.o., 2001)

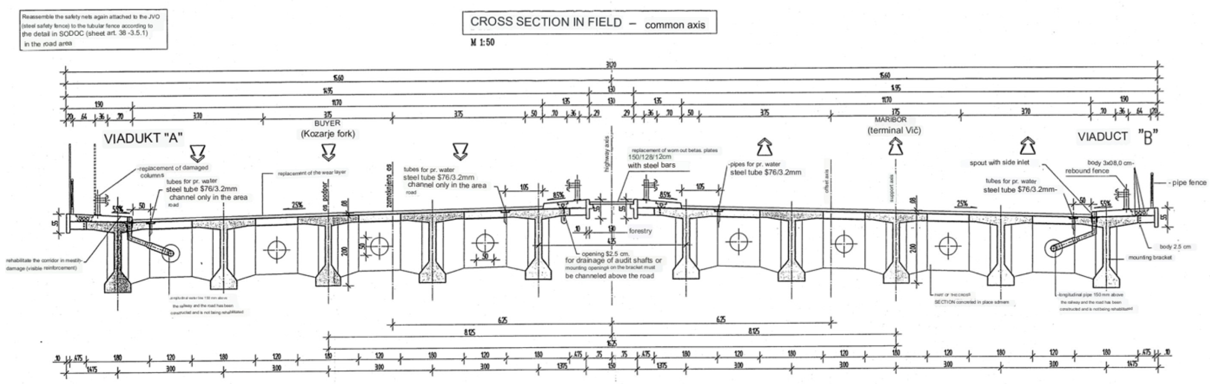


Figure 6: Cross section Viaduct A and Viaduct B.(GRADIS BP Maribor d.o.o., 2001)

The files were provided by GRADIS and contain information such as technical reports, profile views, cross section views, details, formwork and rebar drawings, traffic detour and scan data. In the reports it is possible to check that over time several damages were already found in inspection reports, and rehabilitation actions were taken. On the figure 7 and 8, that was translated to English, it is possible to see drawings with the damages placed on the bridge elements and rehabilitation procedures:

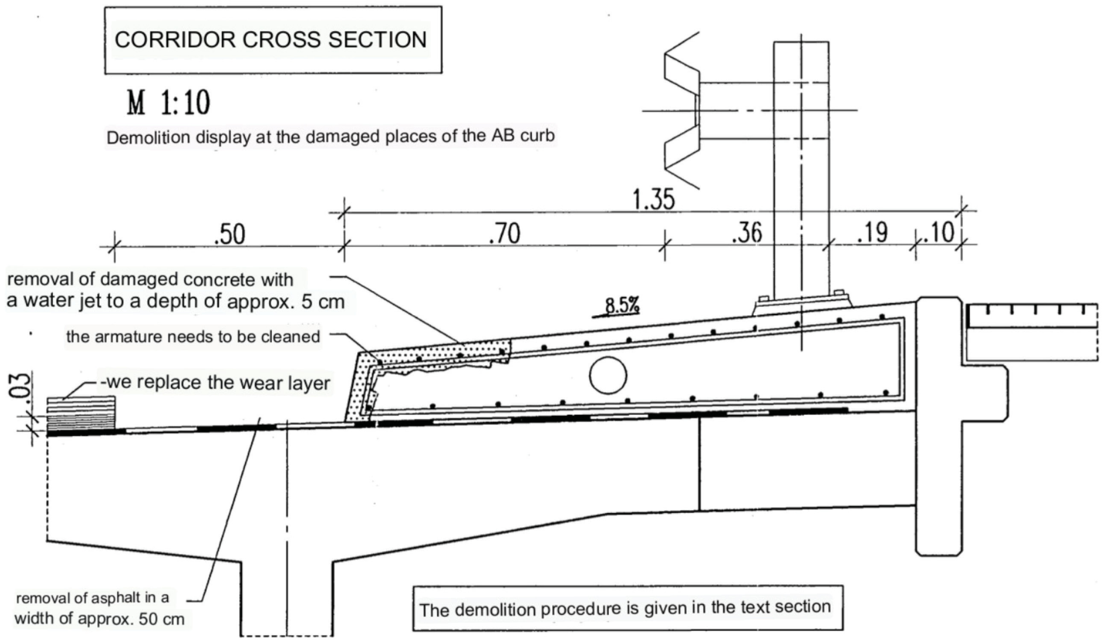


Figure 7: Corridor cross section(GRADIS BP Maribor d.o.o., 2001)

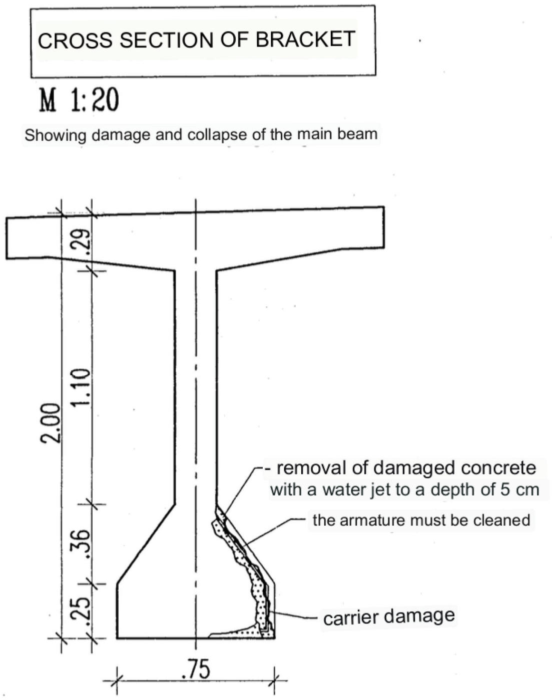


Figure 8: Cross section of bracket.(GRADIS BP Maribor d.o.o., 2001)

Along with the drawings the documentation also contained reports performed on the bridge in which also contains the procedure for rehabilitation of the damaged areas. These documents were used to collect data to model the 3D bridge as explained on the next chapter.

4.2 Simplified model of existing model

To implement BIM in this process it was necessary to model the bridge on 3D with the parameters needed for the determined BIM use. To achieve the purposes of visualization through georeferenced, a simplified model of Viaduct A was made. The modelling process was made initially on InfraWorks, a planning and modelling software that allows to visualize infrastructure design concepts within the context of the built and natural environment. Infraworks was chosen because it allows fast prototyping, offers integration between different datas sources like GIS, CAD and BIM and provides realistic context, including terrain, roads and rivers.

For inserting the location of the bridge, it was used the coordinate system Slovenia-5-S9. Unfortunately, the software does not provide the currently official coordinate system of Slovenia EPSG: 3794, so that needed to be adjusted later on Revit. Using the data collected from the brigde and the geographic reference on InfraWorks the bridge was modelled.

When working on a new model on InfraWorks it is necessary to choose a coordinate system, in this case it was the Slovenia-5-S9 coordinates system, to find the location of the bridge. After selecting a coordination system the area of interested was selected and imported to the model. A planning road was inserted according to the coordinates from the map on InfraWorks. The parameters of the road were adjusted according the dimensions of the bridge, such as width, number of lanes, elevation of the road and other few elements.

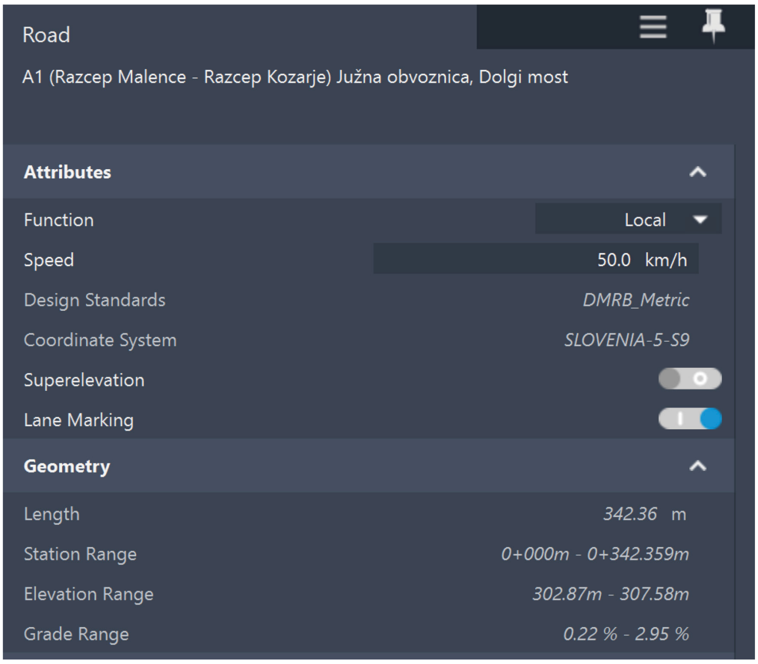


Figure 9: Parameters of the road on InfraWorks.

A parametric bridge was added to the component road. Since the program adds the bridge components (pier, foundation, girders and wings) according to the size of the automatically, this had to be adjusted on the properties of the bridge afterwards so it would match the ones on the documents:

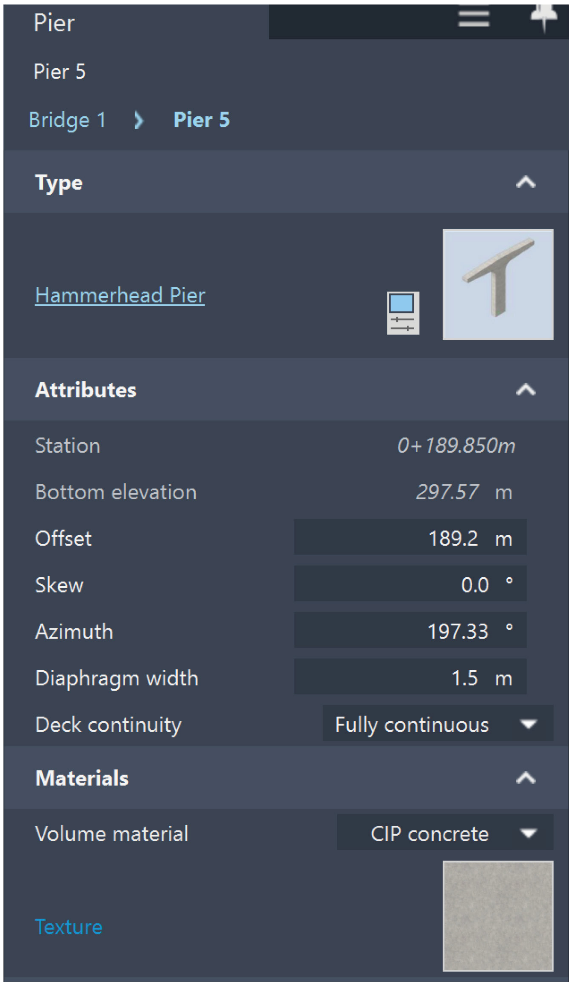


Figure 10: Pier 5 properties on InfraWorks.

Each Pier had to be adjusted individually in height, type, location and other properties. Foundations were also adjusted individually to be more similar to the dimensions of the ones of the real bridge.

The girders were also adjusted according to the size and distribution of the bridge, that was five girders between every pier.

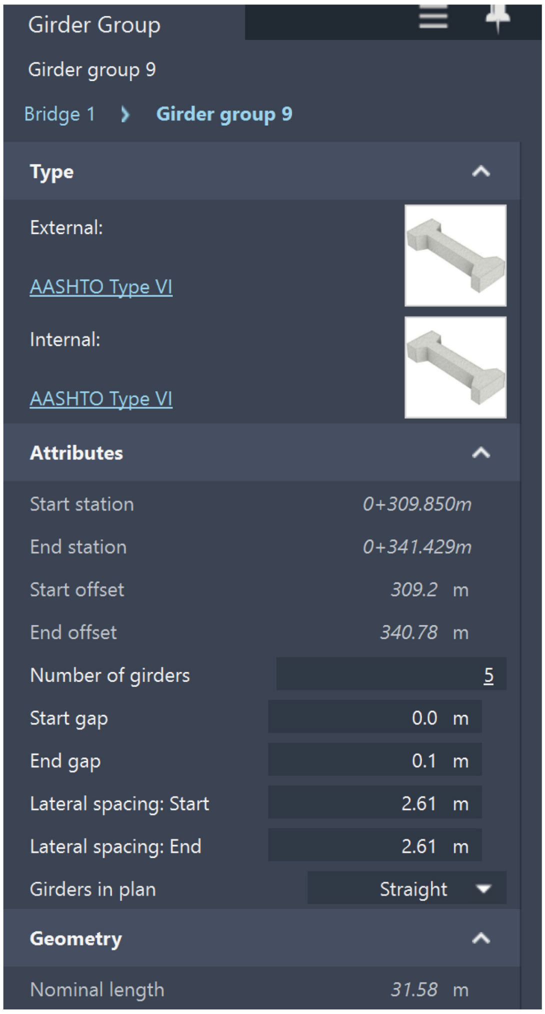


Figure 11: Girder group 9 properties on InfraWorks.

The wings of the bridge were also adjusted to a similar type and dimensions to achieve a similar dimension of the one from the bridge.

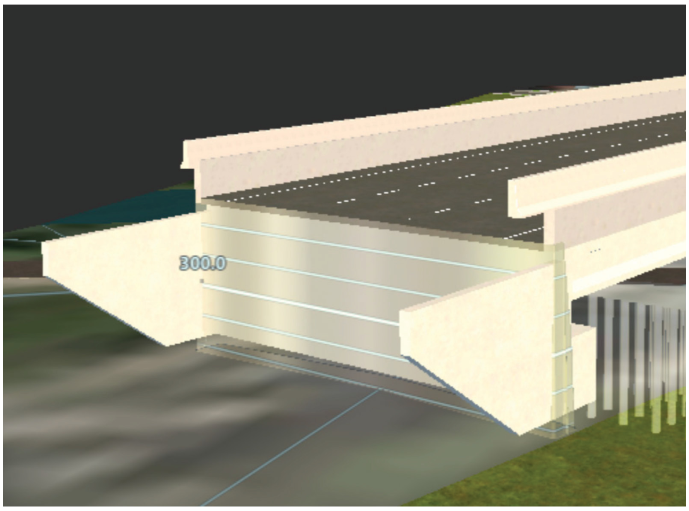


Figure 12: 3D model of bridge's wing on InfraWorks.

Cross frames elements were added on the model to offer a more realistic model of the bridge. The cross frames parameters were also adjusted to similar ones found on the bridge.

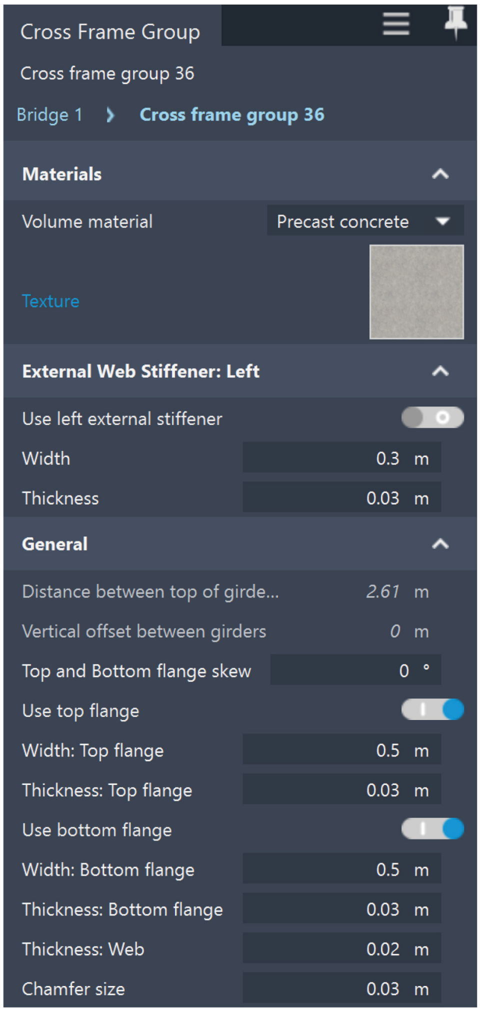


Figure 13: Cross frame properties on InfraWorks

After adjusting the elements of the bridge a few elevation points were added so the elevation of the bridge could me adjusted to match the real bridge.

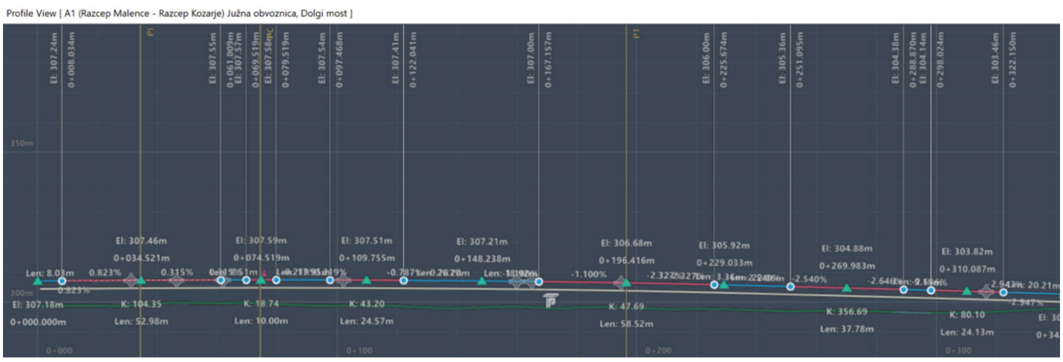


Figure 14: Profile view of the bridge model.

Once the model was adjusted with the right properties the bridge was exported as IMX file. For opening the model on Revit the export process needed to be done differently, instead of a regular IMX exportation the structure had to be published as civil structure on InfraWorks.

Figure 15: Bridge 3D model on InfraWorks.

Figure 16: Bridge 3D on InfraWorks.

To open the model on Revit it was necessary to download an add-in called Revit Infraworks Updater, and then import civil structure.

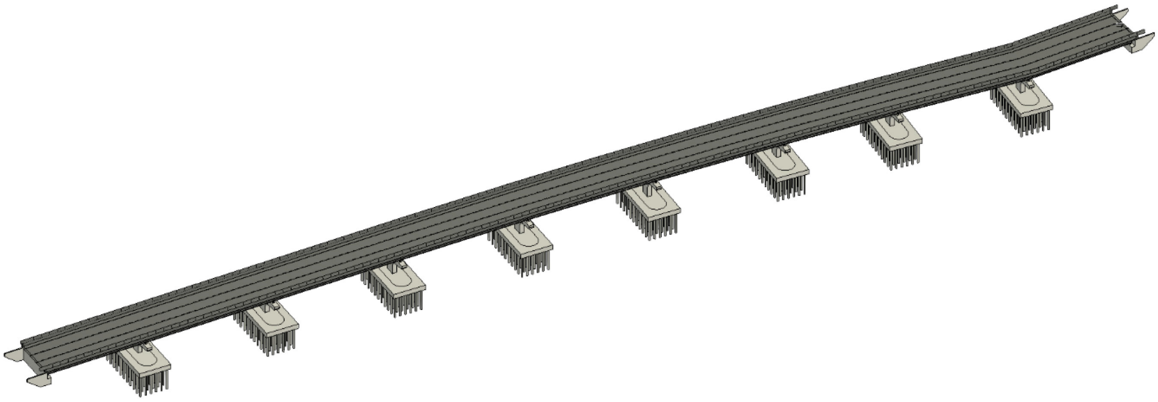


Figure 17: Bridge 3D model opened on Revit.

The last step was to export the bridge on Revit as an IFC file. Revit also does not support the EPSG:3794, the modelled was exported to IFC with the previous coordinate system from Infraworks.

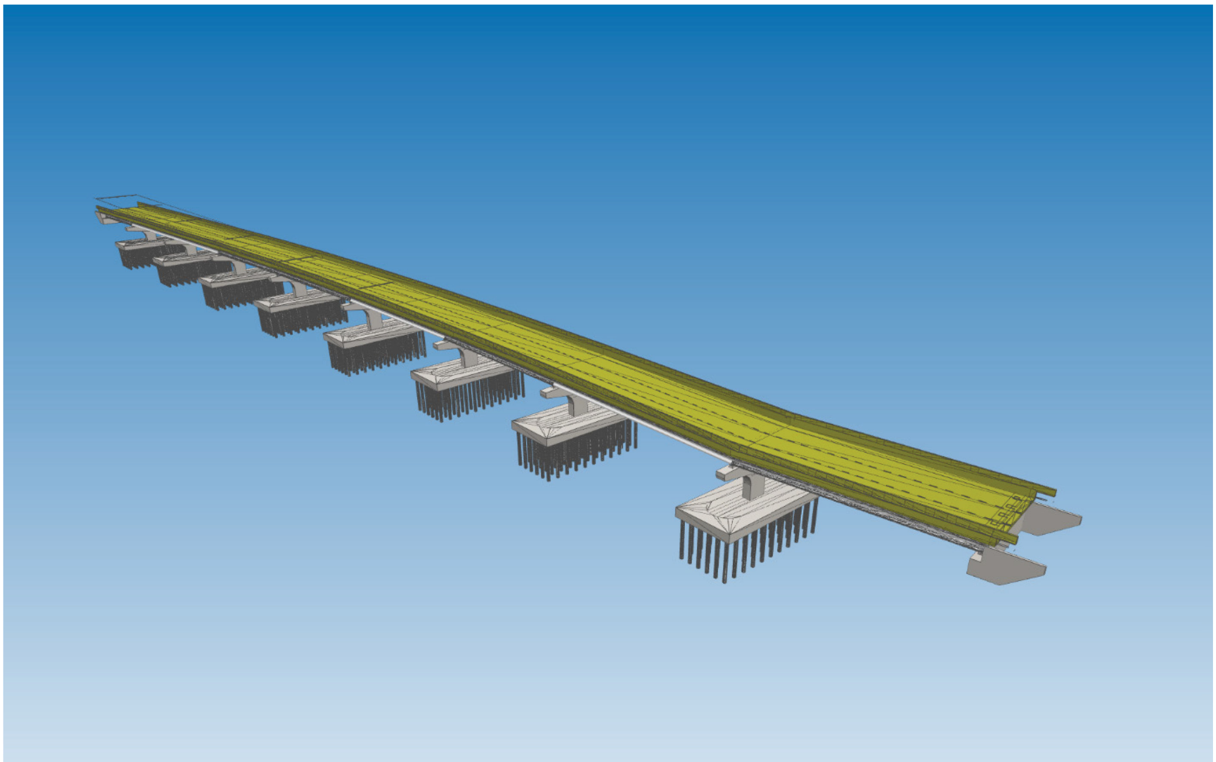


Figure 18: Bridge 3D model opened on BIMCollab.

The advantage of this contribution is arriving on the next phase with construction solutions validated, so the model can be useful along with the other information collected from the bridge conditions.

With the bridge model it was possible to do the integration between the visual inspection explained on the next topic.

4.3 Visual Inspection

This chapter delves into the process of visual inspection realized on the bridge, elucidating its methodologies, objectives and significance in BIM implementation. In order to collect data of the current conditions of the bridge and to connect this data with the bridge model a visual inspection was performed.

In this visual inspection the main objective was to collect visual information and notes so the damages and deterioration could be easily localized. The visual inspection focused on the substructure since the superstructure accessibility was not possible due the vehicles traffic.

The methodology of this visual inspection was made by dividing the elements: wings, piers, girders and pedestrian areas. The procedure was initially to collect data from the right side of the bridge, then the left side along the bridge following the elements: first right wing then left ring, then right side of the pier and left side of pie, followed by right side of the girders then the left side of the girders and the pedestrian area. To facilitate the process of localizing later on the pictures on the bridge the bridge the girders were divided in nine groups and piers in eight groups.

This procedure was repeated until it was reached the end of each bridge, totalizing eighteen groups of five girders, two pedestrian areas and sixteen piers. For the BIM implementation it was only modelled one viaduct, but the visual inspection procedure was performed on both viaducts. On the visual inspection was possible to check corrosion on the wings of each bridge:

Figure 19: Corrosion on the right Wing – Viaduct A.

Figure 20: Wing – Viaduct B.

It was not possible to reach closer the wing areas for a better view because of the vegetation and the grids surrounding the area.

The girders and piers were the areas most affected by corrosion, on the figure 17 and figure 18 it is possible to see big parts of the surface with visible steel.

Figure 21: Corrosion on Girder group 3 – Viaduct B.

Figure 22: Corrosion on Girder group 1 – Viaduct A.

Figure 23: Corrosion on Pier 6 and Girder group 6 – Viaduct B.

Figure 24: Corrosion and cracks on Pier 5 – Viaduct B.

On the girders and piers, it was also possible to check that rehabilitation works were already performed as an attempt to fix the degradation process.

Figure 25: Retrofit on Pier 6 – Viaduct A.

On every pier and on the wings was also possible to verify that there was damage caused by graffiti.

Figure 26: Retrofit on Girder group 4 – Viaduct A.

The rehabilitation work on the pier did not seem to work, since some parts of the structure were exposed as it is possible to see on the figure 25. The pedestrian area also suffered from deterioration, as it is possible to see on the figure 27.

Figure 27: Damage found on the surface bellow the pedestrian area.

After collecting the data from the visual inspection, it was necessary to organize and centralized the data for the BIM implementation. This data was storage on Dalux software along with the documentation from previous visual inspections.

4.4 BIM implementation

To do the BIM implementation it was used the software Dalux. The software provides a centralized platform of storing and managing all project-related data, ensuring that all stakeholders have access to the latest information.

As the first step a new project was created on the software and all the documents provided by NH were uploaded in this project also allowing the data access. It is important to point it out that Dalux prioritizes data secutiry, with implemented encryption and access control to protect project information.

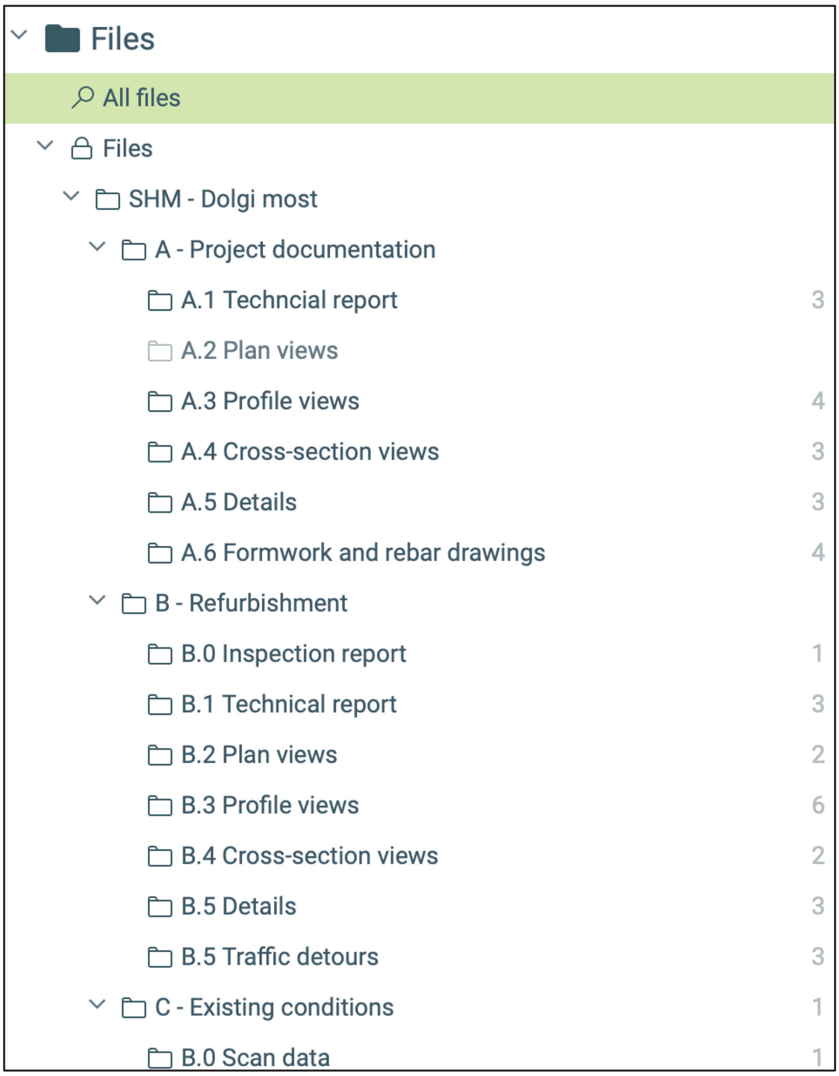


Figure 28: Dalux interface with the project files.

The files were organized inside Dalux according to the documentation and data obtained, so it was divided in groups of project documentation, refurbishment, and existing conditions. After having the documentation on the platform, the 3D model was uploaded on the program as well.

The system allows for different views for the desktop and for the mobile application that allows for monitoring on the site of facility.

The desktop version allows for the GIS integrated view:

Figure 29: GIS integrated with 3D model.

On the GIS integrated view (map) it is possible to select models that are project as layer to GIS. In addition, tasks, inspections – test plans, forms and photos can be presented.

Figure 30: Photo album integrated with GIS location.

Dots represent photos taken at particular locations and can be zoomed in:

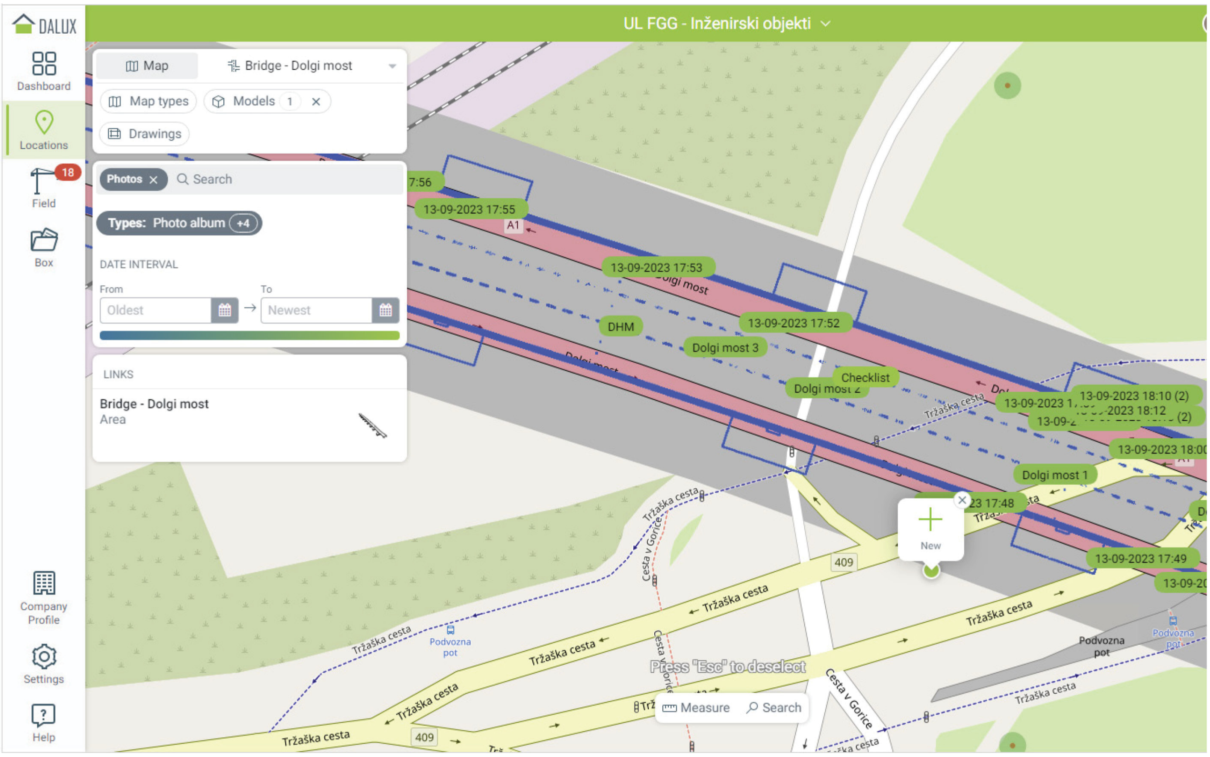


Figure 31: Dots zoomed in showing the photos along with the date.

Figure 32: Dot with the 360º caption zoomed in.

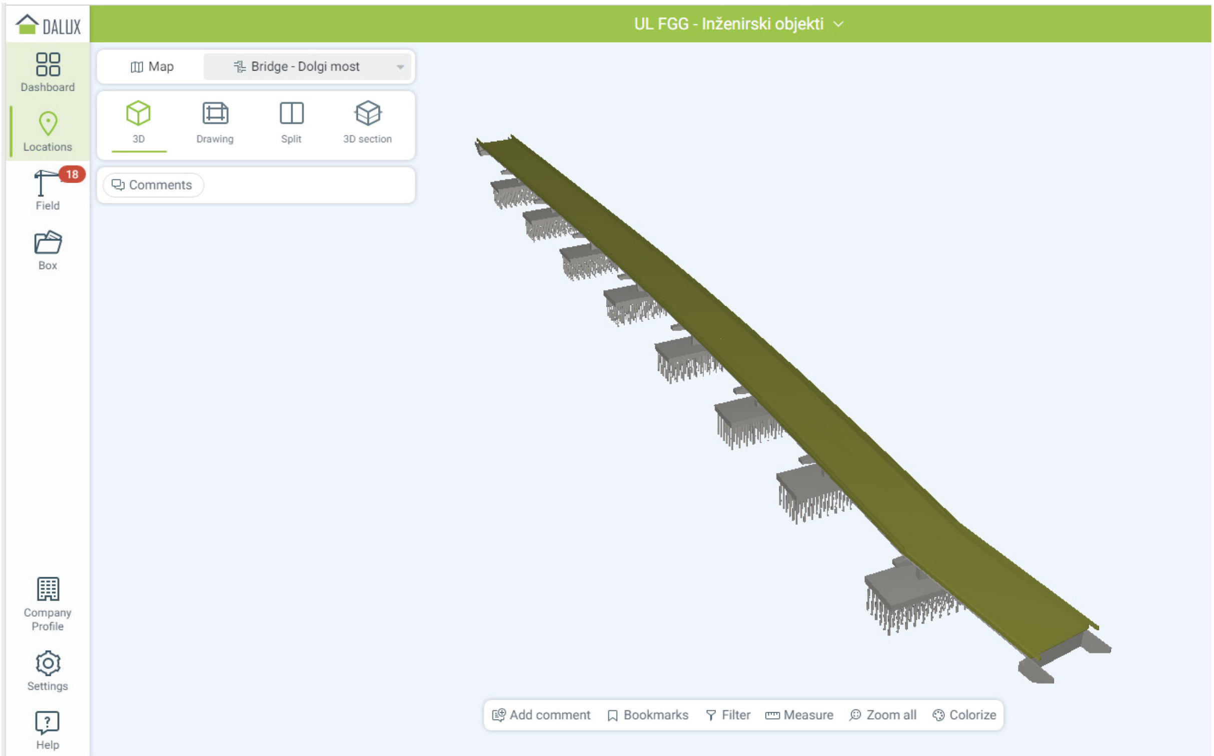


Figure 33: Dalux interface with 3D bridge model opened.

For having the 3D on Dalux along with the location it was to be uploaded in IFC format, which was made through Revit.

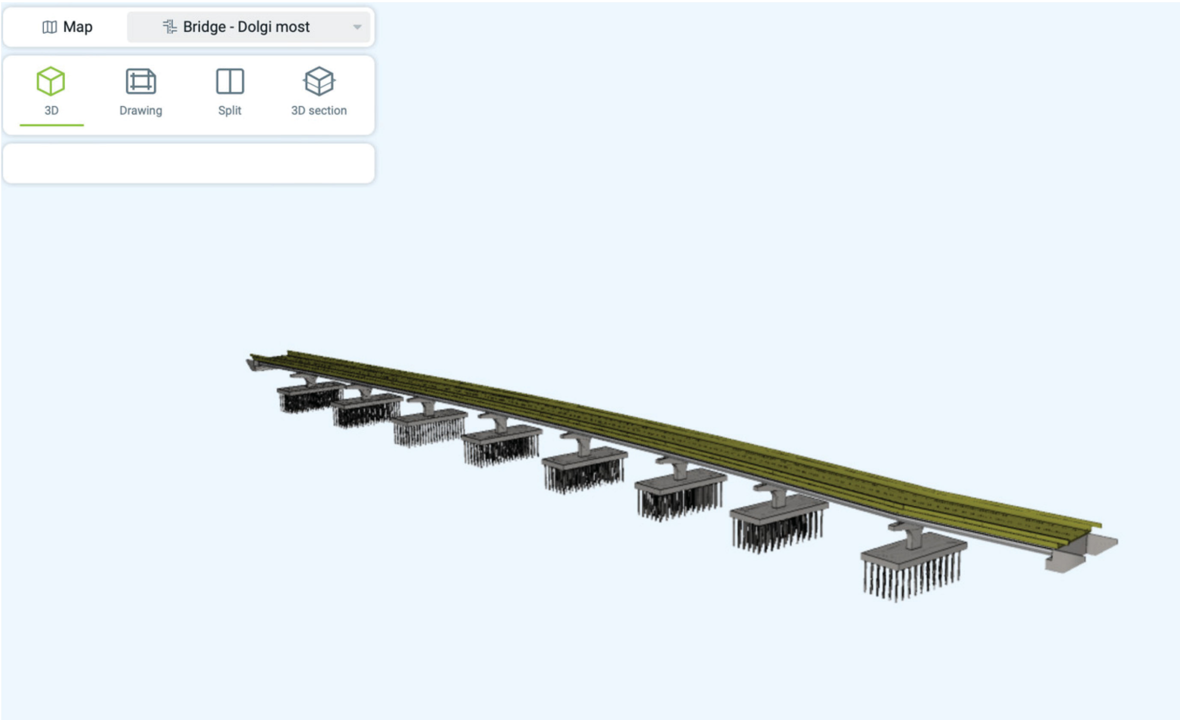


Figure 34: 3D model on Dalux.

The software supports 3D visualization of projects, including the ability to view and interact with BIM models, once the model was uploaded it facilitated the understanding and coordination for the maintenance phase.

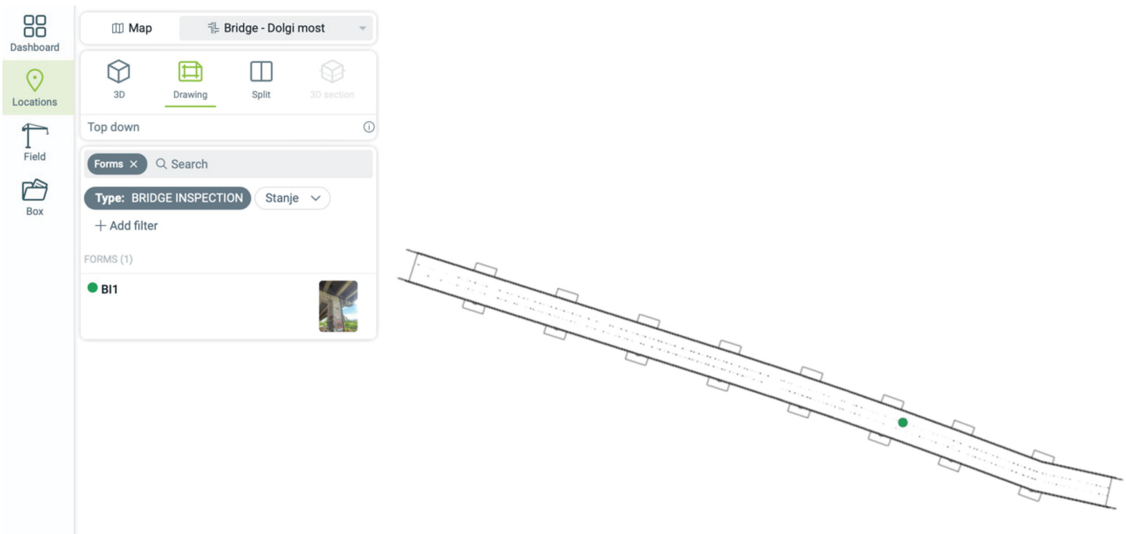


Figure 35: 3D model opened as drawing on Dalux.

With a simple interface the program allows stakeholders to add tasks and find the files easily. On the left side it is possible to see the options and interactions available, such as tasks, comments and inbox.

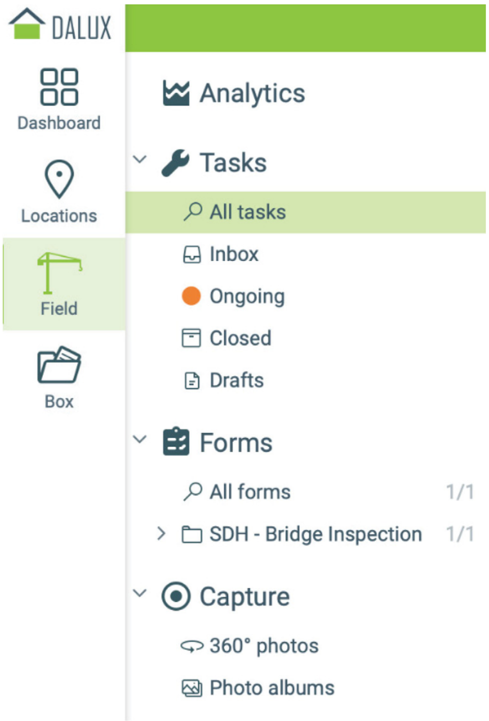


Figure 36: Project files on Dalux.

On Dalux application it was possible to add pictures in real time, regular or 360, and attribute to the right location of the bridge. To show this tool another some pictures of the bridge were taken using a 360º camera.

Figure 37: Location and 360º caption on Dalux.

To add the location of the picture first is necessary to select on the map the location where the picture is being taken, however the Dalux application already points the live location, facilitating the process.

Another tool offered by the software it the possibility to add formularies about the inspection and export it as pdf or excel file. In order to obtain more information about the bridge and to share with the other stakeholders a formulary was created with a few questions about the conditions of the bridge. The formulary was divided by sectors such as general conditions of the bridge, superstructure, substructure, deck and pavement, utilities and infrastructure, environmental factors, structural health monitoring and recommendations.

The formulary was initially created on word and then uploaded and adjusted on Dalux software. To answer the formulary, it is necessary to click on a part of the bridge, then on the process of answering the questions it is possible to add pictures.

Once the formulary is available on Dalux, the inspectors can answer, and any stakeholder related to this project can have access to the information.

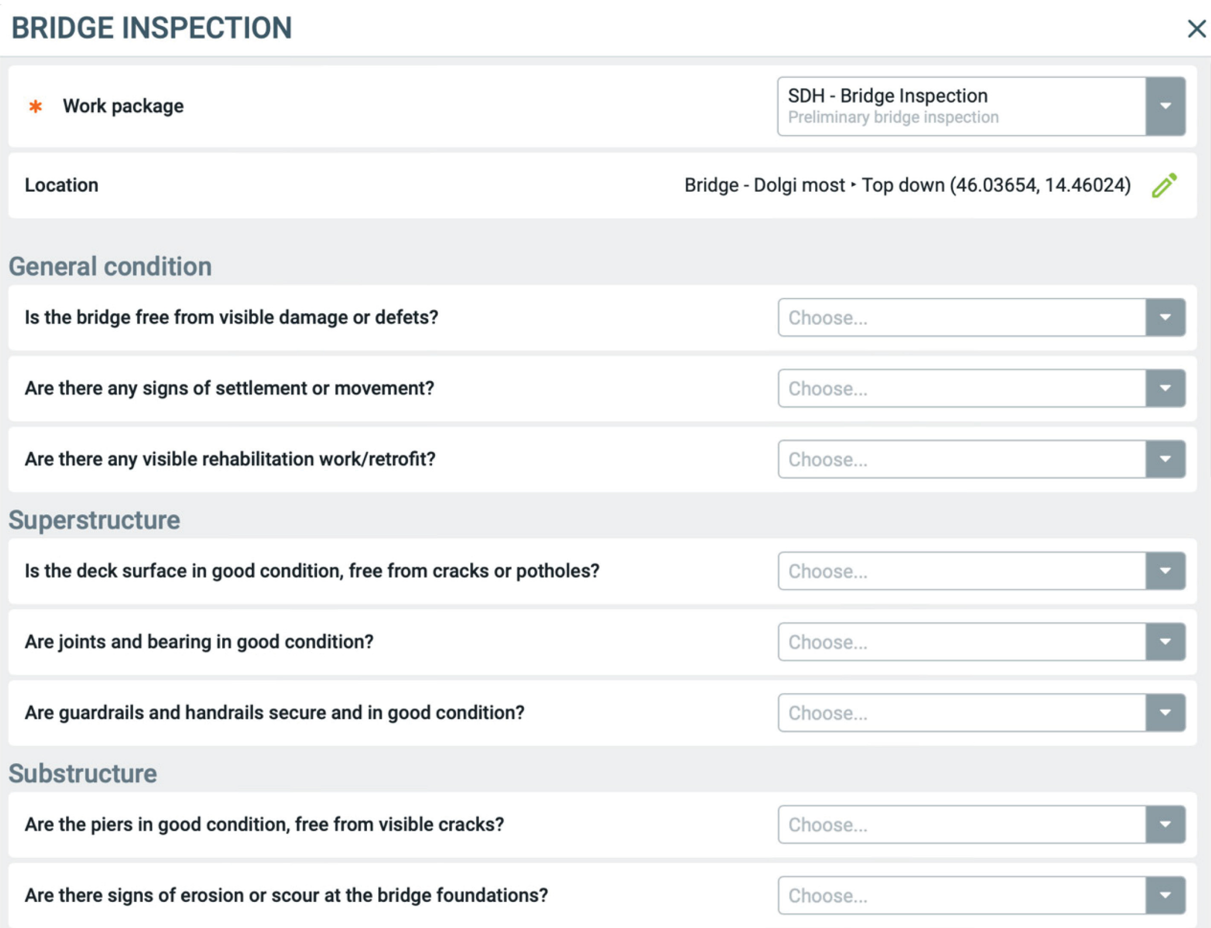


Figure 38: Formulary part 1.

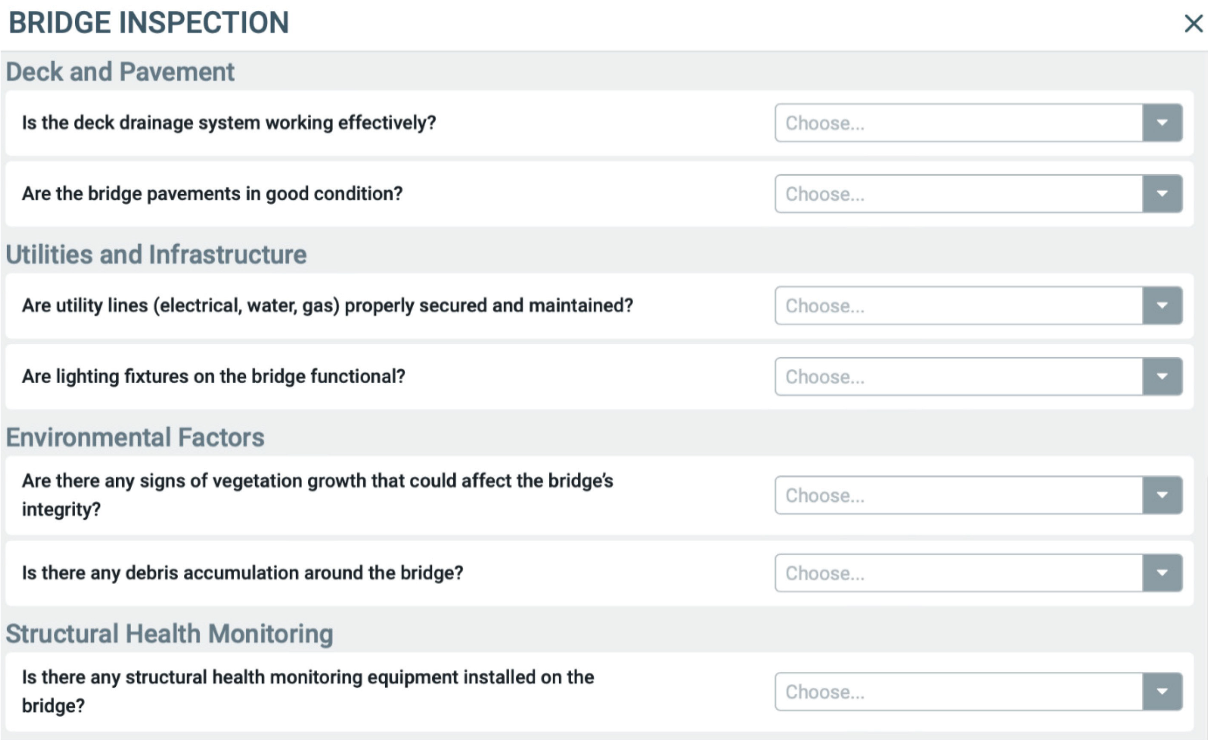


Figure 39: Formulary part 2.

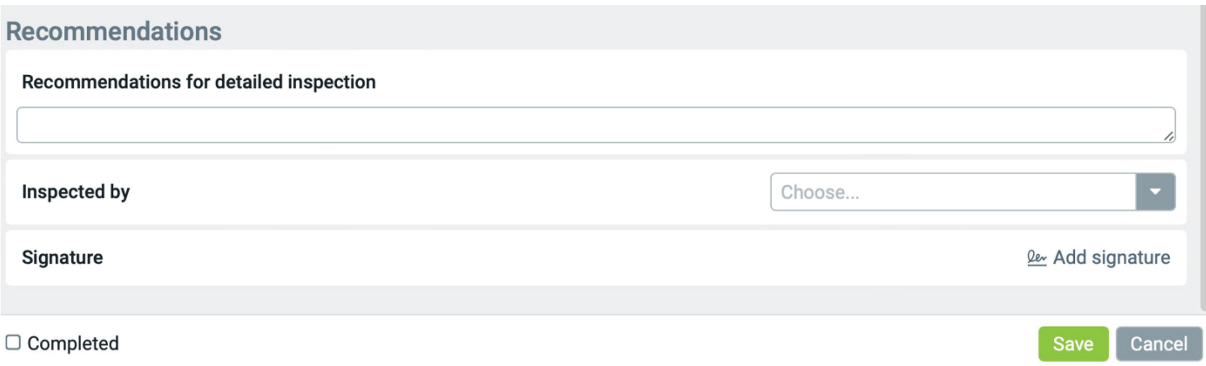


Figure 40: Formulary part 3.

On the end of the formulary, it is necessary to put the information about which inspector filled up the formulary and it is also possible to recommend actions for the project, such as a more detailed inspection on some element, or a rehabilitation plan.

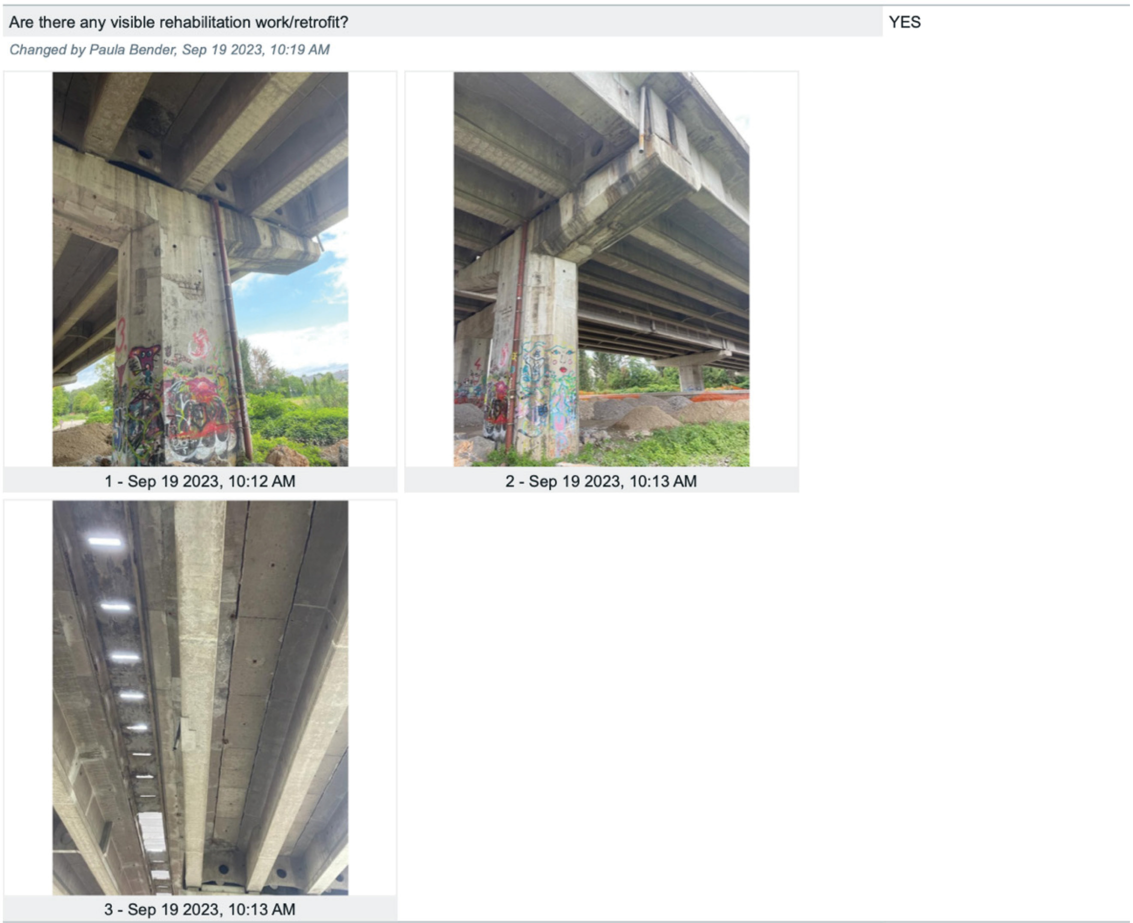


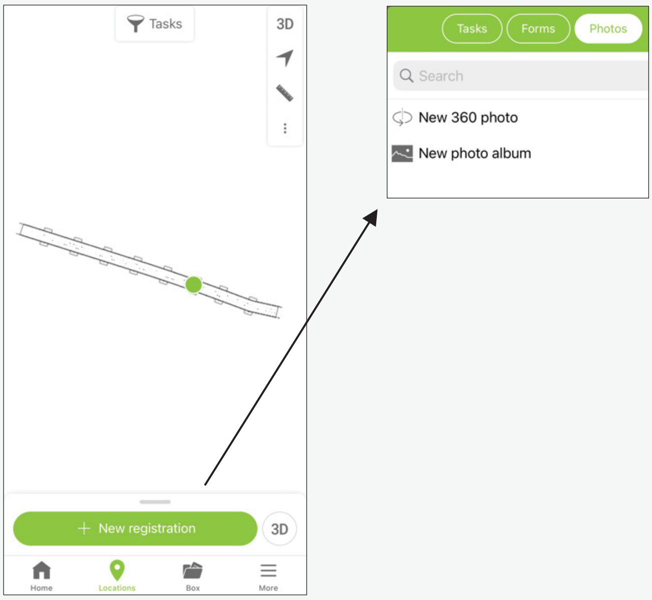
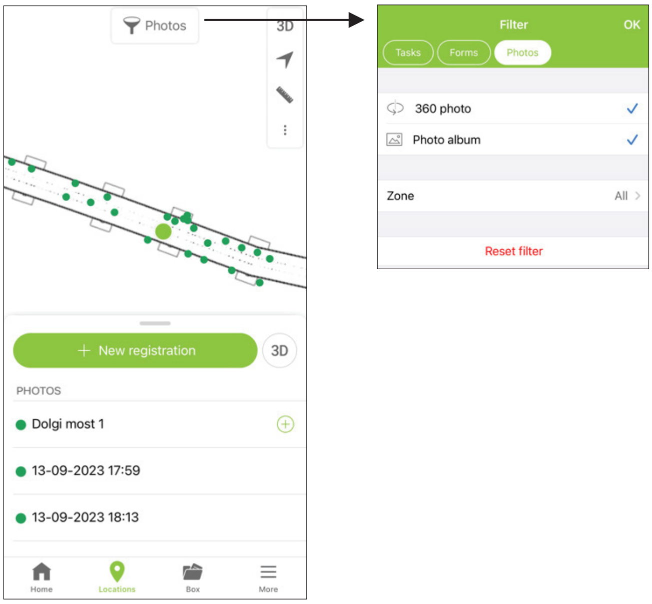
Figure 41: Inspection formulary completed.

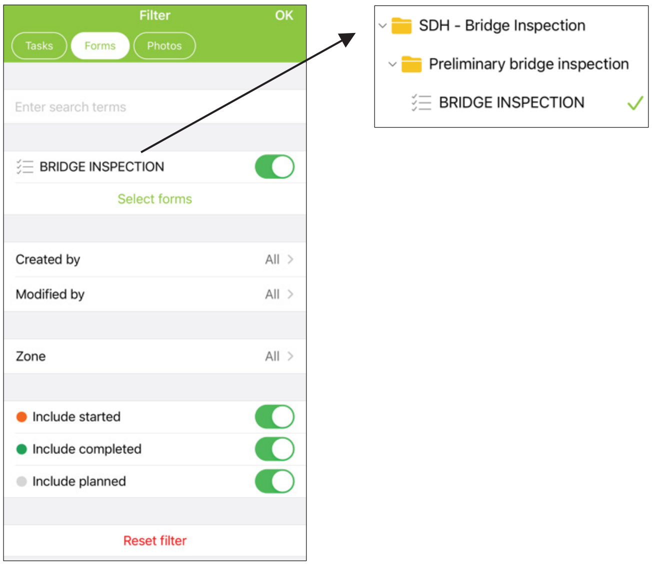
Dalux platform shows off as a powerful tool for implementing BIM in various domains. In the realm of bridge monitoring, where the safety and longevity of critical infrastructure are paramount, the platform offer potential solutions.

As a platform designed to streamline collaboration, data management and visualization in construction, it offers an intuitive interface which is ideal for bridge monitoring applications. It also allows mobility accessibility, facilitating the real-time updated. In this case of study, it was not used sensor data directly, but the software also can incorporate sensor data, which allows data analysis and visualization.

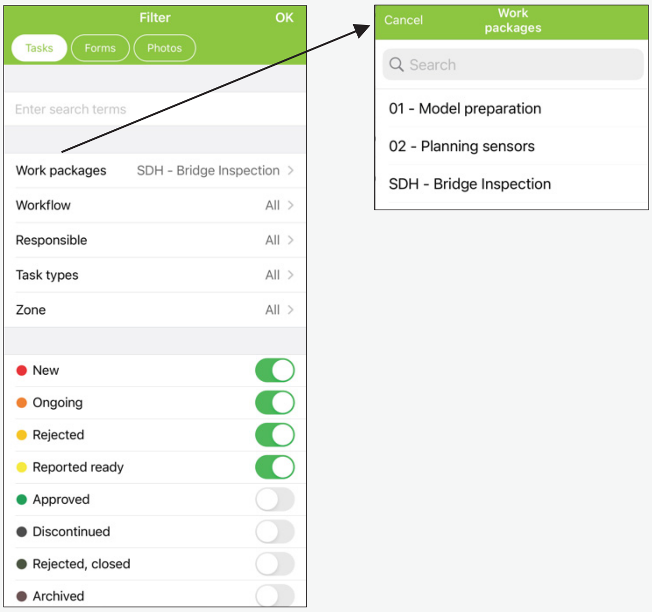
For bridge monitoring purposes the collaboration tools make it possible to do have an efficient communication and can also allow remote inspections using sensing technologies, reducing the need for physical inspections, and minimizing risks.

For the Dalux phone application the functions are similar, on Table 1 it is possible to check the step by step on how the application was used:

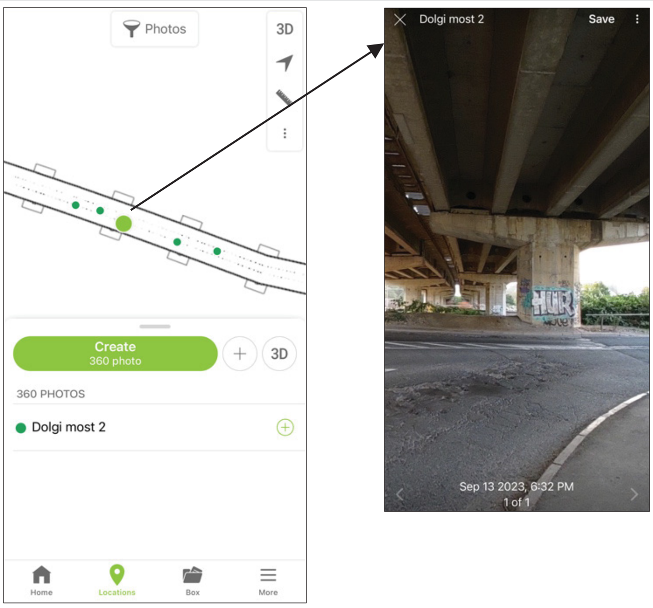
<table>
<tr><th>Dalux application</th><th>Description</th></tr>
<tr><td>
</td><td>In the location section on the application, it is available the bridge model. By clicking on an area of the bridge it is possible to add a new registration, such as regular pictures, forms or tasks.
In the pictures registration there is an option for 360º photos, with 360º caption devices it is possible to connect the app and add pictures.</td></tr>
<tr><td>
</td><td>Once registrations are added to the model, it stays visible according to the location of the register. It is also possible to change the filters in order to find the type of registration desired.</td></tr>
</table>



The filter is also available for forms. On this section it is possible to select the forms available for this project, in this case it was created one form, but it is possible to add more forms according to the needs of the project.



Another option on the application is the tasks section, it is possible to apply filter for tasks and check on the model the tasks recommended. In this case tasks can be related to model preparation, planning sensors and bridge inspection.



When applying the filter for 360º photos the model shows dots as references of the locations where the caption was register and by clicking on the dots it is possible to visualize the picture.

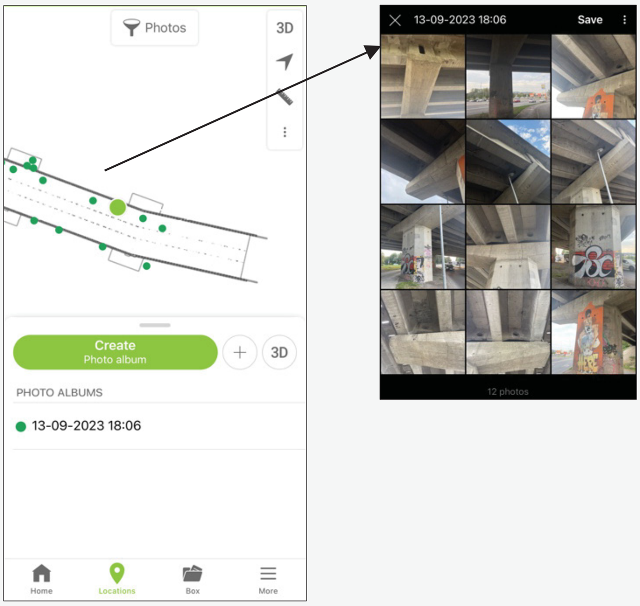
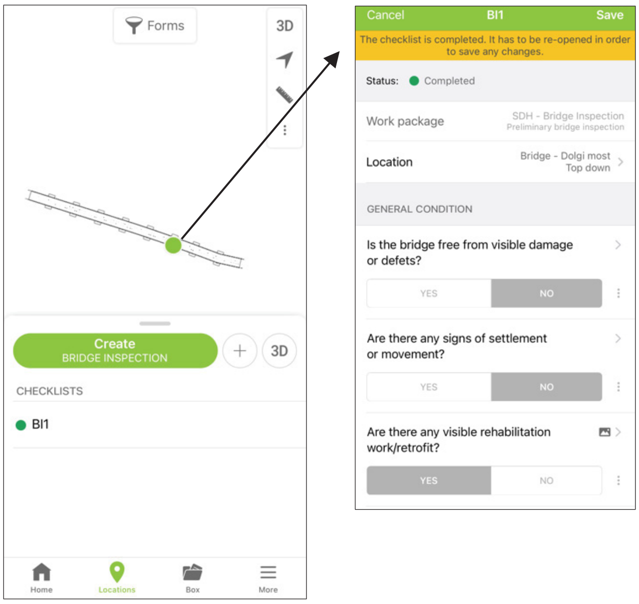
	After selecting a point with pictures, it is possible to check the albums related to that that location.
	On the forms filter it is possible to see the location where the form was registered along with the filled form.

Table 1: Steps on Dalux application for Iphone.

4.5 Comparison between BIM and traditional approaches for bridge monitoring

In an era marked by technological advancements, the integration of Building Information Modeling (BIM) in bridge monitoring has emerged as a game-changer in the sector. This chapter explores the benefits that BIM brings to bridge monitoring practices, from improving data management to enhancing decision-making processes, BIM revolutionizes how we ensure the safety and longevity of critical infrastructure.

BIM provides comprehensive 3D models of bridge structures, offering a visual representation of the entire bridge. This facilitates a deeper understanding of the bridge's intricacies. Meanwhile the traditional methods typically rely on 2D drawings and textual reports, offering less intuitive representations and struggling to capture the full complexity of the bridge.

When it comes to data management BIM acts as a centralized data repository, encompassing designs, inspection reports, and real-time sensor data. The centralization offered by BIM supported software streamlines data management. Traditional systems often involve paper-based records and disjointed digital files, making data management more susceptible to errors.

Another important aspect is the real-time monitoring. Traditional methods typically involve periodic inspections, which may miss dynamic changes in the bridge's condition. Through the BIM approach it is possible to integrate real-time sensor data into the 3D model, allowing engineers to monitor the bridge's condition as it evolves. This affects another area which is cost efficiency between the approaches, while BIM optimizes resource allocation by identifying critical areas that require immediate attention, preventing unnecessary spending, the traditional methods may lead to resource inefficiencies as maintenance efforts are not always target based on real-time data.

Collaboration between stakeholders in traditional approaches may be limited due to the use of disparate data sources and formats. With the data centralization and format standardization BIM offers a more dynamic collaboration between engineers, architects, and maintenance teams. The use of sensor information and historical data can prevent costly repairs and ensures continuous bridge functionality, offering a predictive maintenance. Traditional systems usually rely on routine inspections and may not offer predictive maintenance capabilities.

When effectively applied BIM also improves safety of the structure, through it's real-time monitoring capabilities it is possible to early detect anomalies or structural issues. Other methods may result in delayed detection of safety issues, potentially leading to safety hazards. BIM technology can also simplify documentation and reporting for regulatory compliance, ensuring that bridges adhere to safety standards, while traditional systems may require more manual effort to meet regulatory requirements.

At last BIM can incorporate sustainability parameters, promoting ecological practices in bridge maintenance and management. Traditional methods may not prioritize sustainability to the same extend. In summary, the BIM approach for bridge monitoring systems offers advantages in terms of data visualization, real-time monitoring, collaboration, predictive maintenance, cost efficiency, safety regulatory compliance, and sustainability. It leverages technology to provide a proactive approach to bridge management when compared to traditional methods that often rely on manual processes and periodic inspections.

5 CONCLUSION

This research aimed to implement Building Information Modelling into bridge monitoring and maintenance through a study of case. We provide a brief overview of lessons learned, critique of the approach and suggestions for the future work.

5.1 Lessons learned

As demonstrated by the research and the discussion raised, it is evident that BIM plays a significant role in optimizing processes since the design into the operational phase of a structure. In order to address the challenges of this work, a simulation of BIM implementation for an existent bridge was created.

The outcomes indicate that the BIM approach when compared to traditional approaches can optimize the management of a bridge and improve the decision-making process.

This research has identified that the centralizing the data by a BIM software can improve the usability of information by the stakeholders. Having all the data integrated, visualization tools and real-time monitoring can redefine the standards of bridge maintenance. Systems that integrate GIS through BIM provide a powerful tool to the maintenance of structures and requires collaboration of experts in the field and a gradual implementation of technology.

The study contributes to the understanding of BIM implementation process for existing structures and the tools and advantages that can be explored in this field. The ability of BIM to facilitate communication among stakeholders, has been crucial in optimizing workflows and promoting informed decision-making. Moreover, this process can transform monitoring system into a proactive process, enabling predictive maintenance strategy that can ensure the safety and longevity of bridges.

5.2 Limitations of the study

Defining steps for implementation of BIM was critical in this process, especially when there is so many data to be integrated like in this case of study. This dissertation has provided the benefits of implementing this technology and the difficulties faced by traditional approaches of bridge monitoring, such as visual inspections. Isolate data of structural monitoring can be come inefficient when not properly explored, which leads bridge management more susceptible to errors.

For an effective and accurate implementation and integration it can be demanded a long period of time and the collaboration of different experts in this area, which could make the process difficult and expensive. For this study it was considered a specific bridge, the application of this process in different in different structures or environmental conditions can face issues and limitations.

Overall, this work gathered information of different monitoring approaches, in order to evaluate the systems and try a methodology of implementation for the case of study.

5.3 Future work

Future research could continue to explore the integration of GIS through BIM, focusing on the maintenance and rehabilitation phases, in order to achieve different solution for more types of structures. For instance, in the operational phase, more BIM uses could be considered, such as BIM integration with sensor data and also studies to improve remote inspections for bridges.

6 REFERENCES

Adu-Gyamfi, Y., Chase, S., Aktan, A. in Minaie. (2016). *Synthesis of National and International Methodologies Used for Bridge Health Indices*. https://doi.org/10.13140/RG.2.1.1558.1683

Bien, J. in Kużawa, M. (2020). Dynamic Tests in Bridge Health Monitoring. *Studia Geotechnica et Mechanica*, *42*. https://doi.org/10.2478/sgem-2019-0045

Bień, J., Kużawa, M. in Kamiński, T. (2020). Strategies and tools for the monitoring of concrete bridges. *Structural Concrete*, *21*(4), 1227–1239. https://doi.org/https://doi.org/10.1002/suco.201900410

Board, T. R., of Sciences Engineering in Medicine. (2012). *Estimating Life Expectancies of Highway Assets, Volume 1: Guidebook*. (P. D. Thompson, K. M. Ford, M. H. R. Arman, S. Labi, K. C. Sinha, & A. M. Shirole, Ur.). Washington, DC: The National Academies Press. https://doi.org/10.17226/22782

Boller, C. (2000). Next generation structural health monitoring and its integration into aircraft design. *International Journal of Systems Science*, *31*(11), 1333–1349. https://doi.org/10.1080/00207720050197730

Byun, N., Han, W., Kwon, Y. in Kang, Y. (2021). Development of BIM-Based Bridge Maintenance System Considering Maintenance Data Schema and Information System. *Sustainability*, *13*, 4858. https://doi.org/10.3390/su13094858

Casas, J. in Moughty, J. (2017). Bridge Damage Detection Based on Vibration Data: Past and New Developments. *Frontiers in Built Environment*, *3*. https://doi.org/10.3389/fbuil.2017.00004

Chen, Z., Zhou, X., Wang, X., Dong, L. in Qian, Y. (2017). Deployment of a Smart Structural Health Monitoring System for Long-Span Arch Bridges: A Review and a Case Study. *Sensors*, *17*(9). https://doi.org/10.3390/s17092151

Cheung, W.-F., Lin, T.-H. in Lin, Y.-C. (2018). A Real-Time Construction Safety Monitoring System for Hazardous Gas Integrating Wireless Sensor Network and Building Information Modeling Technologies. *Sensors*, *18*(2). https://doi.org/10.3390/s18020436

Comisu, C. C., Taranu, N., Boaca, G. in Scutaru, M.-C. (2017). Structural health monitoring system of bridges. *Procedia Engineering*, *199*, 2054–2059. https://doi.org/10.1016/j.proeng.2017.09.472

Deivasigamani, A., Daliri, A., Wang, C. in John, S. (2013). A review of passive wireless sensors for structural health monitoring. *Modern Applied Science*, *7*(2), 57–76. https://doi.org/10.5539/mas.v7n2p57

Dessi, D. in Camerlengo, G. (2015). Damage identification techniques via modal curvature analysis: Overview and comparison. *Mechanical Systems and Signal Processing*, *52–53*, 181–205. https://doi.org/https://doi.org/10.1016/j.ymssp.2014.05.031

Dong, S., Li, H. in Yin, Q. (2018). Building information modeling in combination with real time location systems and sensors for safety performance enhancement. *Safety Science*, *102*, 226–237. https://doi.org/https://doi.org/10.1016/j.ssci.2017.10.011

Estes, A. in Frangopol, D. (2001). Bridge Lifetime System Reliability Under Multiple Limit States. *Journal of Bridge Engineering - J BRIDGE ENG*, *6*. https://doi.org/10.1061/(ASCE)1084-0702(2001)6:6(523)

Farrar, C. R. in Worden, Keith. (2007, februar). An introduction to structural health monitoring. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences, 365(1851)*, 303–315. https://doi.org/10.1098/rsta.2006.1928

Figueiredo, E. in Brownjohn, J. (2022). Three decades of statistical pattern recognition paradigm for SHM of bridges. *Structural Health Monitoring*, *21*(6), 3018–3054. https://doi.org/10.1177/14759217221075241

Gattulli, V. in Chiaramonte, L. (2005). Condition Assessment by Visual Inspection for a Bridge Management System. *Computer-Aided Civil and Infrastructure Engineering*, *20*(2), 95–107. https://doi.org/https://doi.org/10.1111/j.1467-8667.2005.00379.x

GRADIS BP Maribor d.o.o. (2001). *Dolgi most project*. Maribor.

Greco, F., Lonetti, P. in Zinno, R. (2002). An analytical delamination model for laminated plates including bridging effects. *International Journal of Solids and Structures*, *39*(9), 2435–2463. https://doi.org/https://doi.org/10.1016/S0020-7683(02)00118-X

Hallermann, N. in Morgenthal, G. (2014). *Visual inspection strategies for large bridges using Unmanned Aerial Vehicles (UAV)*. https://doi.org/10.1201/b17063-96

Ibanez, S. P., Fitz, T. in Smarsly, K. (b. d.). A Semantic Model for Wireless Sensor Networks in Cognitive Buildings. V *Computing in Civil Engineering 2019* (str. 234–241). https://doi.org/10.1061/9780784482445.030

International Association for Bridge and Structural Engineering (IABSE) . (2020, december).

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

Khan, S. M., Atamturktur, S., Chowdhury, M. in Rahman, M. (2016). Integration of Structural Health Monitoring and Intelligent Transportation Systems for Bridge Condition Assessment: Current Status and Future Direction. *IEEE Transactions on Intelligent Transportation Systems*, *17*(8), 2107–2122. https://doi.org/10.1109/TITS.2016.2520499

Lea, F. C. in Middleton, C. R. (2002). *Reliability of visual inspection of highway bridges*. Department of Engineering, University of Cambridge Cambridge, UK.

Li, H. in Ou, J. (2016). The state of the art in structural health monitoring of cable-stayed bridges. *Journal of Civil Structural Health Monitoring*, *6*(1), 43–67. https://doi.org/10.1007/s13349-015-0115-x

Liu, W., Hauser, E., Chen, S. in Haywood, G. (b. d.). A Study on Current Bridge Maintenance Policies. V *ICCTP 2011* (str. 244–254). https://doi.org/10.1061/41186(421)27

Mustapha, S., Lu, Y., Ng, C.-T. in Malinowski, P. (2021). Sensor Networks for Structures Health Monitoring: Placement, Implementations, and Challenges—A Review. *Vibration*, *4*(3), 551–585. https://doi.org/10.3390/vibration4030033

Nassif, H. H., Gindy, M. in Davis, J. (2005). Comparison of laser Doppler vibrometer with contact sensors for monitoring bridge deflection and vibration. *NDT & E International*, *38*(3), 213–218. https://doi.org/https://doi.org/10.1016/j.ndteint.2004.06.012

Nepomuceno, D., Bennetts, J., Pregnolato, M., Tryfonas, T. in Vardanega, P. (2022). Development of a schema for the remote inspection of bridges. *Bridge Engineering*. https://doi.org/10.1680/jbren.22.00027

Nepomuceno, D., Vardanega, P., Tryfonas, T., Pregnolato, M., Bennetts, J. in Webb, G. (2022). A survey of emerging technologies for the future of routine visual inspection of bridge structures (str. 846–854). https://doi.org/10.1201/9781003322641-101

Overbey, L. (2008). Time series analysis and feature extraction techniques for structural health monitoring applications.

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

Rizzo, P. in Enshaeian, A. (2021). Challenges in Bridge Health Monitoring: A Review. *Sensors*, *21*, 4336. https://doi.org/10.3390/s21134336

Runcie, P., Mustapha, S. in Rakotoarivelo, T. (2014). Advances in structural health monitoring system architecture. Pridobljeno s https://api.semanticscholar.org/CorpusID:63036915

Sohn, H., Farrar, C. R., Hemez, F. M. in Czarnecki, J. J. (2002). A Review of Structural Health Review of Structural Health Monitoring Literature 1996-2001. United States. Pridobljeno s https://www.osti.gov/biblio/976152

Tenzera, D., Puz, G. in Radić, J. (2012). Visual inspection in evaluation of bridge condition. *Gradevinar*, *64*, 717–726. https://doi.org/10.14256/JCE.718.2012

THE IABMAS BRIDGE MANAGEMENT COMMITTEE OVERVIEW OF EXISTING BRIDGE MANAGEMENT SYSTEMS 2014. (2014).

Theiler, M. in Smarsly, K. (2018). IFC Monitor – An IFC schema extension for modeling structural health monitoring systems. *Advanced Engineering Informatics*, *37*, 54–65. https://doi.org/https://doi.org/10.1016/j.aei.2018.04.011

Zhao, W. in Liang, Y. (2015). Energy-Efficient and Robust In-Network Inference in Wireless Sensor Networks. *IEEE Transactions on Cybernetics*, *45*(10), 2105–2118. https://doi.org/10.1109/TCYB.2014.2365541

Zinno, R., Haghshenas, S. S., Guido, G. in VItale, A. (2022). Artificial Intelligence and Structural Health Monitoring of Bridges: A Review of the State-of-the-Art. *IEEE Access*, *10*, 88058–88078. https://doi.org/10.1109/ACCESS.2022.3199443

Zinno Raffaele and Artese, S. and C. G. and M. F. and M. S. and M. A. and V. A. (2019). Structural Health Monitoring (SHM). V A. and M. C. and S. G. and V. A. Cicirelli Franco and Guerrieri (ur.), *The Internet of Things for Smart Urban Ecosystems* (str. 225–249). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-96550-5_10