e-BrIM

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Front Cover: *1915Çanakkale Bridge, Turkey* ***Credit:*** *ÇOK A.Ş.*

Back Cover: *BIM and Parametric Modelling in Bridge Engineering* ***Credit:*** *GEN+*

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Dear Readers

The first article provides a brief overview of the ***1915Çanakkale Bridge*** *in Turkey and information on how it is operated and maintained. A bit more detailed insight can be found in the interview with its Project Engineering Manager. At the end, you can also find a link to our special e-mosty edition about the design and construction of the Bridge with an interview with its CEO.*

In the next article, the authors from the company GEN+ propose an ***innovative approach by implementing the AI-BrIM prototype****, which integrates a machine learning-based model at the conceptual stage of the project.*

I was happy to ***interview Professor Marek Salamak*** *who is on the Editorial Board of our magazine. We talked, among other things, about his career, projects, BIM – and BrIM.*

It is followed by a recent study whose aim was the ***integration of the SHM system with MR devices*** *on the industrial scale. For this purpose, field experimentation was performed to integrate a real-life SHM system with BIM technology to visualize the SHM results in MR.*

I would like to ***thank all the people and companies*** *that have been cooperating on this issue and helping me put it together; big thanks to the members of the Editorial Board for reviewing the articles and their cooperation, especially* ***Professor Chang-Su Shim*** *and* ***Professor Marek Salamak.***

We would also like to ***thank our partners for their support****.*

On behalf of the organizers, and as a media partner, we would like to invite you to the ***IABMAS 2024 Conference*** *which will be held in Copenhagen, Denmark from 24th to 28th June 2024. Please find more information on page 8.*

We have started to support ***Enginers in Action****; apart from the regular advertisement, we will also bring articles about their activities and achievements in the next* ***e-mosty&e-BrIM*** *magazines.*

We are already working on the next issue of e-BrIM which will be released on 20th May 2024. The next e-mosty will be released on 20th March 2024 and will be dedicated to American Bridges.

Magdaléna Sobotková

Chief Editor

e-BrIM

The magazine **e-BrIM** is an international, interactive, peer-reviewed magazine about bridge information modelling.

It is published at www.e-brim.com and can be read free of charge (open access) with the possibility to subscribe.

It is typically published three times a year:
20 February, 20 May and 20 October.

The magazines stay **available online** on our website as pdf.

The magazine brings **original articles** about **bridge digital technology** from early planning till operation and maintenance, **theoretical and practical innovations, Case Studies** and much more from around the world.

Its electronic form enables the publishing of high-quality photos, videos, drawings, 3D models, links, etc.

We aim to include **all important and technical information, to share theory and practice, knowledge and experience** and at the same time, to show the grace and beauty of the structures.

We are happy to provide media support for important BIM and bridge conferences, educational activities, charitable projects, books, etc.

Our Editorial Board comprises BIM and bridge experts and engineers from academic, research and business environments and the bridge industry.

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ABOUT BRIDGES

e-mosty

The magazine **e-mosty** ("e-bridges")
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peer-reviewed magazine about bridges.

It is published at www.e-mosty.cz and can be read
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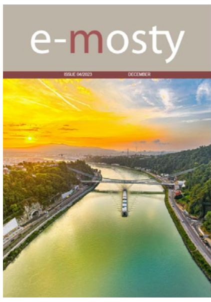

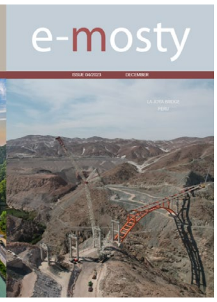

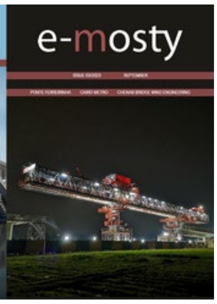

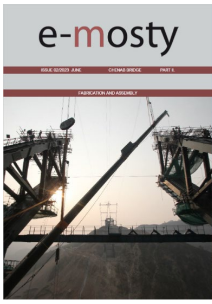

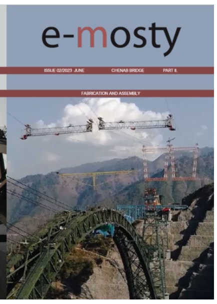

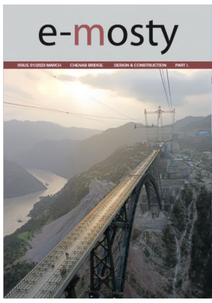

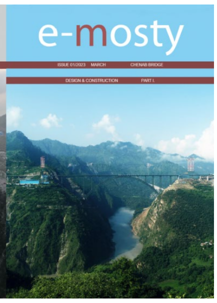

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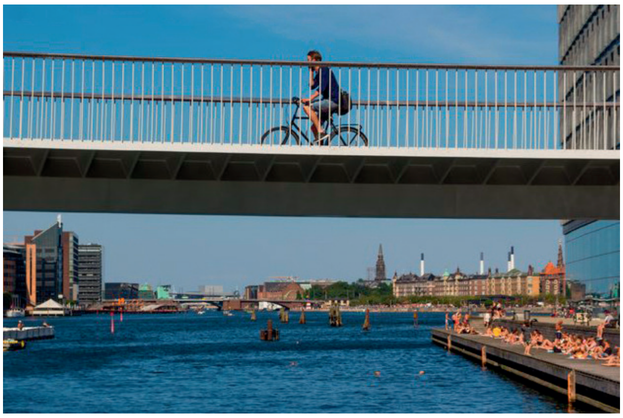

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Join us in the vibrant city of Copenhagen for an unforgettable experience at the forefront of bridge maintenance, safety, and management. The anticipation is building, and we can't wait to welcome you to this hub of innovation and collaboration.

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We look forward to seeing you in Copenhagen

1915ÇANAKKALE BRIDGE, TURKEY
OPERATION AND MAINTENANCE

Ferruh Aytekin
Project Engineering Manager

Figure 1: Night View of the Bridge

ABOUT THE PROJECT

The 1915Çanakkale Bridge and Motorway Project comprises 89 km of the motorway (including the 1915Çanakkale Bridge) and 12 km of access roads between Malkara and Çanakkale, see Figure 2.

It is a segment of the 325km-long Kınalı-Tekirdağ-Çanakkale-Savaştepe Motorway Project.

Besides the 1915Çanakkale Bridge, the project also includes the construction of two concrete viaducts, 12 junctions (including those on the state road), 12 bridges, 43 overpasses (including one ecological overpass), 40 underpasses, 235 culverts, four motorway service areas, two operation and maintenance centres, and five toll plazas.

Figure 2: Project location with the Bridge marked in blue colour

__Project Length:__ 101 km

__Duration of Construction and Operation:__

16 Years 2 Months 12 Days

(5 Years 6 Months Construction
+10 Years 8 Months 12 Operation Days)

__Appointed Company:__ Çanakkale Motorway and Bridge Construction Investment and Operation Inc.

__Contractor:__ DL E&C – Limak – SK ecoplant–Yapı Merkezi

__Operator Company:__ Intertoll Turkey Operation and Maintenance Inc

THE 1915ÇANAKKALE BRIDGE

The Bridge spans Çanakkale Strait (Dardanelles) between Gelibolu and Lapseki. It connects Europe and Asia.

With its main span of 2,023 m, it is currently the longest suspension bridge in the world.

Thanks to the addition of Seyit Onbaşı artillery shell figures to the 318 m steel towers, see Figures 3 and 4, it also has the world's tallest towers at a peak height of 334 m.

The Bridge was opened to traffic on 18th March 2022.

Figures 3 and 4: View of the towers with Seyit Onbaşı artillery shell figures

ORGANIZATION

The General Directorate of Highways commissioned the 1915Çanakkale Bridge and the Kınalı-Tekirdağ-Çanakkale-Savaştepe Motorway Project Malkara - Çanakkale section Motorway Project to a Turkish-Korean joint-venture in 2017 within the framework of the public-private partnership model.

This joint venture was formed by Limak and Yapı Merkezi from Turkey and DL E&C and SK ecoplant from Korea. It was named DLSY JV and established a joint-venture company specific to the project, under the name of Çanakkale Motorway Bridge Construction Investment Management Inc. The joint-venture was awarded a Build-Operate-Transfer contract for the project.

Intertoll Turkey Operation and Maintenance Inc. is the O&M sub-contractor related to the operation and maintenance project Malkara-Çanakkale section, including the 1915Çanakkale Bridge. It is part of Intertoll Europe, an independent infrastructure developer, operator and maintenance provider, and toll operator with its head office in Budapest, Hungary.

PUBLIC-PRIVATE PARTNERSHIP (PPP) MODEL

Public-private partnership (PPP) generally refers to the implementation of investments and services through a contractual agreement, involving the sharing of costs, risks, and returns between the public and private sectors.

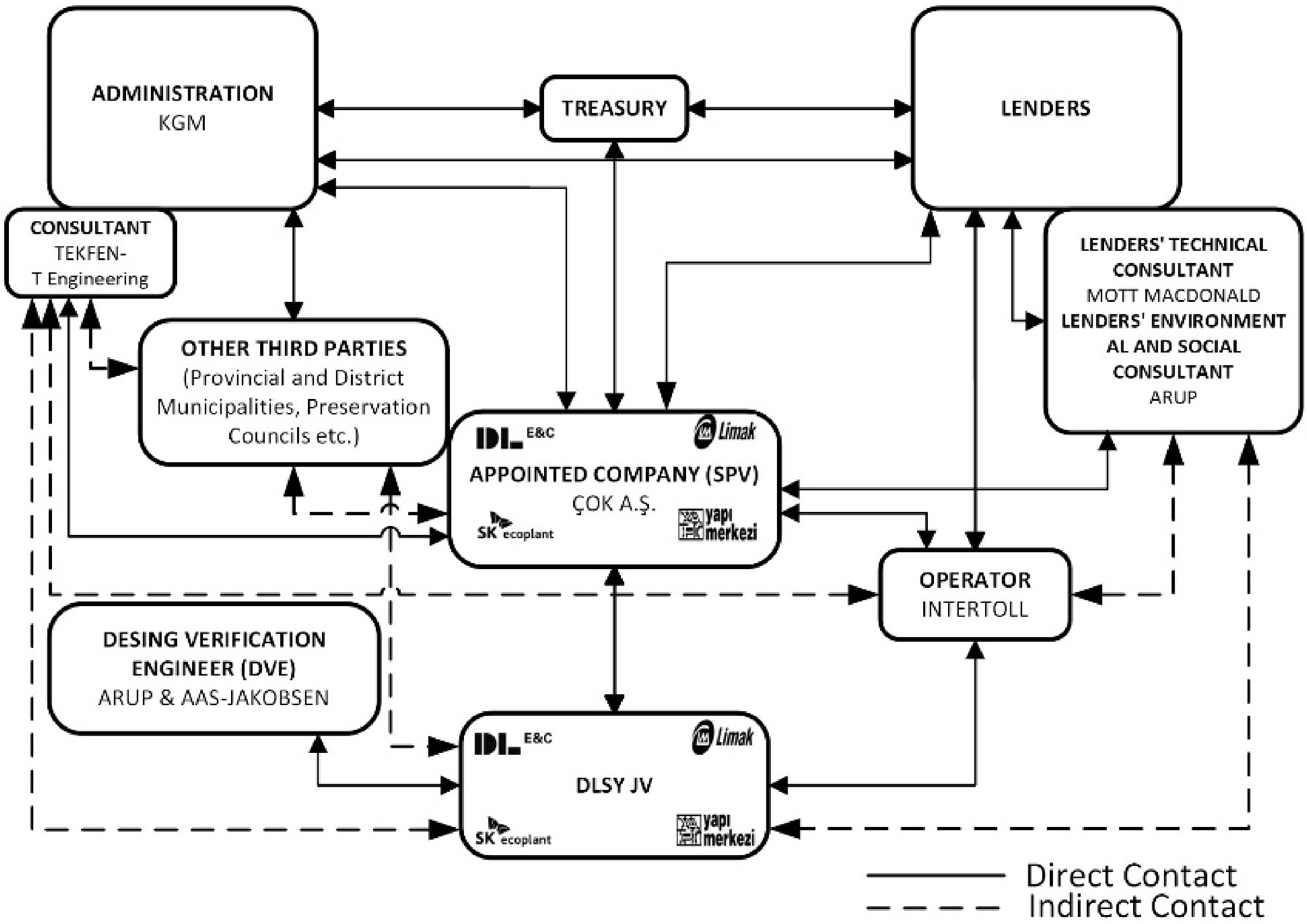


Figure 5: Organizational Chart

Originally conceived as a means to secure financing for national infrastructure projects, PPP has evolved into a model emphasizing the effective managerial capabilities of the private sector.

In this framework, the public sector is strategically positioned to focus on areas such as investment coordination, overarching planning, supervision, and policy formulation.

OPERATION AND MAINTENANCE

The O&M sub-contractor organization is responsible for inspections and monitoring systems.

The long main span combined with extreme wind loads and possible earthquakes put engineering capabilities to the test.

The Bridge faces several challenges including aerodynamics, ship traffic, seismic activity and adverse soil conditions.

The Bridge is critical for enhancing regional connectivity which poses high demands in regard of its maintenance and operation.

You can read more about the Operation and Maintenance of the Bridge in the following interview with Ferruh Aytekin.

Acknowledgement:

Diyez Beksaç, Corporate Communications Senior Manager, ÇOK A.Ş.

Figure 6: The beauty of the bridge enhanced by the beauty of the nature

INTERVIEW WITH FERRUH AYTEKIN PROJECT ENGINEERING MANAGER 1915ÇANAKKALE BRIDGE

Magdaléna Sobotková

First of all, thank you for your time.

How does the PPP model work with regard to the Operation and Maintenance (O&M) scheme?

In a Public-Private Partnership (PPP) model concerning Operation and Maintenance (O&M), the private partner is selected through competitive bidding. The PPP agreement outlines O&M responsibilities, performance standards, and payment mechanisms.

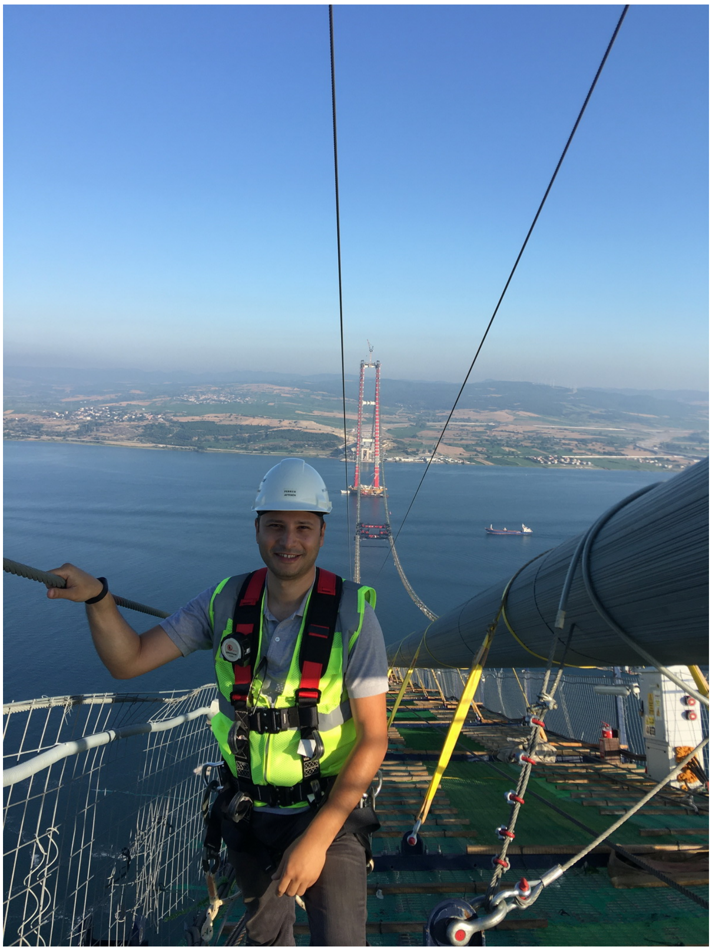
The private partner manages O&M throughout the concession period, with the public sector monitoring. The payment structure, risk allocation, and asset transfer at the end of the concession period are key aspects, ensuring sustained infrastructure or service functionality.

Therefore these are the advantages of their PPP models.

What is your approach to the maintenance of the Bridge? Do you have a structural health monitoring system (SHMS) and a bridge maintenance system (BMS)?

The design service life of the Bridge is planned as 100 years. This design life will be achieved via routine maintenance as well as via the replacement of elements associated with design service lives below 100 years.

SHMS will play a major role in providing input to data-driven decision-making affecting the maintenance strategy of the bridge and timing the replacements. We have implemented possibly the most comprehensive SHM system to fulfil these objectives.



On the bridge´s catwalk during construction

1034 sensors are the sources of big data, ensuring that the bridge is well maintained and serving the R&D activities for public and private partners.

How are the inspection and maintenance activities arranged? How often do you have periodical inspections of the Bridge?

Inspection and maintenance procedures adhere to the specifications outlined by the General Directorate of Highways, following the guidelines in the I&M manual provided by the Bridge designer and the O&M manuals of suppliers. These activities are categorized into five types: "routine inspections/maintenance," "principal inspections," "special inspections," "major maintenance," and "surveying." This classification aids in the systematic organization of efforts to ensure the safety and optimal functioning of equipment and infrastructure.

Routine inspection and maintenance tasks are conducted at regular intervals, spanning weeks, months, or annually. These tasks primarily involve visual inspections and ad-hoc maintenance activities, often carried out by walking or driving on the Bridge. Permanent inspection and maintenance personnel typically handle routine tasks.

How do you arrive at the decision to restrict usage of a bridge?

The 1915Çanakkale Bridge is subject to important traffic intensities. The safety of all users crossing the Bridge is of the utmost importance. In this regard, the SHMS is used to monitor the environmental conditions loads and load responses of the Bridge and detect situations where user safety is reduced.

For those situations, alert notifications are being sent to relevant stakeholders to take appropriate traffic management actions. Below you see the different 5 stages of wind-related restrictions.

What are the activities for winter maintenance?

During the winter season, meteorological data obtained from the General Directorate of Meteorology and external winter maintenance services are monitored. When the asphalt temperature, as recorded by on-site patrols, drops below 2°C, preventive maintenance activities are initiated for the suspension bridge.

To counteract the adverse effects of NaCl on the steel surface of the Bridge, a urea solution is applied.

Inspection of bearings

If the snowfall is within normal limits and the urea solution can effectively melt the snow, snow ploughing is not undertaken.

However, in extreme conditions where the solution proves insufficient to melt the snow on the bridge, snow ploughing is carried out across all three lanes. In instances where the shoulder width is inadequate to accommodate snow accumulation due to heavy snowfall, winter maintenance is conducted through snow ploughing in only two lanes, considering the absence of a shoulder on the bridge section.

In situations where temperatures are too low for the urea solution to function optimally, there is a planned use of magnesium chloride and a corrosion inhibitor solution as alternatives.

Ready for winter maintenance

Gust wind speed at deck level (m/s)	Restrictions
15 m/s	65 km/h speed limit on all traffic
20 m/s	Closed to double-decker buses
22 m/s	Closed to high-sided heavy goods vehicles and wind susceptible vehicles
29 m/s	Closed to all vehicles except cars
35 m/s	Closed to all vehicles

How often do you inspect the Bridge? What activities does it involve?

Principal inspections involve a detailed visual examination aimed at evaluating the current condition of the structure, analysing defect development, and assessing maintenance needs. These inspections occur at predetermined intervals, often set at 5 or 10-year spans according to the guidelines outlined in the designer manual.

On the other hand, special inspections typically require specialized personnel and equipment to perform measurements and testing. These inspections are usually prompted by the findings of principal inspections or routine I&M, indicating the necessity for further investigation to ascertain the structure's condition and the need for repairs. Such special inspections are particularly initiated after significant events with potential structural implications, such as fires, earthquakes, ship impacts, high winds, or vehicular collisions.

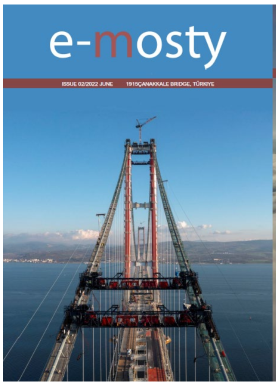
What is the length of the main cable and how long does it take to walk from one side to another?

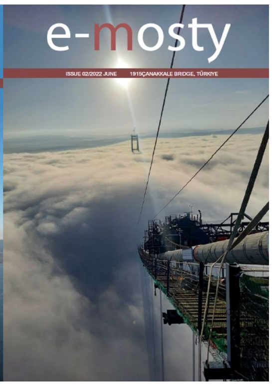
The main cable extends approximately 4.5 km in length, and traversing it takes approximately two hours. However, it is uncommon, from a practical standpoint, to walk the entire main cable for inspection purposes. Instead, inspections are typically conducted at specific points.

If a comprehensive inspection of the main cable is needed, one that does not necessarily require human contact, drones are the preferred choice.

Main Control Room

You can read about the design and construction of the Bridge
and an interview with its CEO Mustafa Tanrıverdi in the special e-mosty edition:





AI-BrIM: A PROTOTYPE FOR BRIDGE CONCEPTUAL DESIGN BASED ON HISTORICAL DATA

Alejandro Palpan, Project Manager, Fabrizio Inga, Bridge Computational Designer, Viviana Raraz, Research & Development

GEN+

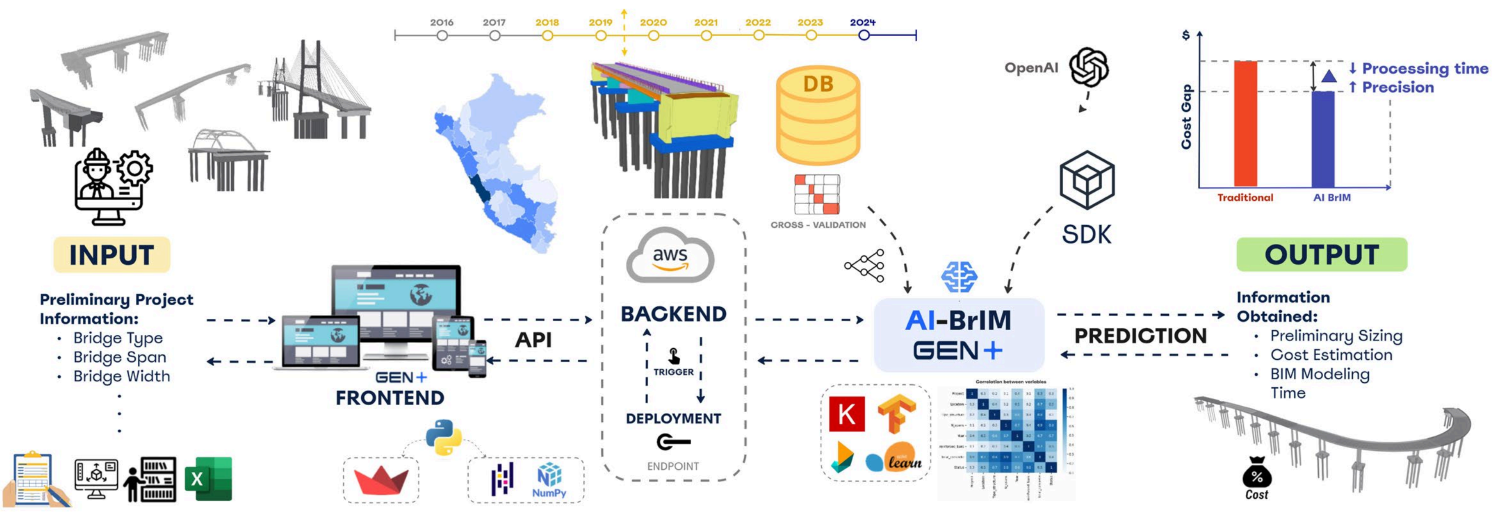


Figure 1: AI-BrIM prototype

INTRODUCTION

In the engineering and construction industry, accurate cost estimating is a vital element to the success of any project. Specifically, in the conceptual and schematic design phases, owners seek more accurate estimates to make crucial decisions about project feasibility. However, in these early stages, project scope information can be fluid and subject to change.

Currently, conceptual cost estimates are based on ratios obtained from historical data from previous projects. This practice, although common, often leads to rough estimates, resulting in a gap between actual and estimated costs.

The introduction of statistical and artificial intelligence methods is creating a noticeable change in this landscape. Machine learning, in particular, has emerged as a promising tool for improving the accuracy of cost estimates in engineering and construction. This technology offers automation, prediction and various forms of learning that can revolutionize project management and reduce associated costs. However, it is crucial to recognize that the success of these methods depends largely on the quality and preparation of the data used. Despite technological advances, the construction industry is still lagging behind in terms of digitization adoption, falling behind other industries.

In this context, this paper proposes an innovative approach by implementing the AI-BrIM prototype, which integrates a machine learning-based model at the conceptual stage of the project. To address the challenges of limited data, the use of the k-fold Cross Validation method is proposed to optimize the model. In addition, four Machine Learning models will be tested and evaluated to select the most accurate one.

Finally, the implementation of this prototype on the web is proposed to make it accessible and easy to use, performing fast and accurate estimates with the objective of closing the gap between conceptual and final cost estimates.

ARTIFICIAL INTELLIGENCE

Artificial intelligence (AI) is currently an advanced technology applied in various ways in several sectors. One of the sectors with the greatest potential for application is the AEC (Architecture, Engineering and Construction) industry since there are opportunities to optimize decision making, automate tasks and reduce costs in the construction cycle.

There are also multiple initiatives to integrate artificial intelligence tools to enhance building information modelling (BIM).

On the other hand, machine learning (ML) has the ability to predict using historical data. There are three types of ML techniques: supervised, unsupervised and reinforcement learning. The presented analysis benefits from the availability of historical data in the cost estimation process, highlighting the effectiveness of supervised learning. In addition, it is crucial to use machine learning models that enable the estimation of multiple variables to obtain more complete and accurate results.

BRIDGE INFORMATION MANAGEMENT

Every engineering project has inherent variability due to the difference in site conditions and the particularities of each project. To reduce this variability, it is necessary to integrate the various specialities and manage the information integrally. It is in this context that the BIM methodology arises, which seeks to generate an integral flow and a collaborative environment that allows the early detection of conflicts.

Bridges, as complex structures, require the collaboration of various specialities and disciplines. In addition, they must handle a large amount of data associated with design and construction.

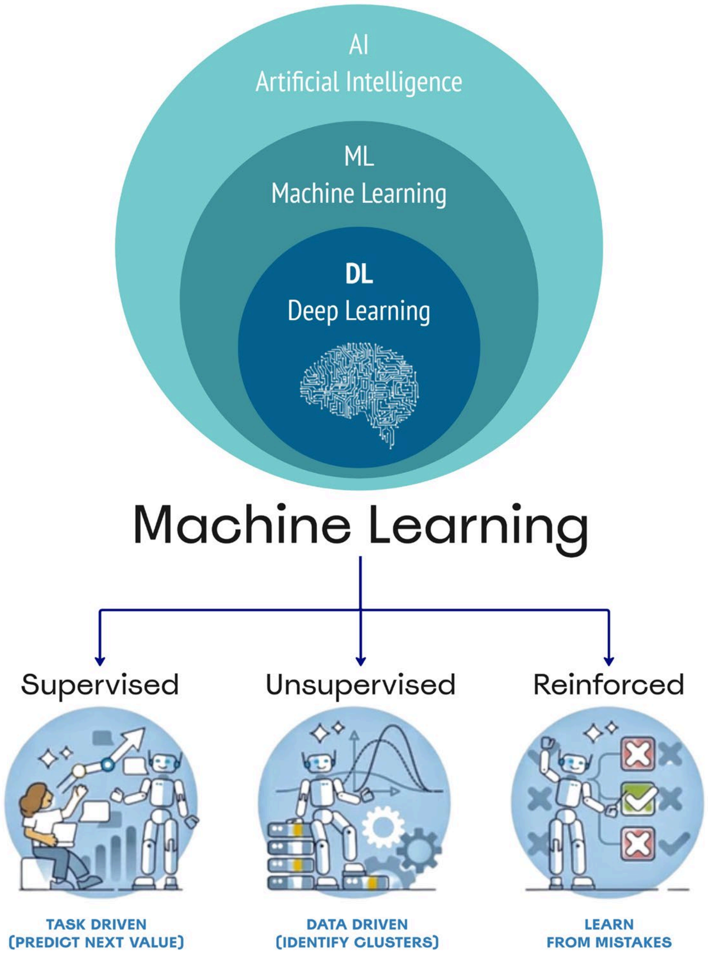


Figure 2: Artificial Intelligence and types of Machine Learning

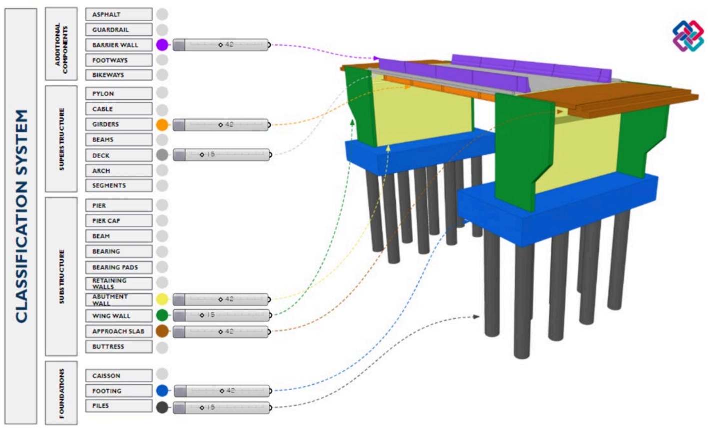


Figure 3: BIM and Parametric Modelling in Bridge Engineering

In this context, the adoption of BIM methodology in this area gives rise to BrIM, a methodology that allows the early identification of design and construction conflicts through efficient information management and the management of a collaborative and multidisciplinary environment.

Parametric modelling provides the flexibility and agility required for any project that is constantly subject to change. This ability to adapt to project variations integrates seamlessly with the BrIM methodology, allowing for seamless information management and early conflict detection, contributing to efficiency and quality in bridge design and construction.

AI-BrIM PROTOTYPE DEVELOPMENT PROCESS

For the implementation of the AI-BrIM tool, being a multidisciplinary development, it is necessary to cover several aspects, the first consists of structuring the data, choosing the input and output variables necessary for the estimates in conceptual stages; the second is the training of the Machine Learning Model to make predictions from the information provided by the user; the third is the development of a Chatbot that can answer user queries in relation to the project and complement with additional information and finally the web implementation of the tool for online access. Each aspect is detailed in the following sections:

1. Data Collection

   The process begins with data collection, which was obtained based on information from past bridge projects within the period 2016-2024, then proceeded to the selection of the information to be entered as INPUT, this must have the necessary criteria to generate an adequate estimate of the project cost, and the information to be generated as OUTPUT, which comprises the estimated cost of the project, concrete volumes, amount of steel and the estimated modelling time that this would entail.

2. Data Preprocessing

   Data preparation encompasses cleaning of human errors, normalization to reduce data scales and data transformation to address missing values. In this case, we have chosen to fill in missing data with similar values and apply complementation techniques.

   In addition, a thorough statistical exploration is carried out, analyzing measures such as mean, mode and quantiles. The significance of each variable is also assessed and statistical graphs such as frequency bars, histograms and boxplots are generated to better understand the behaviour of the data. Dispersion analysis and heat mapping are used to understand the relationships between variables. All these actions are carried out in order to obtain a clean data set ready for implementation in the model, ensuring accurate and reliable results.

3. Cross Validation

   The k-fold cross-validation is presented as a robust strategy for machine learning models when the amount of data is limited. It splits the data into k iterations to train and evaluate the model with different subsets, providing a more accurate estimation of performance and detecting stability issues.

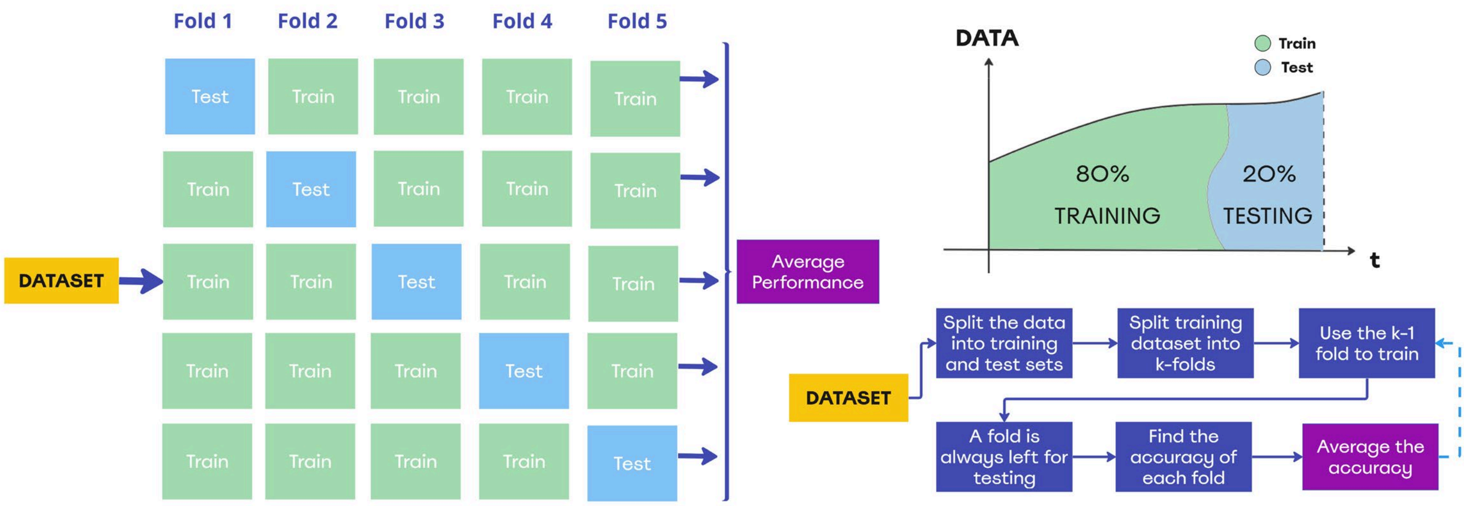


Figure 4: Cross - Validation

The data is then divided into 80% for training and 20% for testing the model, reducing overfitting and allowing an objective and reliable evaluation of the model.

4. Choice of Machine Learning Model

To select the Machine Learning Model, it is crucial to perform tests to evaluate its performance using specific metrics. Since our goal is to predict costs, we have several models to perform these tests depending on the characteristics of the database, such as its linearity, complexity and the number of variables.

The models we plan to evaluate are XGBoost, decision tree, SVM, linear regression and polynomial regression. Each model will be individually tested and subsequently evaluated using the confusion matrix and metrics derived from it.

5. Validation of Model Metrics

Once we have tested the models, we will compare the metrics resulting from the confusion matrices, evaluating the accuracy, sensitivity, and R2 score.

With the model defined, we will proceed to the implementation of the necessary endpoints to present the results required in the application of the model.

6. Development of the Chat Bot

OpenAI's Large Language Model (LLM) was integrated into the tool in order to be able to process natural language queries about the projects.

For this purpose, the categorical data of the database was linked to other files in CSV and Excel format containing frequently asked questions and answers related to the research topic.

This additional data will be processed through a framework called LangChain, which will allow us to adapt the data to the LLM model by splitting the text into small units (tokenization) and numerically representing the tokens in a vector space (embedding).

Subsequently, the Retrieval QA function was implemented, which will facilitate the interaction between queries and answers.

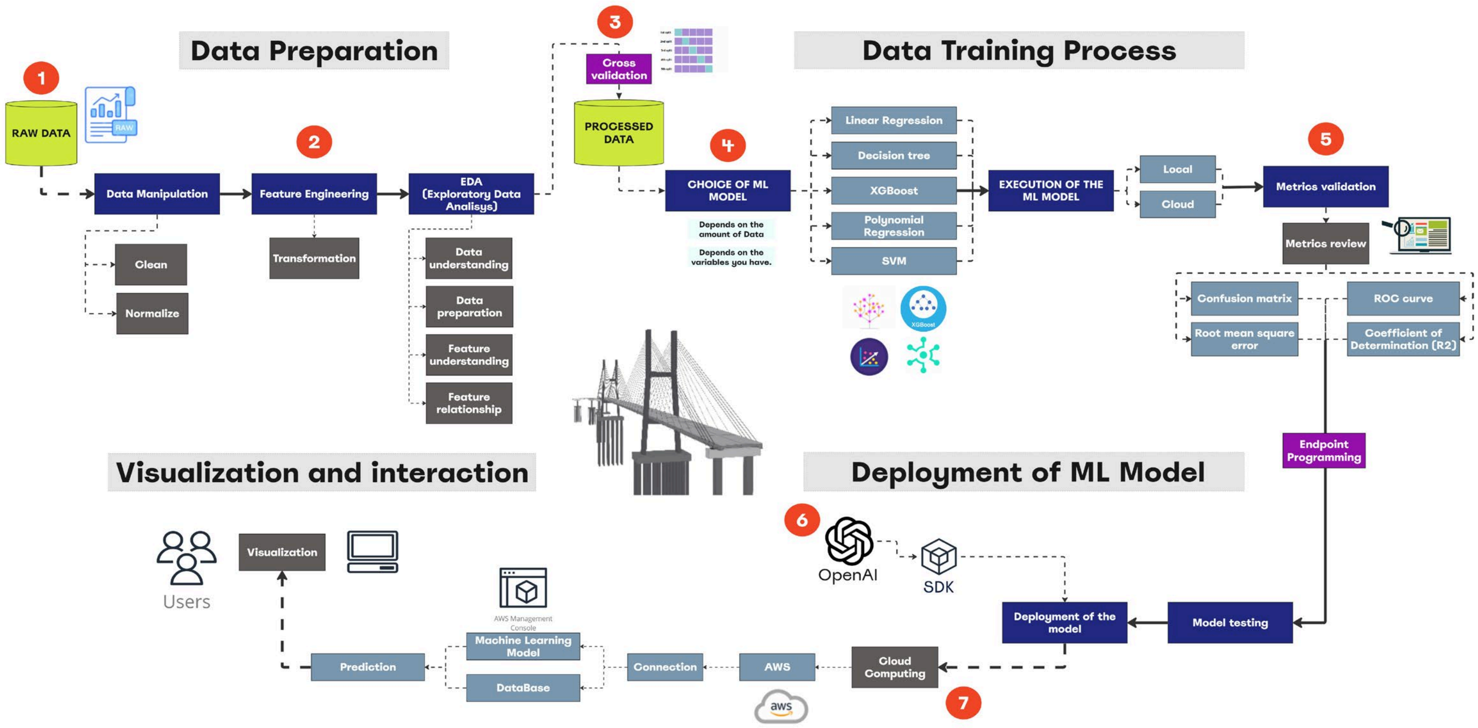


Figure 5: AI-BrIM Tool development process

7. <u>Web Deployment</u>

In the process of deployment in a cloud service, users interact with the web page to enter the data needed for predictions. At this point, interaction with the backend, which constitutes the server layer responsible for data processing and application logic, begins. This raw data is securely stored in the AWS cloud database. Then, data transformation is performed within the cloud to utilize the storage in the AWS storage service and perform ML model training. Once the prediction results are obtained, they are visualized with the AWS visualization tool. Once the backend processes are finished, the results are seamlessly integrated with the frontend of the web page through the AWS storage service.

AI-BrIM TOOL IMPLEMENTATION

The first step of the implementation consisted in the compilation of the historical database of bridge projects and the selection of the relevant and necessary parameters for the cost estimation, here it is necessary to consider variables that directly influence the magnitude and complexity of the structure, such as the span of the bridge, its typology, its location, among others.

Once the information was collected, the database was preprocessed to have an overview of its distribution, in order to obtain a clean data set prepared for its implementation in the model, which will contribute to accurate and reliable results in the subsequent stages of the research.

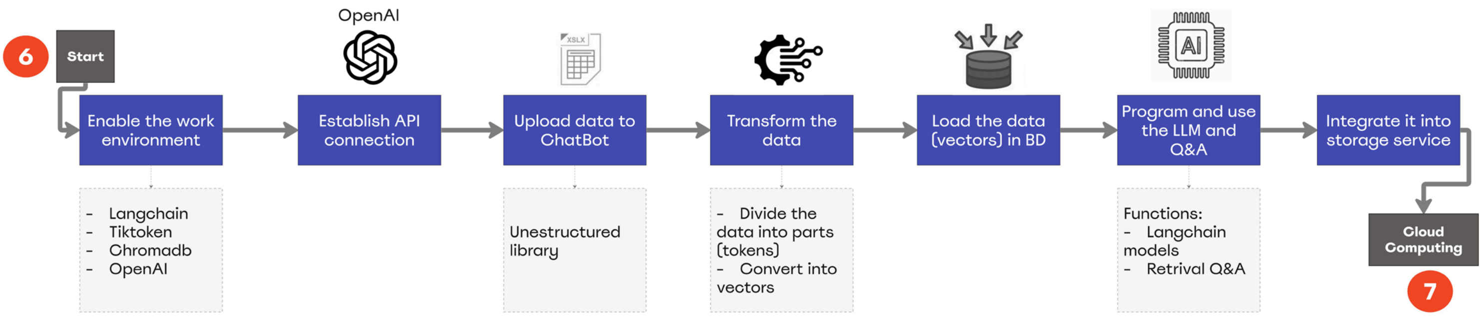
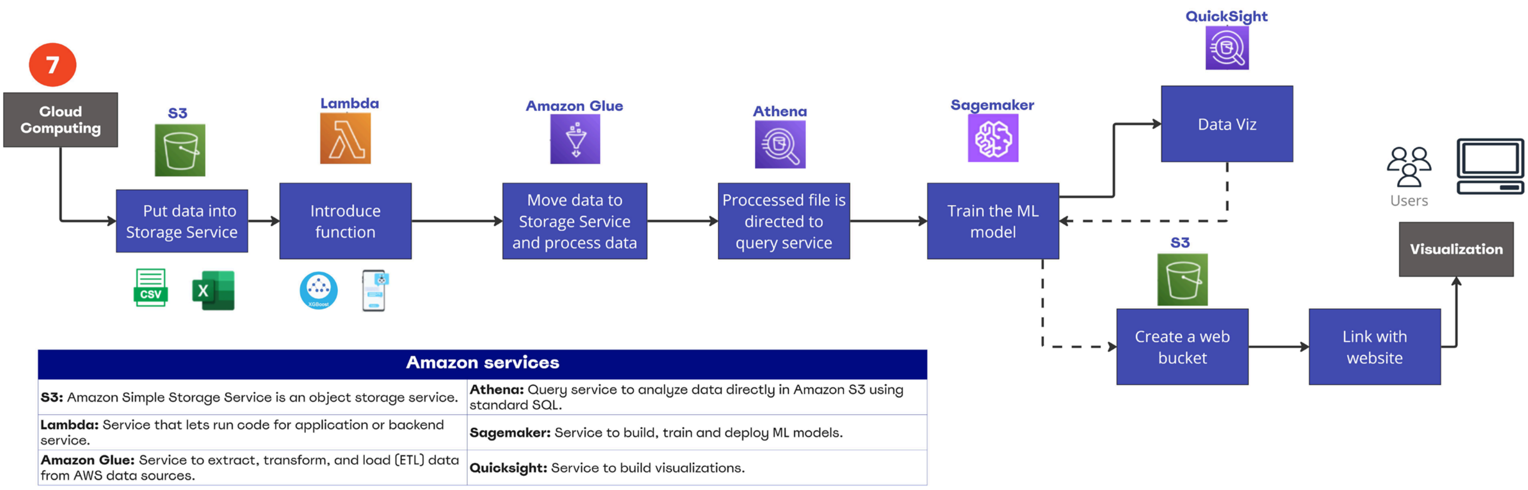
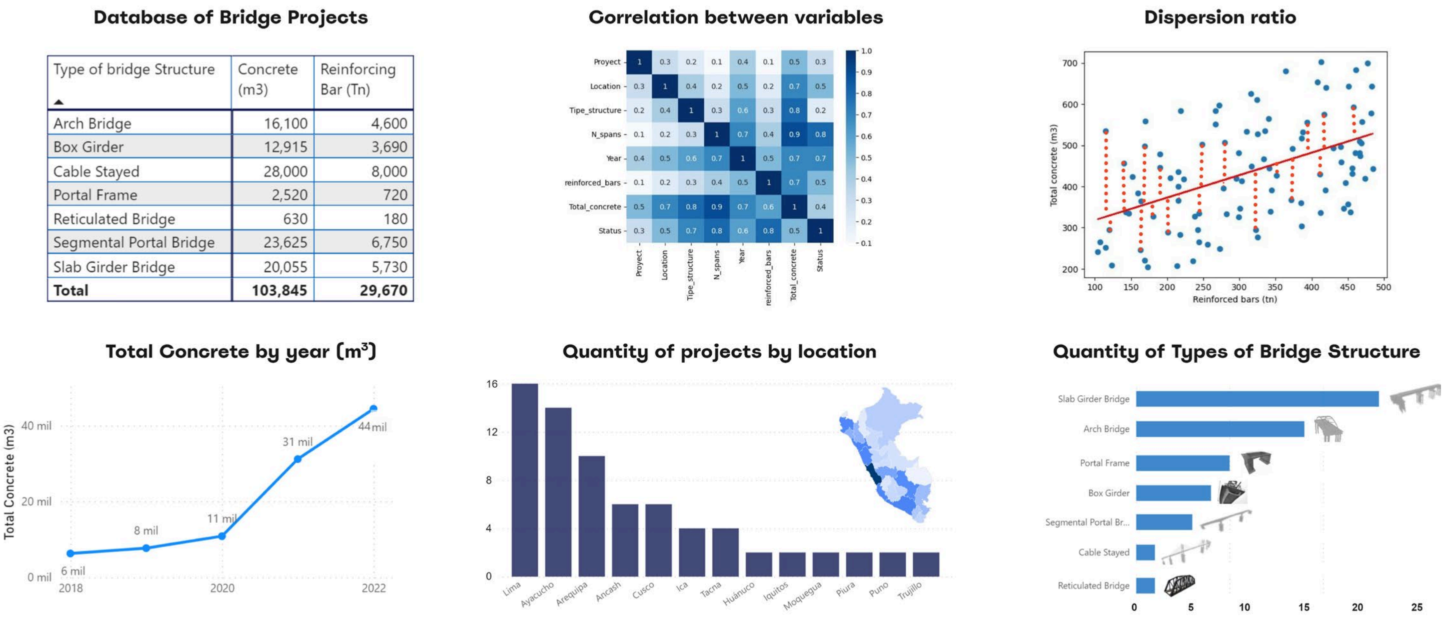


Figure 6: Large Language Model Process



Amazon services	
S3: Amazon Simple Storage Service is an object storage service.	**Athena:** Query service to analyze data directly in Amazon S3 using standard SQL.
Lambda: Service that lets run code for application or backend service.	**Sagemaker:** Service to build, train and deploy ML models.
Amazon Glue: Service to extract, transform, and load (ETL) data from AWS data sources.	**Quicksight:** Service to build visualizations.

Figure 7: Web Implementation in AWS



Type of bridge Structure	Concrete (m3)	Reinforcing Bar (Tn)
Arch Bridge	16,100	4,600
Box Girder	12,915	3,690
Cable Stayed	28,000	8,000
Portal Frame	2,520	720
Reticulated Bridge	630	180
Segmental Portal Bridge	23,625	6,750
Slab Girder Bridge	20,055	5,730
Total	**103,845**	**29,670**

Figure 8: Analysis and preprocessing of the database

For this purpose, statistical graphs represented in Figure 8 were made, which allow us to observe and understand the distribution of each variable, the relationships between variables and trends over time; thus knowing their influence on the final machine learning model.

In addition, in order to know the correlation between the variables, heat map plots and scatter analysis were performed, obtaining the results that most of the variables have a moderate correlation, but not in a linear way, which means that the variables can be used to predict the project costs more accurately.

Finally, there is a positive linear relationship between the two variables rebar (tn) and total concrete (m^3); that is, for every increase in concrete, an increase in steel reinforcement is expected.

Figure 9: Choice of the Machine Learning Model by estimating the R2 ratio

The outliers could represent bridges with an unusual design or with high-quality construction materials.

Having the database ready, we proceeded with the testing of the Machine Learning Models by obtaining the root mean square error, thus obtaining the graphs represented in Figure 9, where we can notice that the behaviour of the various models has been heterogeneous, as shown in the attached table.

It is also observed that the XGBoost and SVM models have yielded the highest R2 values, which indicates that they are the most accurate in cost prediction, being the XGBoost model the one with the best performance.

Once the model was chosen, we proceeded to the web implementation of the prototype, as well as its linkage with the ChatBot through the use of Open AI's LLM. Once the AI-BrIM tool was developed, its implementation was considered in the conceptual estimation process.

A more agile and precise flow was designed to reduce the gap between the cost found at the defined level and the cost estimated at the conceptual level, aimed at reducing variability and improving process efficiency.

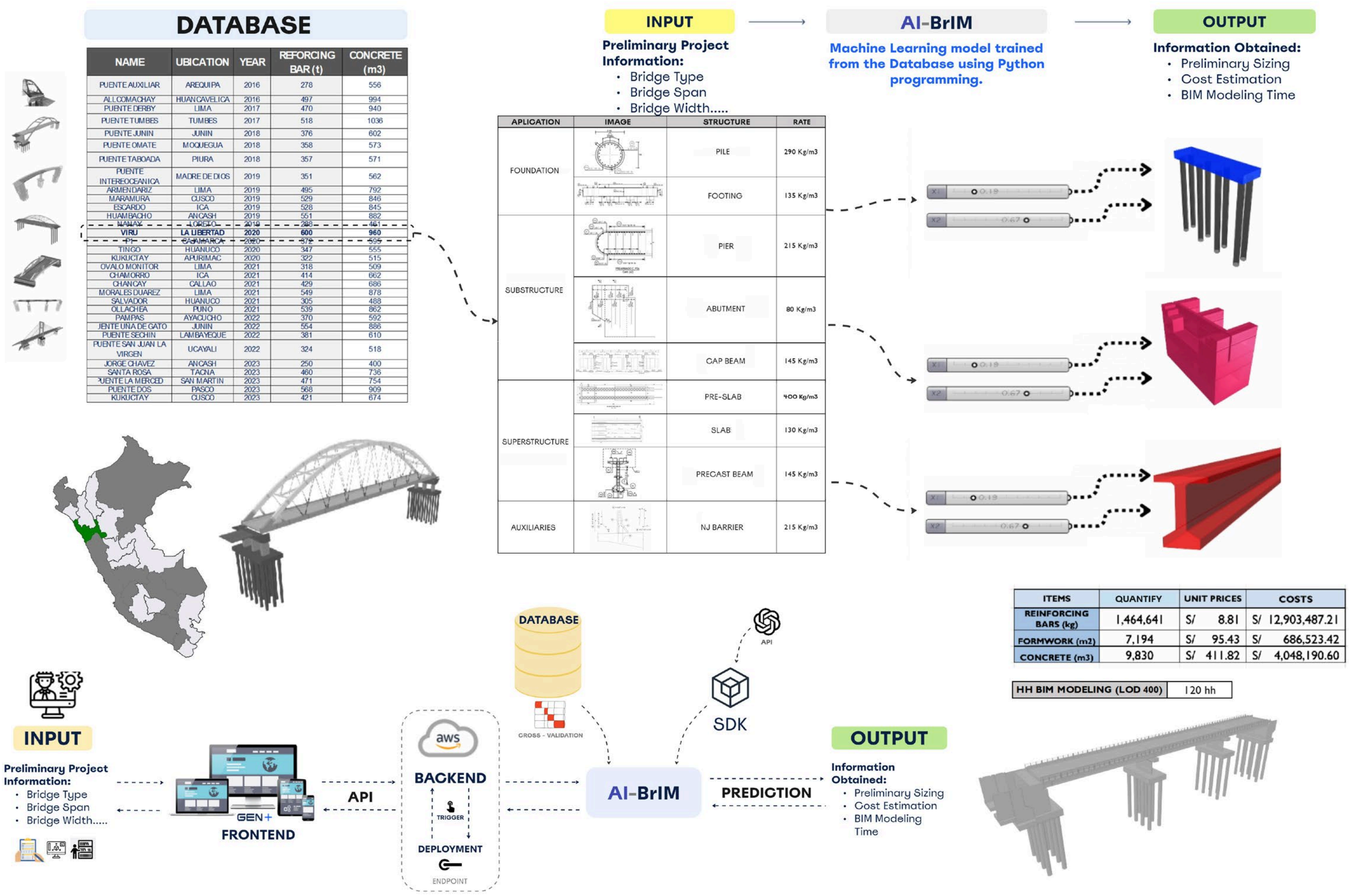


Figure 10: AI-BrIM prototype Operation Diagram

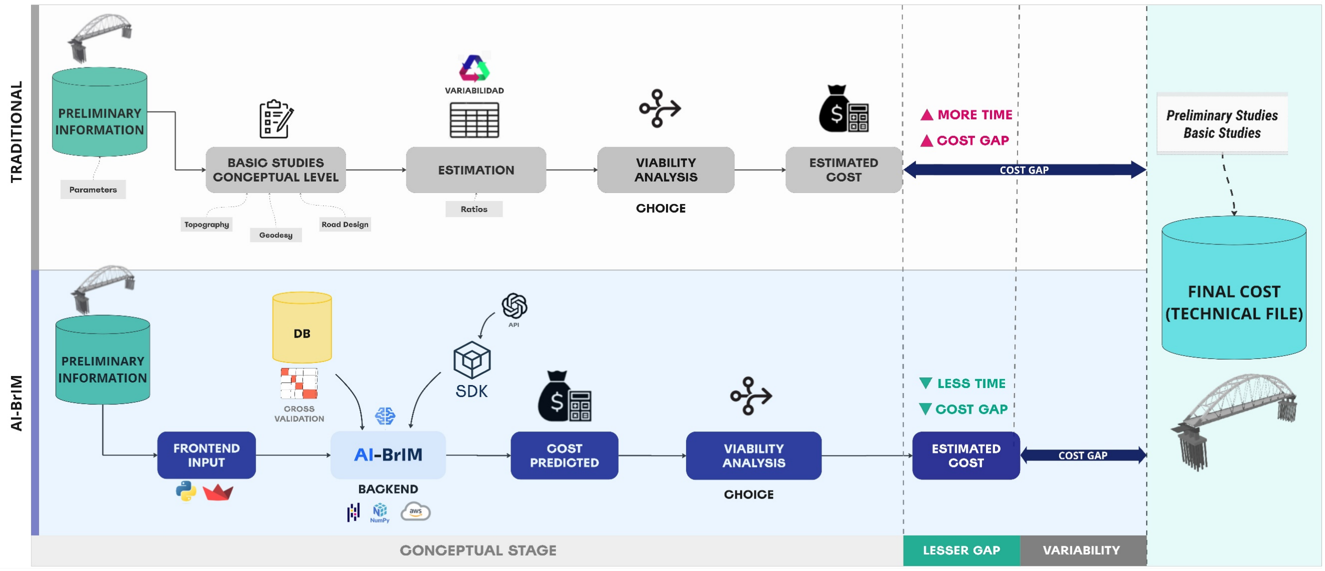


Figure 11: Traditional Estimation Process vs AI-BrIM Tool

CONCLUSIONS

In this research, a conceptual cost estimation flow was proposed with the implementation of the AI-BrIM tool, with the objective of obtaining an optimization of the process, reducing time and reducing the existing gap between the defined cost and the estimated cost at the conceptual level, in addition to the reduction of variability and the improvement of the efficiency in the process.

For the development of the tool, it was necessary to correctly identify the variables involved in the cost estimation, in addition to a sophisticated structuring and analysis of the database to know the distribution and interrelation of the variables and thus be able to generate much more accurate estimates, obtaining that our data presents an adequate behaviour to perform the training process in a more accurate way.

In addition, it was determined that of the models analyzed, the XGBoost model was the one that presented the best performance in cost estimation, obtaining an R2 value of 0.99, determining that this model adapts correctly to the behaviour of the data used, which being information coming from bridge projects, present a high degree of variability and complexity in their interrelation.

Integrating technologies such as artificial intelligence and bridge information modelling in bridge projects can provide substantial improvements in terms of prediction and information management from the early stages.

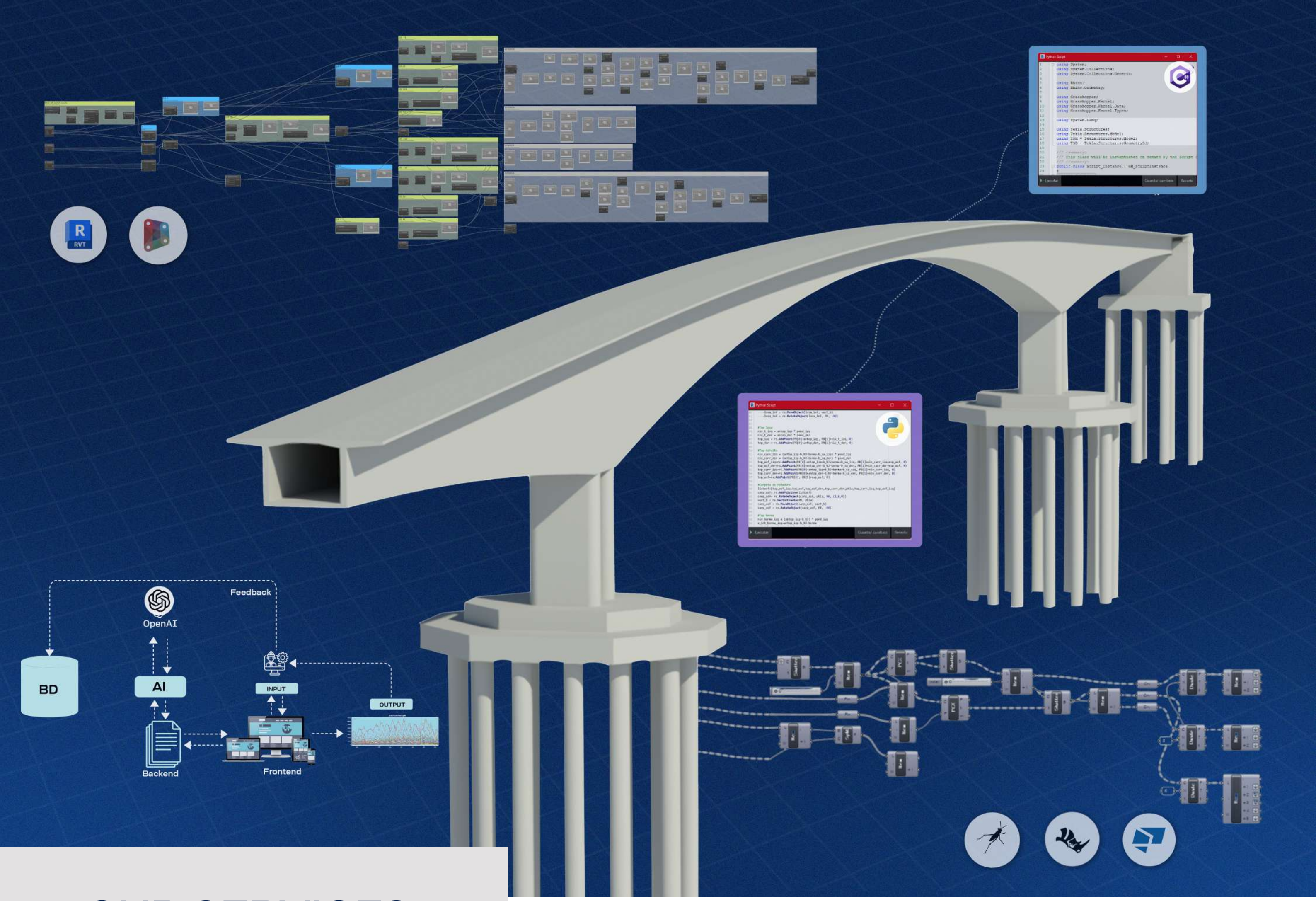
LIMITATIONS AND FUTURE WORK

The prototype proposed in this study, although offering numerous advantages, is subject to certain limitations, data availability being one of the main ones. The practical solution to this problem is the implementation of the k-fold cross-validation method to maximize the utilization of the available data.

However, expansion of the database is planned to improve the accuracy of cost estimates and promote model sustainability considering that structural models in general have a high number of parameters given the inherent engineering variability.

On the other hand, the prototype is in an initial phase focused on conceptual cost estimation, quantifications and integration with a ChatBot, the latter to complement the information inherent to the model or structure.

In addition, a second phase of the prototype is being worked on, which includes linking the database with automated parametric models to generate preliminary 3D geometric models, thus implementing the BIM methodology from the early stages, which will improve the quality and sustainability of engineering projects. This evolution towards a more integrated and data-driven approach promotes efficient database management and the adoption of artificial intelligence from the early stages of the project (conceptual model), driving innovation and efficiency in the engineering and construction industry.



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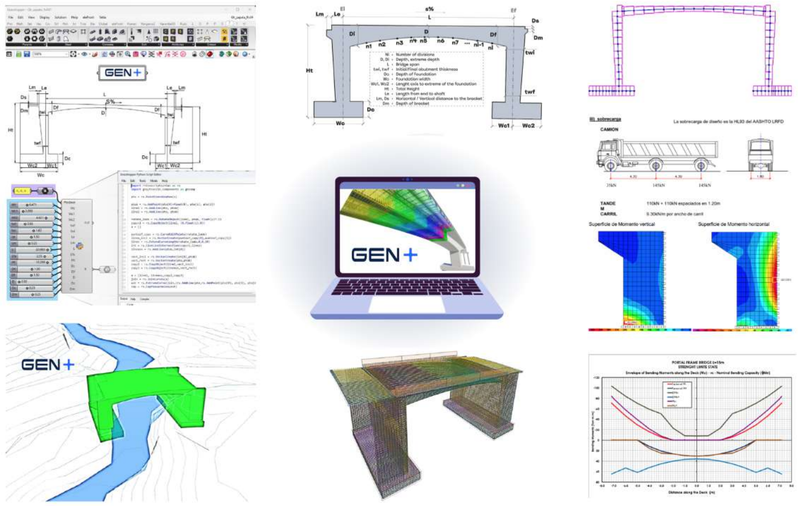

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INTERVIEW WITH PROFESSOR MAREK SALAMAK

SILESIAN UNIVERSITY OF TECHNOLOGY, POLAND

Magdaléna Sobotková

First of all, thank you for your time for this interview. Also thank you for all your valuable assistance with our magazine e-BrIM for which you act as a Member of the Editorial Board.

Thank you for inviting me to cooperate. Co-creating this magazine gives me great satisfaction. After all, something completely new is being created. Not only when it comes to committing the complex connection of the BIM methodology with bridges. Also, in terms of the form of this magazine and its high accessibility to readers worldwide.

Let me start with our typical question: why bridges and BIM and how it started? What inspired you to dedicate your career to bridges?

Actually, I accidentally came across bridges during my studies when choosing my specialization in the 1980s. Lectures on bridges were much more enjoyable for me then than lessons in laying bricks or reinforcing concrete stairs ;-) Especially since, for some people, learning to build houses still had ideological undertones. You must know that I studied in Poland during the end of communism. Many of my teachers still believed that they were building mythical socialism with their work. Bridges, or perhaps bridge engineering professors, were free from this. So, the bridges stayed with me forever. And then, for me, they were an attempt to escape from the hopelessness and dullness of those times.

But today, I don't regret this randomness. Note that when we talk about new road or rail network investments, it is usually illustrated not with a piece of repetitive and boring highway but with the construction of a large and impressive bridge.

Almost every movie, whether about love, war, gangsters, politicians, or the Wild West, often includes a scene with a bridge. A couple on a bridge confesses their love for each other. Some racing cars speed along the bridge. A helicopter or plane hits a bridge pylon. Or they destroy entirely the poor Golden Gate again or maybe some other famous bridge in the world.

Bridges are simply sexy ;-) But bridges are not built to be admired and photographed only. We need them to connect us. To overcome the obstacles that have previously divided us. And we see how important this is in today's highly divided and polarized world.

So how and when did BIM appear? What do you specialize in?

It started in the early 1990s, and at the beginning, it was CAD. After graduating, I quickly moved from the drawing board to a computer with CAD programs. It was not easy at that time because the effects of communist martial law in Poland, as well as the painful economic transformation at the turn of the 1980s and 1990s, put our entire region in a massive crisis. At the same time, I had enormous amounts of hope that I would be able to overcome it all. I believed that through work and escape from Soviet dependence, we would catch up with the Western world technologically. Therefore, I took advantage of each trip abroad to absorb knowledge and buy Western books, which were incredibly expensive for us at that time. I was not yet thirty years old when I went on my first internship in Denmark.

However, I noticed that when I created my first CAD programs there, I was no worse than many engineers there. When I returned to Poland, I already knew what I would do - supporting bridge design with our applications in CAD environments. We quickly founded the CADmost company and introduced our first AutoCAD overlay to the market. And it was still release 11, which worked before the era of Windows. So, after twenty years of designing bridges and developing our CAD software, the transition to a BIM environment was a natural process for me.

Can you remember the number of bridges you have been involved in? What was your role?

No, I don't remember that. I still counted them in the beginning, but then there was no time for it. Besides, there weren't any mega bridges. Most often, I designed small and medium-sized structures on local roads. When I started my career, Poland was beginning to create its infrastructure almost from scratch due to years of Soviet dependence. Not as many new bridges were built as today.

Everything suddenly accelerated after joining the European Union in 2005 and just before the Euro 2012 Championship. We were designing dozens of repeated viaducts over new highways at that time. New employees also appeared in our company, and my responsibilities began to change. I also became more involved in scientific and research activities. As the bridge team leader at the Silesian University of Technology, I conducted more and more lectures and R&D projects. Many were carried out as part of doctoral dissertations with my PhD students. I must admit that I no longer have that much time for design. Nowadays, design has become much less engineering and more clerical. These are mainly numerous and tedious arrangements with various institutions, which no longer give me as much satisfaction as taking research risks.

Are there any projects special for you? What are your favourite ones? Have you worked on any of them?

As I said, there haven't been any impressive structures in my career. However, I remember the geometrically complex flyover in the centre of Warsaw. In addition to this bridge's complex geometry and prestressing, there was also a phased construction, span by span. The design tools available at the time were very limited, requiring a lot of effort. That's why my programming skills and parameterization of the structure turned out to be helpful.

An exciting project was the pedestrian and bicycle suspension bridge over the San River in Sanok, which was to have a prestressed concrete ribbon bridge. Unfortunately, it could not be built in this form because the city did not obtain funds then. After 20 years, another cable-stayed bridge will be erected in this place, but I am no longer its designer. My career just took a different course.

Who has most influenced you, your career, mission and way of thinking?

There were, of course, several Polish engineers who are probably not known in the world. For me, however, they were a model of efficiency and self-confidence in implementing their projects. This attitude is also critical. Especially at the beginning of a career, young engineers are troubled by doubts and a lack of faith in their abilities.

But regarding the world-famous engineer, I should mention Fritz Leonhard, from whose books I learned how to design prestressed concrete bridges. However, this is an entirely different generation, and meeting him was impossible. However, I had such an opportunity with a contemporary celebrity in bridge engineering, undoubtedly Prof. Jiri Strasky from Brno. You probably know him much better than I do. His concrete ribbon bridges were my inspiration. And I went to take a closer look at the record span of the Vranov Lake Bridge. This inspired our bridge on the San River, which I have already mentioned and which we were designing at that time.

Can you comment on the changes in bridge technology over your career? What do you see has been the most significant technical advance?

I have been a bridge engineer for almost 40 years. During this time, there may have been no spectacular technological changes comparable to the landing on Mars. However, successive changes in various aspects and areas of bridge engineering could be observed.

I would start by saying that the improvement in the quality of traditional construction materials, such as concrete and steel, and the refinement and integration of various construction methods made designers bold to create wholly new and non-obvious forms of their bridges. We experienced this at the beginning of the century, when bridges were built in many cities worldwide, serving as monuments of the millennium. They even received names of millennium bridges related to this breakthrough period.

On the other hand, even in traditional forms of bridges, completely new materials were used, which were previously only available in the aerospace industry. What I mean here is polymer composites from the FRP group. There are also known cases of using biocomposites or modified wood in bridges. And it is fully modified mechanically and chemically, not just glued. Experience shows that an even better synergy effect from new materials can be achieved by combining them with traditional ones. In this way, hybrid structures are created, in which we have

polymer girders and a concrete deck slab or steel or wooden elements combined with a glass deck. It should be remembered that concrete or steel, known to us for over a hundred years, are also entirely different today. Modern concretes are characterized by much better mechanical properties and durability. And today, we can even create them as tailor-made. We are changing the way concrete is reinforced. For this purpose, we use FRP, textile or dispersed reinforcement. We often use the once-too-expensive duplex or weathering steel in metal structures. Aluminium alloys are also changing.

You are mainly talking about new forms of bridges or materials, but what is the role of BIM in these changes?

BIM, of course, also plays a part in this. First, we must remember that these technological and material changes are not only about reducing costs but also about shortening the construction time and the burden on the environment and society. Moreover, all bridge engineers are driven by endless competition to see who can build a larger span, a longer bridge or a taller pillar or tower. And often over a previously inaccessible obstacle. That's why we need new and industrialized methods of construction.

Therefore, we develop or combine methods such as longitudinal sliding, span by span, cantilever and rotary techniques, and assembly of prefabricated segments or entire spans. An increasing scope of automation and robotization is being introduced. These are the needs that drive us towards the BIM methodology and modelling. To be honest, I can't imagine robotization without BIM. If robots are ever introduced on construction sites, we must start using BIM models. Robots cannot read paper drawings or make handwritten annotations on them.

That's true. So how has the introduction of BIM changed your work?

My job hasn't changed that much. Of course, digitization, in general, has had and still has a significant impact on it. Instead, it is about technologies and tools that are changing our work and how we process information. I mentioned at the beginning that I no longer design or model bridges.

I don't have time for this, which I regret very much. Parameterization and 3D modelling in connection with the metadata that can be collected and processed in the BIM methodology have always been very close to me. I envy modern designers because I didn't have such tools and opportunities back then.

Due to my main activities in the academic world, BIM is present in my lectures, in the dissertations of my PhD students and in R&D projects. Usually, it is not only BIM itself but various associated digital technologies, such as virtual or mixed reality, 3D reconstruction techniques, digital twins, artificial intelligence, etc.

All these areas are so new and dynamically developing that their exploration is fascinating. Much more than following the tiresome path of BIM processes in design, which have been described in a highly indigestible form in hundreds of pages of international standards. This doesn't excite me at all anymore.

In our e-BrIM magazine, we have the pleasure to present the current development of BIM in Poland. What is the level of digitalization in the bridge industry in Poland and are bridges there already typically designed in BIM technology?

It's not all that impressive. I think it's better in the Czech Republic. We do not yet have BIM standards fully translated into Polish. I hope this process will end soon, and we will move on to the next stage with their implementation in public procurement because this is the only way bridges are built throughout Europe. In the construction industry in Poland, we have more examples of investments in which the BIM methodology was consciously used. However, there are more private investors and more freedom of action for designers or contractors in this area. In terms of infrastructure, individual BIM pilot projects are currently underway.

The ongoing political confusion does not make matters easier because, unfortunately, those in power focus on the immediate political fight instead of the country's development strategy and the economy. In the field of BIM, there was some acceleration in Poland on the occasion of the launch of the multi-industry Solidarity Central Communication Port (CPK) project. In addition to the large airport, a new high-speed rail network and many access roads were to be built. The design is already underway, entirely by the strict BIM methodology. This forces continuous improvement of awareness and competencies both on the designer market and on the part of the public ordering party. This process and changes positively surprised me. Especially the fact that the client's staff was very young and had no complexes in the field of BIM. Many had previously worked on BIM contracts in Scandinavia or Great Britain. Unfortunately, political changes may stop this process, which worries me greatly.

How can BIM be used in the O&M of bridges and their preservation?

Most bridge engineers or representatives of the administration responsible for managing bridge infrastructure associate BIM only with tools for designers. For them, it is just a new way of modelling new structures that use a 3D model and attractive visualizations.

However, this understanding and perception of BIM is very narrow and limited. BIM methodology and models can and should be used at all stages of the life of investment projects. In my opinion, the benefits that infrastructure owners will have from using BIM models in managing their facilities will be much more significant than at the design or construction stage. Of course, we have to start with these stages, but they last relatively short compared to the operational phase. Usually, a few years, while bridges serve us for a hundred years, and sometimes much more. Over this long period, we have to manage them and optimize public expenditure. We must repeatedly maintain, repair, prevent degradation, rehabilitate, modernize, strengthen, or expand them.

In developed countries, these activities used methods and tools called Bridge Management Systems (BMS). Their basis was a record of their bridges (assets), which usually took the form of a more or less complex database. More advanced systems have been supplemented with the ability to collect data from cyclical inspections,

maintenance activities, work planning or the need to replace bridges with new ones. Unfortunately, the structural models of the bridges used in these systems were very primitive. Often, these were point models that contained only a basic description of the type of structure with associated records in the cadastral database. However, BIM methodology and models can completely change this field of knowledge called Infrastructure Asset Management (IAM). There is enormous synergy between IAM and BIM. This has already been written down in the relevant ISO standards, although there are few cases of practical implementation of such an integrated approach.

And do you see any significant difference in the use of BIM in bridge engineering compared to what is used in buildings?

Of course. Just pay attention to the abbreviation you use in the name of your magazine - BrIM. It means consciously introducing the word Bridge instead of the word Building. This is not only due to the specificity of bridges in terms of their geometry or nomenclature. The last word in this abbreviation can be interpreted differently. For designers, M stands for modelling, but for me (and infrastructure owners), the word management is closer. And this is how we expand this shortcut to Bridge Management Systems. And in my opinion, in the future, BrIM will replace the BMS systems used today by bridge managers. However, I suggest not getting used to any names or abbreviations because technology development and commercial implementations may change often. It is enough if we follow, for example, how the concept of a digital twin is changing and developing.

How does the bridge inspection work in Poland? Are there already any standards, which might be digitized and used in the BIM O&M phase?

Inspections of the technical condition of bridges in Poland are still performed traditionally, and little has changed since BIM appeared. They are visual, and paper forms are still used for this purpose. Special diagnostic techniques are used only in the case of more detailed inspections and initially identified damage, for example, from the NDT arsenal or dedicated sensors. I think this is no different from the approach used in even the most developed countries in the world. This is confirmed there, sometimes even with very tragic consequences of catastrophes of old and degraded bridges. Fortunately, we do not have such drastic cases in Poland, which may be because our infrastructure is much younger and has not yet been degraded.

Unfortunately, as our infrastructure is renewed, our bridge management standards are not updated, at least not to the extent that would allow for the digitization of resources managed by road or railway administrations at various levels. And since there are no such digital resources, it is difficult to imagine that there will be widespread use of tools enabling electronic recording of bridge inspection results already on the facility in the field or using devices from the arsenal of mixed reality or artificial intelligence algorithms. Such cases are known from ongoing research projects, as in my team, as we wrote about in our articles published in e-BrIM magazine.

What future do you think BrIM will have? What development and utilisation can we expect? What are the tasks and challenges for the future?

You say BrIM, not BIM. So, first of all, we need to popularize the acronym BrIM and this approach. For many, it is not apparent or even known. It is, therefore, necessary to build awareness in the engineering community about the differences and needs between buildings and bridges. No tools also allow for the convenient modelling of bridges with matching dictionaries and metadata, even as effective as have already been created for usually orthogonal buildings. We are coping, but many engineers are terrified by the need for several modelling environments that do not always cooperate reasonably or support this work with special scripts that often require programming skills.

The next stage will probably be transitioning from modelling bridges to managing them. This means moving from outdated BMS systems to an approach compliant with BrIM. This cannot be easy in many cases because some administrations only use paper forms and drawings or simple spreadsheets. In such organizations, it will be an almost Copernican revolution. What if we wanted to offer digital twins to someone like that? This will sound like science fiction to them.

However, suppose you are asking what the future of BrIM will be. In that case, I think it will be digital twins, which I understand as a system of systems integrating various types of data and infrastructure that will one day have to interact with each other. It is enough to realize the situation in which autonomous cars will one day appear on our roads and bridges.

What advice would you give to young engineers starting their careers?

I wouldn't say I like playing the role of an all-knowing expert who has lost all common sense. Moreover, many young people do not take such advice at all. Unfortunately, they have to experience some things themselves, and they also have to gain practical knowledge and self-confidence.

Many will probably feel like the best expert at the beginning of their career. In the case of BIM, there is such a temptation among young people because older engineers may not keep up. I think I also went through this when I started my adventure with CAD, and my more senior colleagues couldn't get to the computer.

Fortunately, the first failures quickly set us on the proper development path. Unfortunately, this involves arduous overcoming obstacles and solving mounting problems. But the nice thing is that it gets easier and easier to do over time. On the other hand, unfortunately, the requirements for such experienced people are increasing.

And my last question. What are your plans for the future?

Take a break from constant work. Especially from hundreds of weekly emails and disturbing phone calls throughout the day. The flow of information today is so fast that I cannot understand how I used to function with traditional paper mail, a telephone only on my desk at work, or without a car.

And my plans are usually not very far-reaching. I used to play many card games like bridge, and I like cards in general. Well, the card may be different in each hand and not consistently strong. And today, I know there is no good or bad card. It's similar to life; you must know how to play every card.

The winners are those who can make the most of even the weakest cards. So every day, every month and every year, I wait for the next hand or card, and each one is good for me.

And, of course, my plans may also change in each of them. And this is beautiful.

ABOUT PROFESSOR MAREK SALAMAK

Short bio

Full Professor at the Silesian University of Technology, bridge engineer, CAD, BIM and digital construction expert. PhD supervisor in bridge dynamics, prestressed concrete, SHM and AI in bridge optimization and diagnostics.

Interests: BIM, Asset Management, Mixed Reality in bridge maintenance and inspection.

Creator of the infraBIM Expo event and the accredited bridge research laboratory.

Author or co-author of almost 200 publications, including the textbook "BIM in the life cycle of bridges”.

MONITORING OF THE TECHNICAL CONDITION OF AN ARCH ROAD BRIDGE USING BIM AND AR TECHNOLOGIES

Muhammad Fawad[1], Marek Salamak[2], Koris Kalman[3]

INTRODUCTION

For a couple of decades, many engineers and researchers have been interested in Structural Health Monitoring (SHM) of bridges [1]. To enhance SHM systems, numerous studies have been carried out in the past [2]. According to recent advancements in this field of study, improved technological solutions are required for bridge health monitoring, including the applications of Building Information Modelling (BIM) technology for the SHM system [3].

In simpler terms, current methods for monitoring bridge health sometimes fall short in providing comprehensive information and understanding the complex 3D nature of these structures. As a result, there is a growing need for innovative solutions to overcome these limitations and ensure a thorough understanding of a bridge's condition. Emerging technologies like Augmented/Mixed Reality (AR/MR) and Building Information Modelling (BIM) show promise in revolutionizing bridge health monitoring by offering enhanced data management, automated control, and three-dimensional visualization [4].

Bridge health may be intelligently monitored with the help of BIM technology. It has a significant part to play in the models' integration of sensing technologies through the use of a cloud-based automation solution [5]. By employing the BIM tools, the sensors can be integrated into the BIM model and connected to the cloud-based data platform.

This allows for the on-site or remote recording, monitoring, assessment, and visualisation of SHM data. Additionally, advancements in this field of study can scale these integrated BIM models to platforms for Mixed Reality (MR), Augmented Reality (AR), and Virtual Reality (VR), allowing SHM data to be more effectively visualised even on-site utilising smart cyber-physical devices [6].

The integration of MR technology with BIM in bridge health monitoring is considered a cutting-edge tool [7]. This approach combines real-time AR experiences with SHM data, bridging the gap between digital and physical assets [8].

By overlaying digital information onto the physical bridge, MR enhances visualization, real-time data analysis, and decision-making capabilities [9]. These capabilities of BIM and MR tools are explored in this research and their applications are tested on a real-life bridge.

This way, this article aims to develop an Integrate bridge health monitoring system within an MR environment to assist infrastructure management and monitoring. The immersive health monitoring system is designed to detect damage for intervention planning.

The study explores various aspects of implementing this framework, including designing, initial data collection, and visualization of SHM data using MR devices. The emphasis is on how this integrated system supports predictive decision-making, allowing authorities to anticipate

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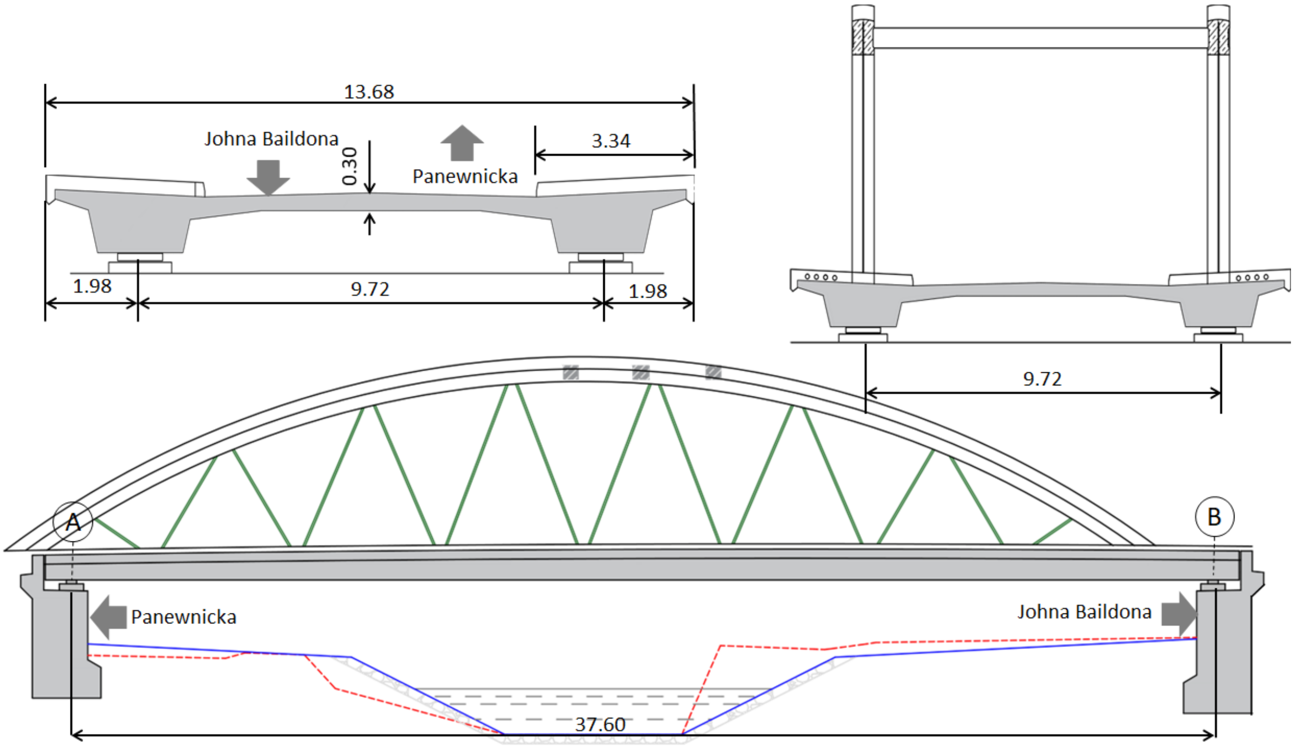


Figure 1: The layout of the case study bridge

structural problems, optimize maintenance plans, and schedule interventions proactively. Overall, these technological advancements are transforming the way we monitor and manage the health of bridges.

PURPOSE OF THE STUDY

The major aim of this study is the integration of the SHM system with MR devices on the industrial scale. For this purpose, field experimentation was performed to integrate a real-life SHM system with BIM technology to visualize the SHM results in MR. In addition, the monitoring results will be used to determine the causes of the buckling of the steel hangers and to assess the impact of this irregularity on the bridge's load capacity.

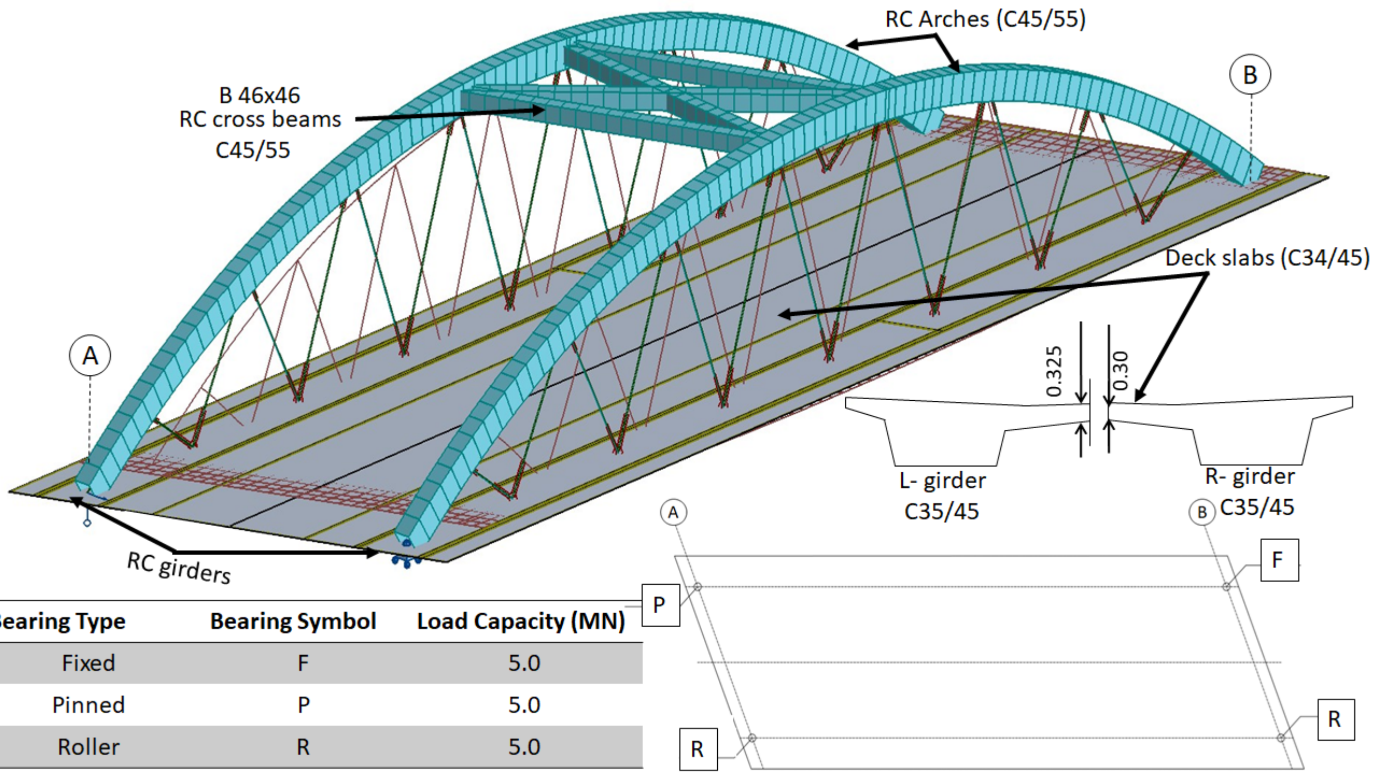
SCOPE OF THE STUDY

This study involves the assessment of an existing condition of the bridge using Finite Element Analysis (FEA) and design of the bridge SHM system. Then the SHM system was installed on an arch bridge and bridge monitoring was performed for a period of three weeks (30 May 2023 to 19 June 2023). Usually, such type of SHM system is installed for a longer period and for accurate identification of bridge damage but there were certain limitations in the case of this bridge. First of all, the duration of the experiment was very short and then the number and types of sensors were also limited. The major reason was the agreement and the availability of devices from the industrial partners.

Only the demo system was provided by the industrial partner which only contains three types of sensors. Moreover, it was also considered that expanding the scope would involve a significant increase in costs which was not needed in the case of this study as these sensors were enough to fulfill the course of this pilot project. Moreover, the risk of damage and theft of the sensors was also very high as the bridge was the home of some homeless people.

DESCRIPTION OF THE BRIDGE FACILITY

The bridge selected for this experiment is situated on Panewnicka Street in close proximity to The Silesian University of Technology in Gliwice, Poland spanning over the Klodnica River. This particular bridge is characterized by a single-span concrete arch design, measuring a length of 37.60 m. The deck of the bridge is constructed with a 0.30m thick concrete slab. The overall width of the bridge is 13.68 m, featuring two concrete girders positioned 9.72 m apart.



Bearing Type	Bearing Symbol	Load Capacity (MN)
Fixed	F	5.0
Pinned	P	5.0
Roller	R	5.0

Figure 2: Finite element model of the bridge used to design the SHM system

On each side of the bridge, there are two concrete arches intricately connected to the deck slab through the use of steel hangers. This architectural configuration adds structural integrity to the bridge. For a visual representation, refer to Figure 1, which illustrates the layout and components of the bridge.

FINITE ELEMENT ANALYSIS OF THE BRIDGE FOR THE DESIGN OF SHM SYSTEM

The Finite Element Analysis (FEA) of the bridge involves calculating internal forces and displacements, which are crucial for designing the Structural Health Monitoring (SHM) system. The SHM system is tailored based on the maximum values of bridge deflection, stresses, strains and internal forces. The static linear analysis utilizes a linear elastic model for the bridge, represented as a shell and linear element. The bridge deck, composed of C60/75 concrete, is supported by edge girders and features diaphragms to resist lateral forces and transfer loads to the support.

Concrete C60/75 arches on both sides of the bridge deck, connected by tied steel hangers having a reduced circular cross-section.

Torsional moments are calculated throughout the girder. The design incorporates standard parameters of the concrete elasticity modulus, following Eurocode-2 guidelines. Loading conditions include self-weight, superimposed dead load, uniform temperature load (-29 °C to 31 °C), and a vehicular load of 32t (calculated for the heaviest vehicles). The developed FE model of the bridge is illustrated in Figure 2.

DESCRIPTION OF SHM SENSORS AND USED DEVICES

Based on the results of FEA, the SHM system was designed to identify the location and need of the specific sensors. The designed SHM system of this bridge includes the following devices.

- FlatMesh 3G Gateway: to communicate with the wireless sensors and Sencieve web platform.
- 1x FlatMesh Crack Sensor Node (CM): for the measurement of longitudinal displacement.
- 1x FlatMesh Tilt Meter Node (TM): for the measurement of rotation angle showing the bridge rotation in 3-axis.

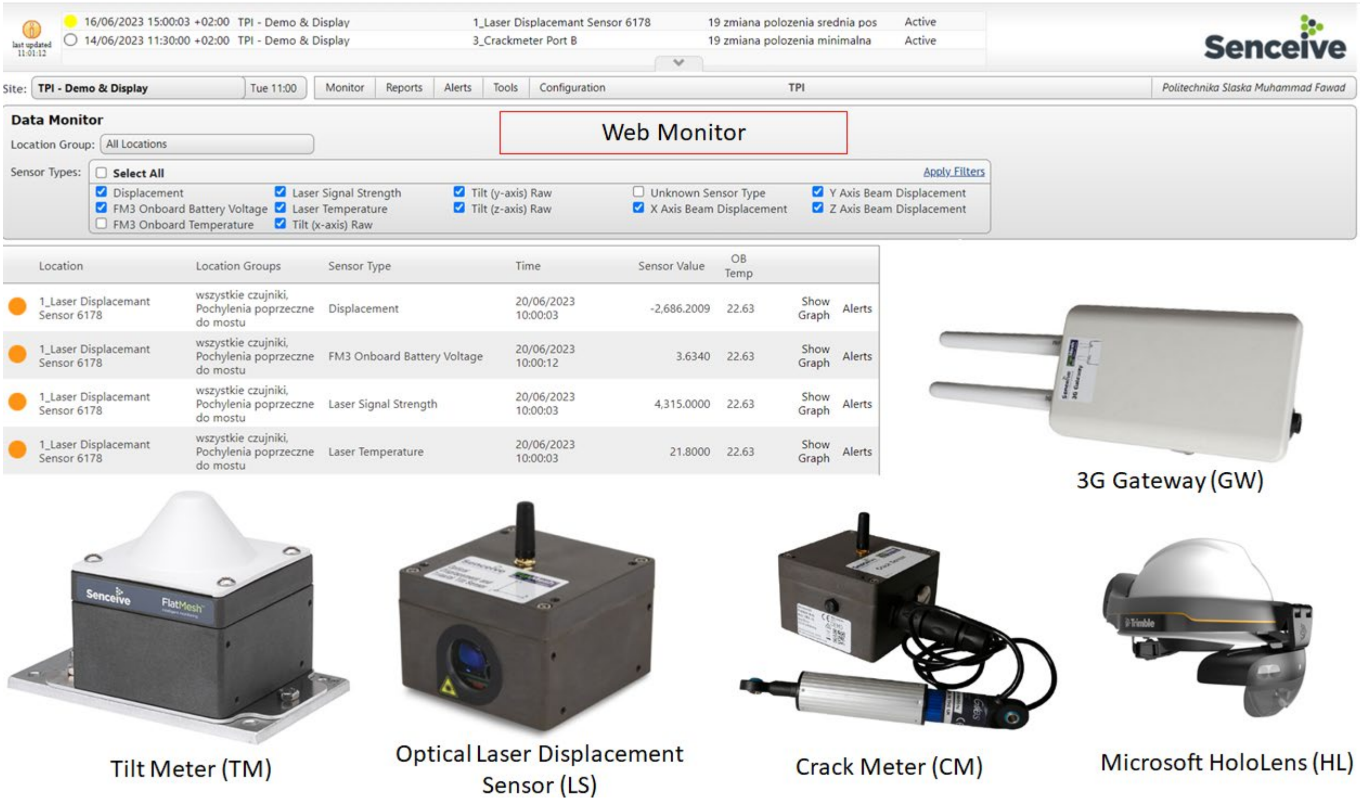


Figure 3: SHM devices and web platform used in this research

- 1x FlatMesh Optical Displacement Sensor Node (LDS): for the measurement of vertical displacement and rotation at the centre of the bridge deck.

FE analysis revealed that temperature is the major parameter affecting the bridge measurements, so, onboard temperature measurement readings were also considered for each sensor.

In addition to the above-mentioned sensors, the SHM system is provided with the web platform which is used to monitor and manage the SHM data. This web platform provides the data storage facility with the possibility of visualizing the data in graphical format and also downloading this data as an Excel file.

All these sensors and the layout of the web platform are shown in Figure 3.

THE LAYOUT OF THE SENSOR INSTALLATION

Based on the results of the FE analysis, bridge deflection for the installation of a laser displacement sensor, bridge rotation for the installation of a tilt meter, and bridge longitudinal movement for the installation of a crack meter were monitored.

This monitoring helped to identify the maximum valued locations where the sensors can be installed.

The expansion joint at support A is found to be the best-suited place for the installation of CM. Further, it is observed that the bridge rotation can be best monitored at a distance of 0.5 m from the left bearing of support A, so the TM is proposed to be installed at this location.

For monitoring of the vertical displacement, deflected shape of the bridge deck was observed, proposing that the LD sensor should be installed near the centre of the bridge deck. All the locations of the installed sensors are shown in Figure 4.

EXPERIMENT DETAILS

After successfully developing the installation plan, the system was installed as per the design. Initially, it was planned that the measurements would be recorded for two weeks, but considering the success of field implementation, the duration was extended to three weeks.

So, sensors were installed on 30 May 2023 and measurements were carried out till 19 June 2023.

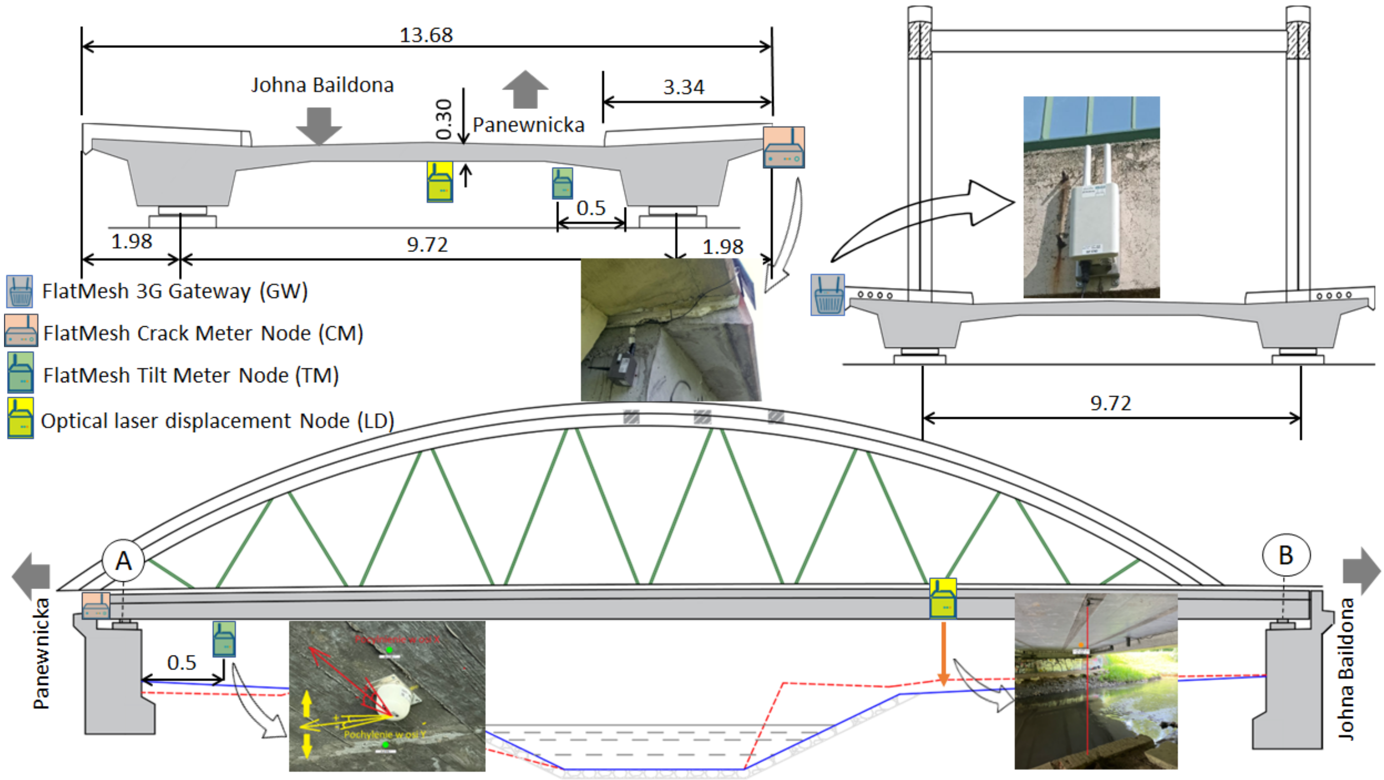


Figure 4: The layout of the SHM sensors

Out of the full measurement capabilities of each sensor, only selected parameters were chosen for this study.

These parameters are enlisted in Table 1.

The mentioned data is recorded from 12.00 of 30 May 2023 till 10.00 of 19 June 2023. Before dismantling the whole SHM system, data was stored in a graphical as well as tabular form for further processing and analysis of bridge health.

The measured data is downloaded into an Excel file where it will be used for further processing.

The planned utilization of this data involves the training of the data set using the Artificial Neural Network (ANN), where temperature values will be used as an Input for the training of the dataset whereas displacement and rotation angles will be used as output. Once the data is trained, it will be used to predict the output parameters by changing the inputs for any period.

The recorded readings of the temperature, displacement, and rotation around the x and y axis, during the measurement period, are shown in Figure 5a, Figure 5b, Figure 5c, and Figure 5d.

Measurement Parameters	Crack Meter (CM)	Tilt Meter (TM)	Laser Displacement (LD)
Displacement (mm)	√		√
Temperature (˚c)	√	√	√
x-axis rotation (˚)		√	√
y-axis rotation (˚)		√	√
z-axis rotation (˚)		√	√

Table 1: Measurement parameters of the installed sensors

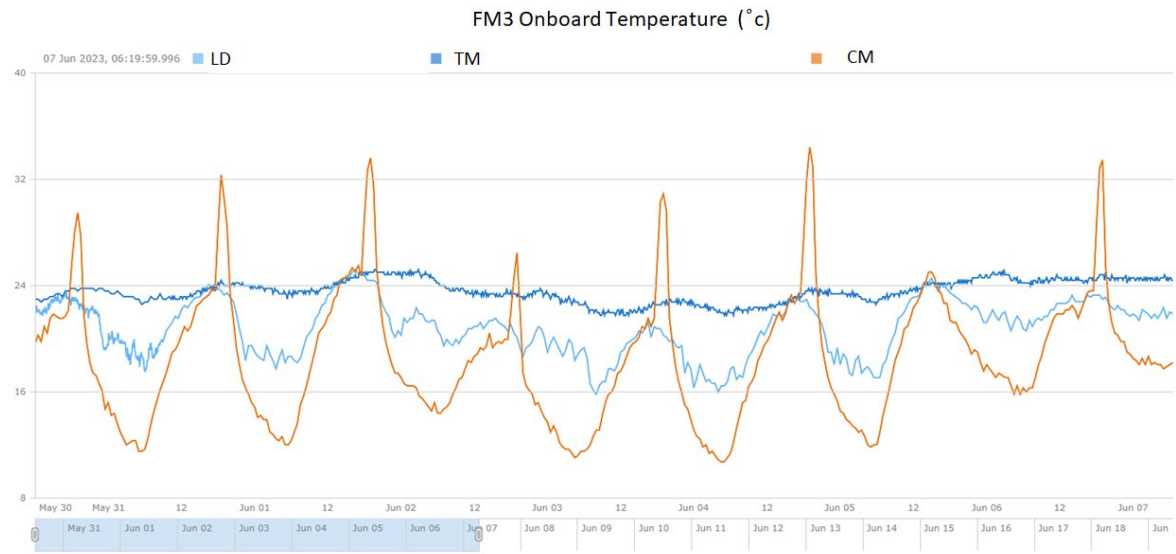


Figure 5a: Temperature measurement by all sensors

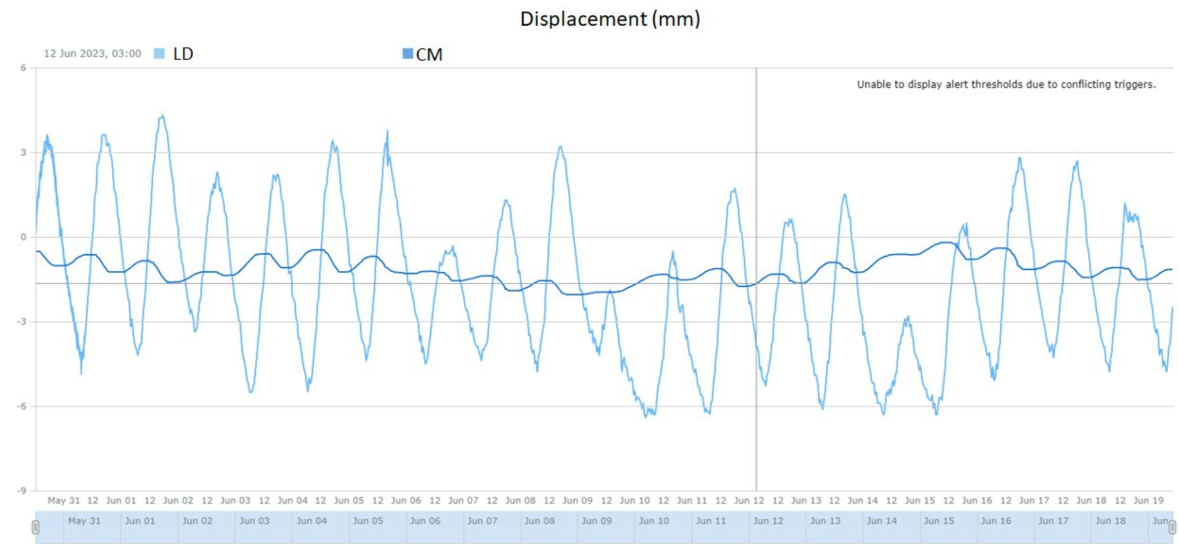


Figure 5b: Displacement measurement by LD and CM

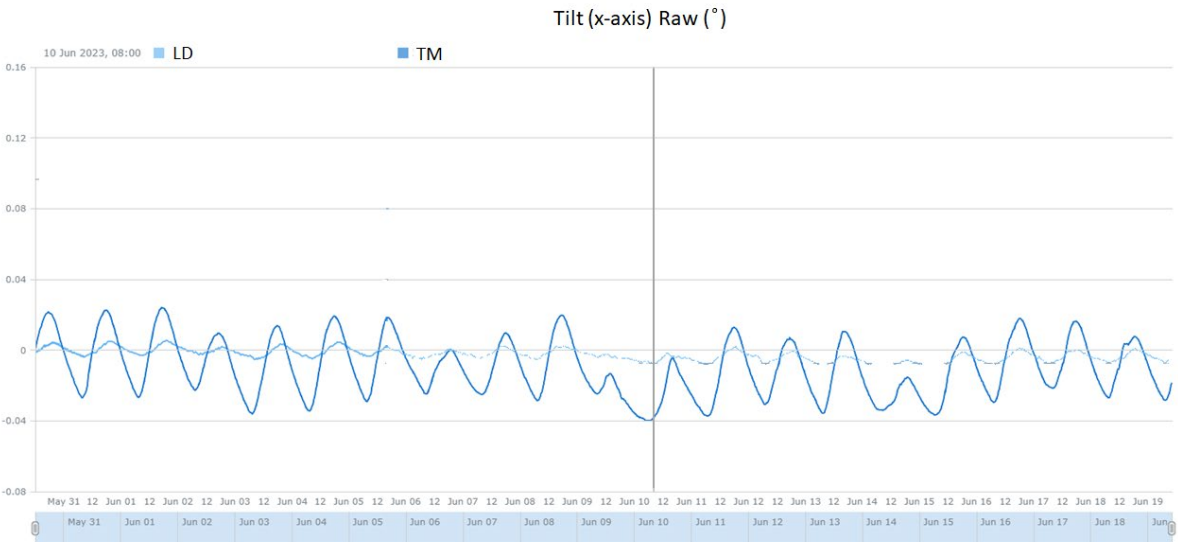


Figure 5c: Rotation of bridge deck in x-axis by TM and LD

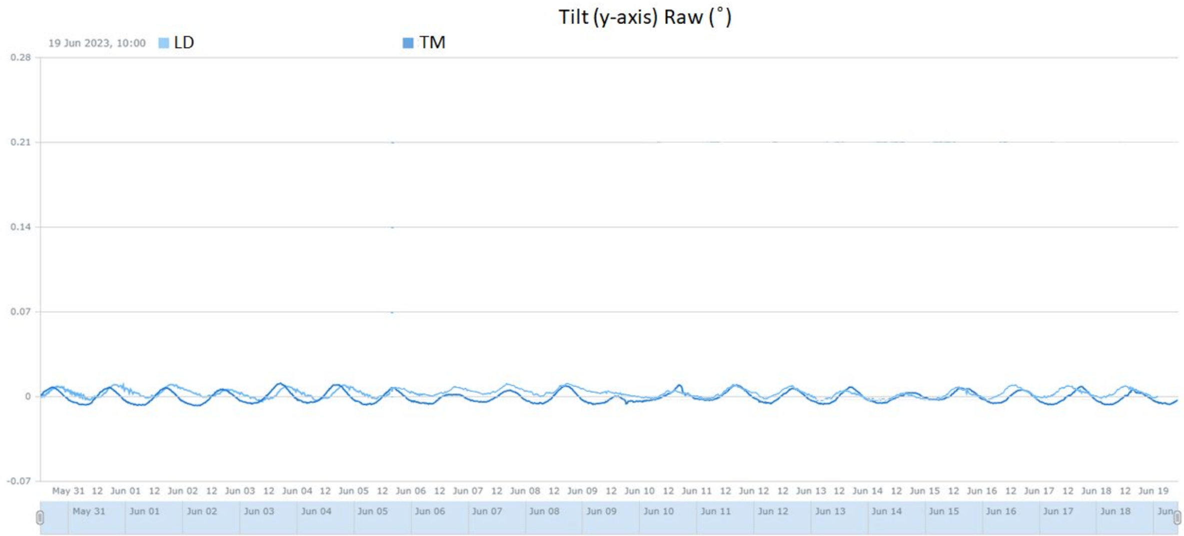


Figure 5d: Rotation of bridge deck in y-axis by TM and LD

DATA VISUALIZATION IN MR

The research was planned to develop a platform that can be used to integrate the SHM system with BIM technology and its further visualization in MR. This integration is established using the HoloLens device which is used to visualize the SHM data in MR.

Besides just the visualization, it also offers smart health monitoring possibilities where bridge inspectors can see the virtual as well as the real assets at the same time. This way the bridge monitoring data can be downloaded and shared from the bridge site.

Moreover, the collaboration tool of the HL allows several partners to join the bridge inspection remotely and assist the bridge inspector in decision-making regarding onsite bridge health issues. Implementation of the bridge in MR is shown in Figure 6 in the MR environment.

Figure 6: MR implementation using HL

In quest of the above goal, an MR app is developed in UNITY 3D and deployed to HL. The BIM model of the bridge was used as the source file for developing the MR platform which helps to develop the application in UNITY.

In this application, the virtual icons of each installed sensor were developed to replicate the real SHM devices in MR. These virtual sensors are then linked with the real sensors using Visual Studio.

Each virtual sensor is embedded with the graphical interface of real sensors so clicking the sensors directly opens the sensor's graph, shown in Figure 7. After successfully developing the app in UNITY, it was deployed to HL.

After the deployment of the application to the HL, it was tested on the subject bridge in the field conditions. All the SHM devices were found to be attached to the bridge model at the same location where actual sensors were installed.

Clicking each sensor opens the web platform where real-time data can be visualized in a graphical format. This data can be visualized over a certain period.

Data can also be stored in HL as a CSV file which can further be transferred to any workstation. This way a complete visualization of SHM data can be performed onsite or remotely and data can be shared with the stakeholders over the Internet. The developed app was run in the HL and with just a click popped up the sensor data in MR with the possibility of changing certain parameters as per the bridge inspection's need.

The final view of this MR implementation is shown in Figure 8.

Figure 7: SHM data visualization in MR

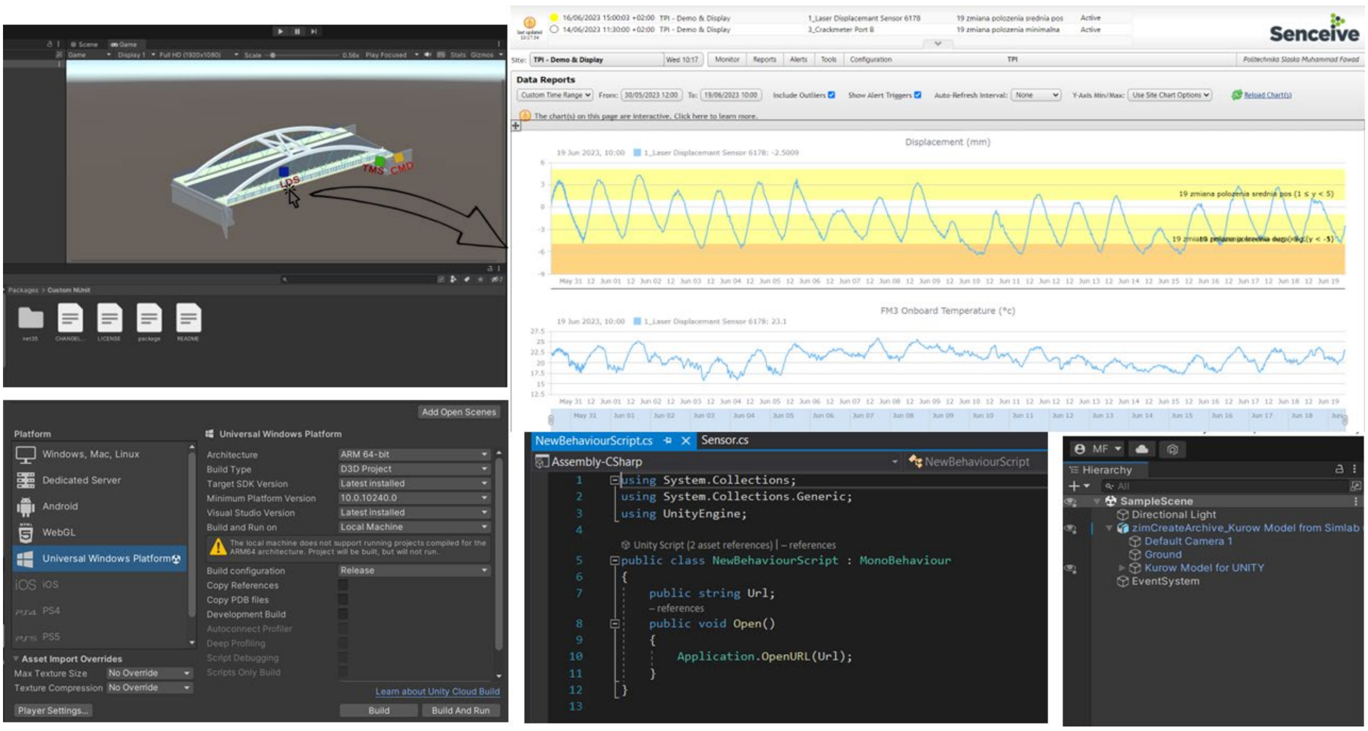


Figure 8: MR App development in UNITY

CONCLUSIONS

This research has performed the integration of SHM and BIM technology where the AR tools are used to visualize the SHM data. The major outcomes of this research are summarized as:

- The FEA of the bridge was performed to design the SHM system of the bridge;
- The SHM system involves the Crack Meter (CM): for the measurement of longitudinal displacement, the Tilt Meter (TM): for the measurement of rotation angle showing the bridge rotation in 3-axis, the Laser Displacement Sensor (LDS) for the measurement of vertical displacement and rotation at the center of the bridge deck. Additionally, a 3G Gateway is also the part of the SHM system, which helps to connect SHM system with the IoT web platform;
- The SHM of the bridge was performed for three weeks and data was recorded for further diagnostics of bridge health;
- Implementation of bridge model in MR.

The project started with the FE analysis of the bridge in order to identify the measurement parameters and associated sensors. Based on the results of the FE analysis crack meter, tilt meter, and optical laser displacement sensors were proposed to be installed on the bridge. As per the plan said sensors were installed and measurements were carried out for three weeks after which the sensors were dismantled and measured data was stored for further processing using ML algorithms.

Further, the research was supplemented with the implementation of the bridge's BIM model in MR using HL. This implementation helped to visualize the SHM data in MR. For this purpose, an MR app was developed in UNITY 3D and deployed to HL. This app includes all the SHM devices integrated into the IoT web platform. Implementation of this app in MR allows the visualization of each sensor's data in MR and offers the possibility of data sharing over the Internet.

This way the research has explored the possibilities of smart structural health monitoring of bridges using the applications of MR.

Thus, this research tries to establish a hub of different growing fields like SHM, BIM, and AR.

ACKNOWLEDGMENT

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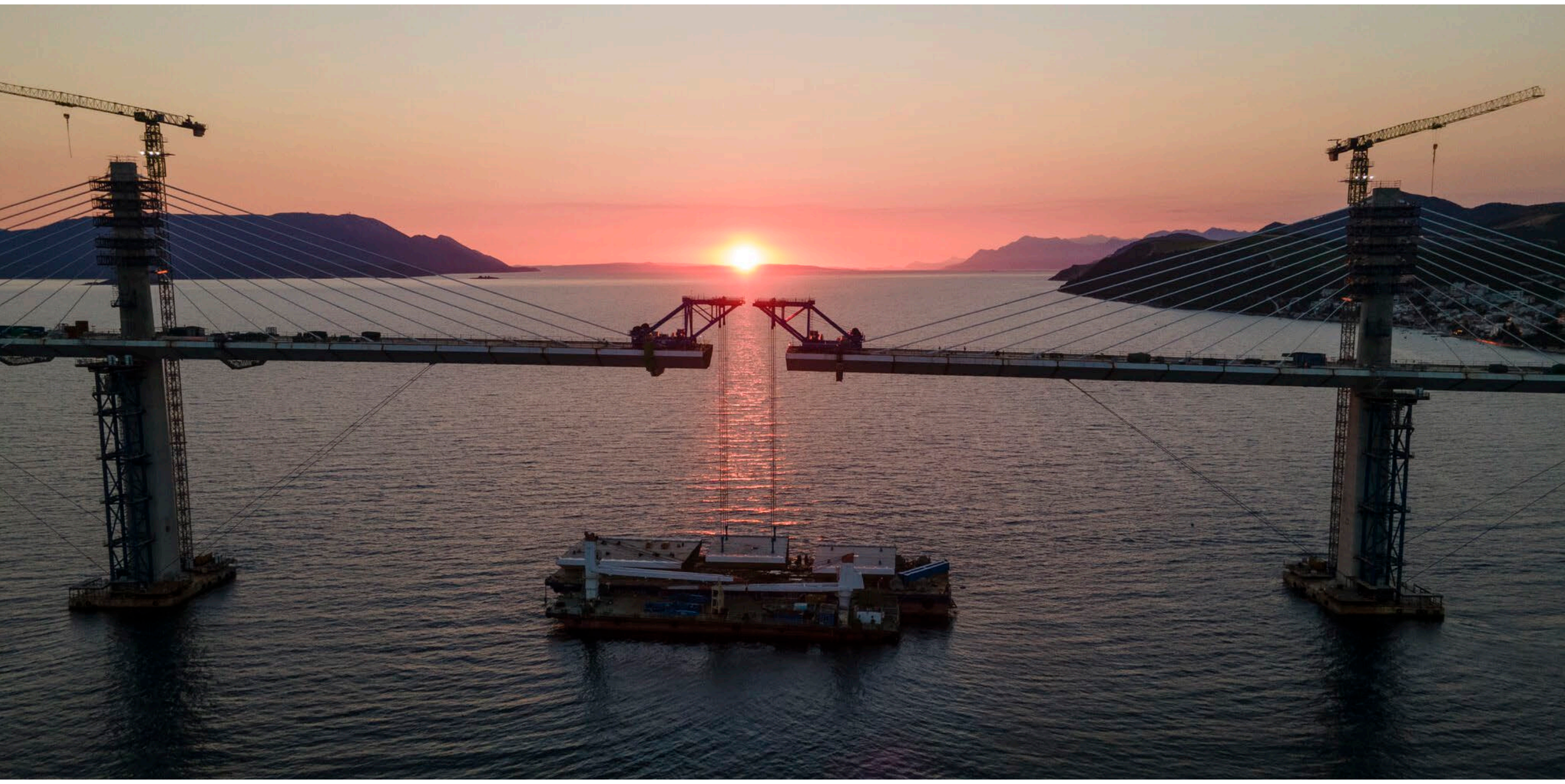

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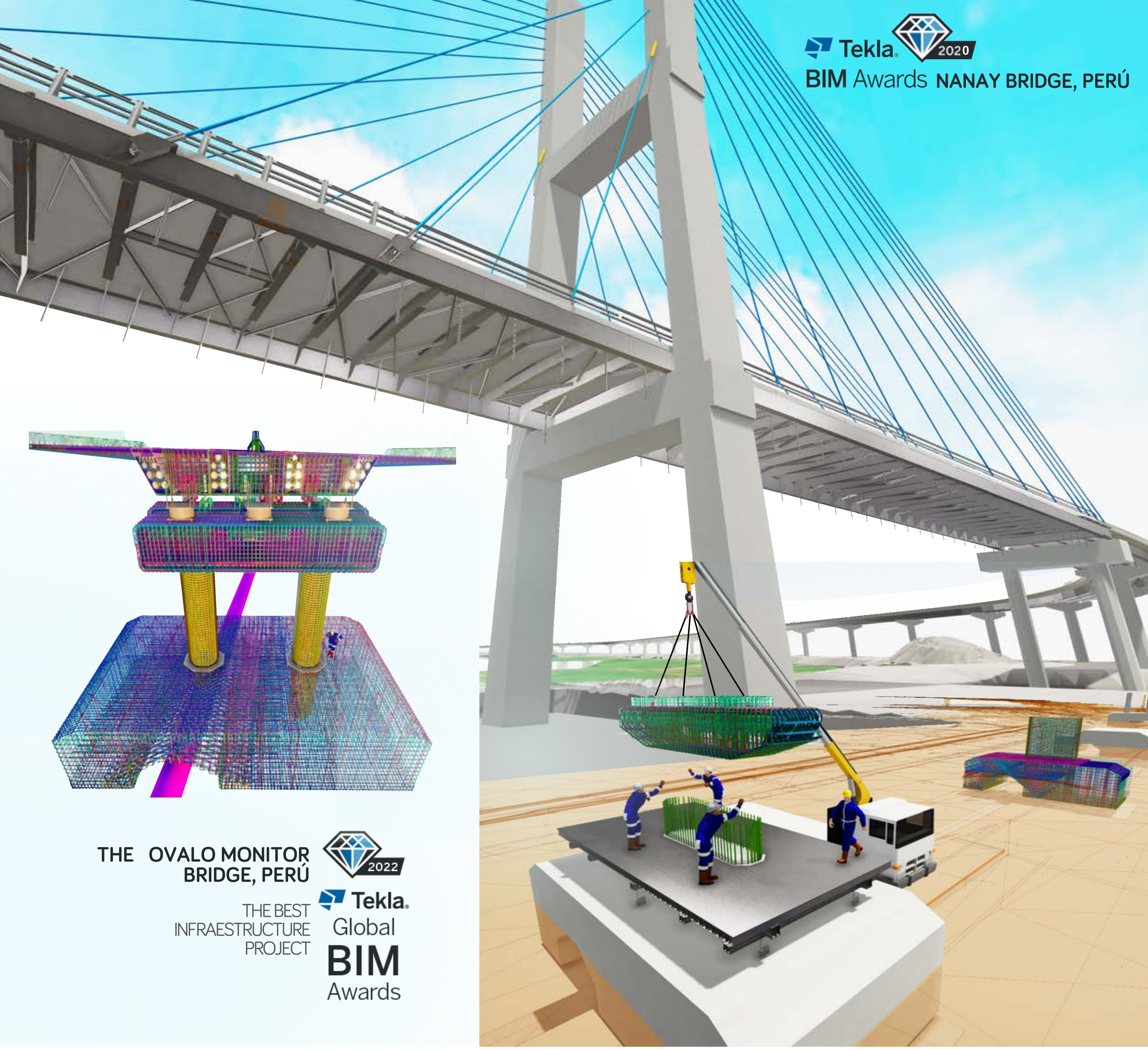

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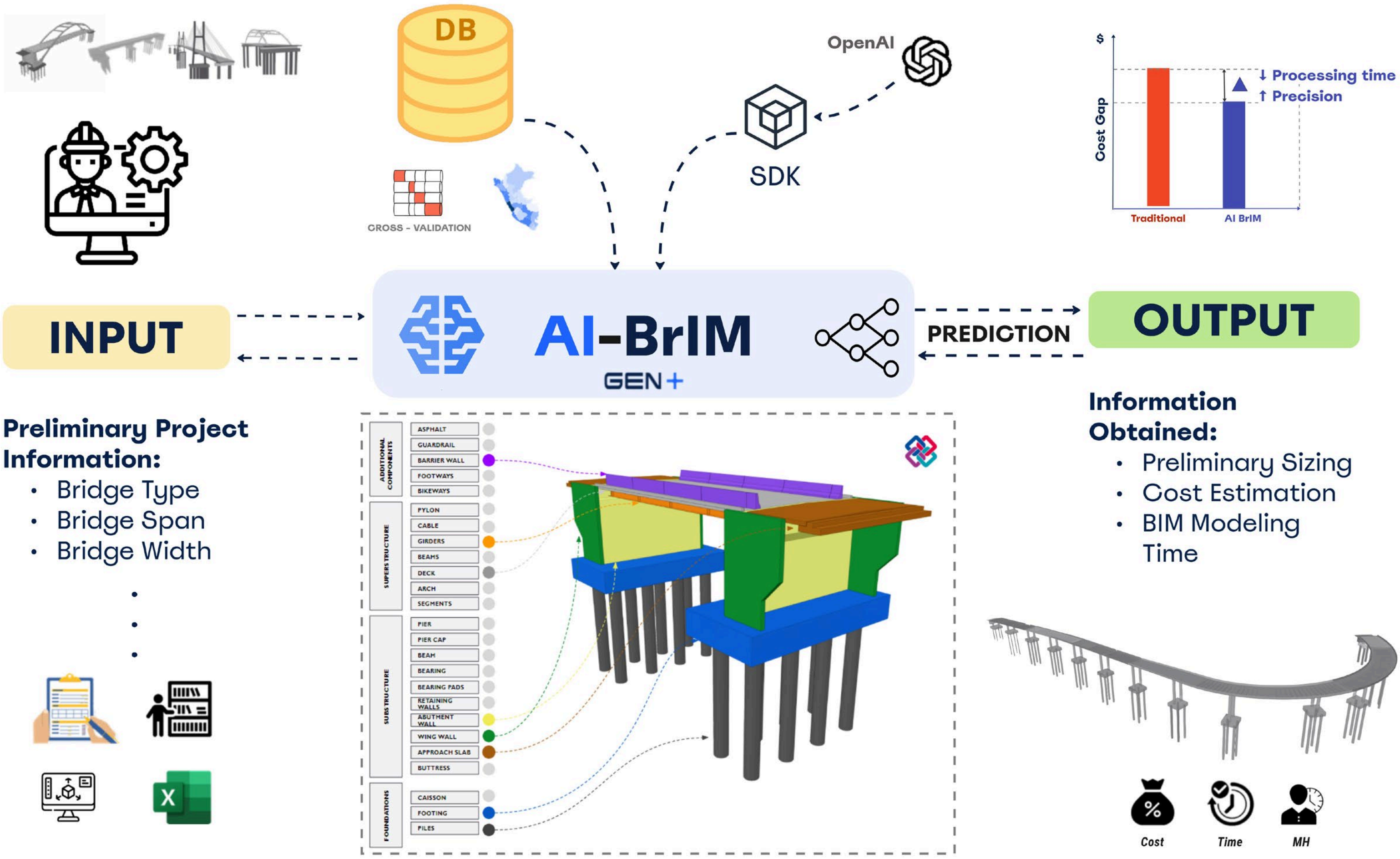

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