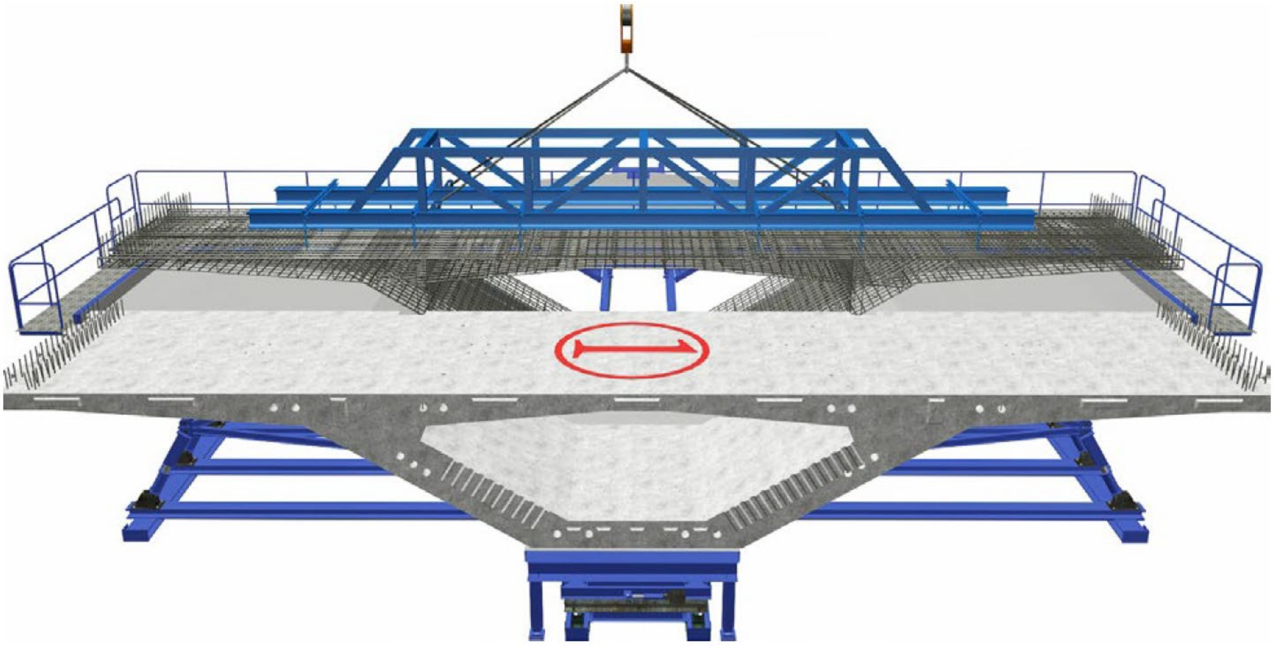

e-BrIM

ISSUE 01/2023 FEBRUARY

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Front Cover: 4th Ring Transportation Corridor in Zhengzhou, Henan, China
Credit: Sun Engineering & Technology International

International, interactive magazine about Bridge Information Modelling. Peer-reviewed.

It is published at www.e-brim.com. Open Access.

Release on:

20 February, 20 May and 20 October

Number: 01/2023, February **Year:** II.

Chief Editor: Magdaléna Sobotková

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Editorial Board

The Publisher: PROF-ENG, s. r. o. (Ltd.)
Velká Hraštice 112, 262 03 Czech Republic
VAT Id. Number: CZ02577933

ISSN: 2788-0540

Dear Readers

In the first article of this issue, you can read about an additional elevated expressway to increase the traffic capacity from 10 lanes to 18 lanes on the 4th **Ring Transportation Corridor** to connect the inner city with the suburban areas of the City of Zhengzhou, China. For the entire project, including ramps and interchanges, close to 50,000 precast segments were needed and the ABC was used, utilizing an efficient paperless process.

The article is followed by the **Interview with Tina Vejrum** who has recently been elected President of IABSE.

Bridge management teams around the world are faced with the challenge to endure user safety and manage the sustainability of bridges. The third article of this issue focuses on **BMS enhancement incorporating futuristic technologies**.

The next article presents a **geometric approach of introducing BIM to BMS**. Rather than trying to thoroughly connect these two robust systems on the object definition level, this approach focuses on geometry.

The authors of the next article describe their **research aimed to create an automatic damage identification technique for reinforced concrete traffic bridges using machine learning algorithms.** For this, a digital twin of the bridge was created using a verified 3D finite element model based on plans and actual environmental conditions and loads.

The last article of this issue is the 2nd part of a series, focusing on the field **applications of digital technologies** in structural, especially bridge engineering. The first part analysed the use of VR for the assessment of bridge concepts whereas, in this part, the authors are implementing the use of MR for the assessment of bridge concepts.

I would like to **thank all 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.

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

On behalf of the organizers, we would like to invite you to the **InfraBIM Conference** which will be held from 23rd to 25th May 2023 in Cracow, Poland. You can find more information on page 67.

On the following pages, you can also find more information about both our magazines e-mosty & e-BrIM, and also our Partnership Offer. I can also prepare a tailor-made partnership plan for you and your company; we will be happy to welcome you as our partner.

We are already working on the next issue of e-BrIM which will be released on 20th May. We welcome your articles for the May edition, with the deadline for the first drafts 20th March 2023.

The next issue of the e-mosty magazine will be published on 20th March and will be dedicated to the Chenab Bridge in India.

Magdaléna Sobotková

Chief Editor

e-BrIM

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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.

The readers are mainly bridge leaders, project owners, bridge managers and inspectors, bridge engineers and designers, contractors, BIM experts and managers, university lecturers and students, or people who just love bridges.

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20 May 2023 Edition:

Deadline for first drafts: 20 March 2023

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INTERNATIONAL ONLINE PEER-REVIEWED MAGAZINE
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ISSN: E-MOSTY 2336-8179

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MEGA PROJECT - UPGRADING THE 4TH RING TRANSPORTATION CORRIDOR IN ZHENGZHOU, HENAN, CHINA

Gernot Komar
Sun Engineering & Technology International, Inc., San Diego, USA

Dr. Junling Sun, Yong Ping He, Wenbin Lei, Chongju Peng
Sun Engineering Consultants International, Inc., Guangzhou, China

Figure 1: Aerial View of Intersection on West Line south of the Sports Complex

ABSTRACT

The City of Zhengzhou, with a history of 5,000 years, is the capital of the Henan Province with a population of 10 million people.

Zhengzhou is a major transportation hub in the heart of China. The fast-growing city was in need of an additional elevated expressway to increase the traffic capacity from 10 lanes to 18 lanes on the 4th Ring Transportation Corridor to connect the inner city with the suburban areas.

The additional elevated expressway has a total length of 93 km without traffic lights and faced complex boundary conditions, which includes the design of 27 main interchanges, 12 railway crossings, and 21 river crossings.

The focus of this project is to increase the capacity, by reducing the impact to the current traffic flow in a very short time frame and to meet the government requirements to implement green construction technology, which calls for an innovative solution.

Figure 2: West Ring Road

Figure 3: West Line transition between side-road and mid-road

The Accelerated Bridge Construction with the precast segmental bridge technology using the short-line match-casting method was deemed to be the only answer to fulfill the requirements from the owner and the government.

In order to provide a cost-effective solution about 1,200 precast bridge frames with span lengths between 36m and 46m were designed.

For the entire project, including ramps and interchanges, close to 50,000 precast segments were needed and the ABC was used.

Another remarkable aspect are the precast yards. Eight completely new PC yards with over 400 PC stations were designed and were ready for production within 5 months.

The locations of the eight precast yards were strategically selected with a cost-distance analysis to guarantee an ideal workflow.

A state-of-the-art data management system and geometry control software was combined to analyze millions of data daily.

This entire paperless process was extremely efficient, allowing the production of 200 precast segments every day at the peak production speed.

The largest precast segmental bridge project in the world was opened partially to traffic in 2020 and is now fully operational.

Keywords: Zhengzhou, elevated expressway, precast segmental bridge technology, precast yards, short-line match casting, green construction technology, geometry control, ABC.

This project was awarded the 2021 ASBI Bridge Award of Excellence as well as the 2021 International ABC Conference Award of Best International ABC Projects Constructed Outside U.S. and received an ENR 2022 Global Best Projects Award.

"I have a dream, to support the country in the development of Green Construction and Engineering IT in Transportation Infrastructure."

我有一个梦想,

支持国家发展交通基础设施的绿色建筑和工程信息技术。

Dr. Junling Sun

"The 4th Ring Road in Zhengzhou was a one-of-a-kind record-breaking project. When it started – I was a stranger to everyone involved.

After 2 years of working very closely together in Zhengzhou, I became a friend and left with great respect for the craftsperson, and all my peers and colleagues.

I am very grateful for this memorable experience."

Gernot Komar, Dipl.-Ing., P.E.

1. INTRODUCTION

The city of Zhengzhou, with a history of over 5,000 years, is the capital of the Henan Province and a major transportation hub. Zhengzhou has a population of 10.1 million.

Due to the poverty-alleviation relocation project, within the next 10 years, roughly 5 million more people will move into the city, making large infrastructure projects imperative.

To satisfy the needs of the fast-growing city, the 4^{th} Ring Transportation Corridor was developed. This expansion is considered one of the largest transportation projects in China.

The 4^{th} Ring Transportation Corridor in Zhengzhou is an elevated viaduct expressway above the existing 4^{th} Ring around the city center.

It increased the traffic capacity from 10 lanes to 18 lanes and improved the connection of the inner city with its suburban areas.

The industrialization technology of bridge design, fabrication, erection, and construction has been fully implemented to the greatest extent in this project.

The necessity of reducing the impact of the current traffic flow during construction and meeting the requirements of the city and government to implement green construction technology called for an innovative solution.

Accelerated Bridge Construction with the precast segmental bridge technology, using the short-line match casting method and continuous rigid bridge frame systems without bearings, is deemed to be the best solution for this Mega-Project.

Based on this infrastructure development, a series of successful industrial standards for precast segment fabrication were established.

Being one of the largest precast segmental bridge projects in China and providing an excellent demonstration in green construction with significance nationwide, it attracted government officials, owners, engineers, and contractors from all over the country to visit the site and learn about the project and the process.

Groundbreaking for the 4^{th} Ring Transportation Corridor Project in Zhengzhou was in December 2017 and it was officially opened to public on April 30^{th}, 2021.

Various main roads were successively opened earlier once the necessary access ramps were completed.

Numerous facts demonstrate the large scale of this project.

The total project area, including surface roads and bridge viaducts, adds up to 3.16 million m^2, which is equivalent to the area of 500 football fields.

The total concrete volume for the bridge viaducts is 6.0 million m^3, which is more than the volume of the three Pyramids of Giza.

The total steel used for the bridge is 1.2 million tons, which can be used to build more than 170 Eiffel Towers.

With over 50,000 segments this is the largest precast segmental bridge construction project in the world.

2. BRIM TECHNOLOGY TO SUPPORT DESIGN AND CONSTRUCTION

The Zhengzhou 4^{th} Ring Project uses BrIM to establish a virtual 3D model of the bridge frame and uses a complete and consistent database to provide this model and apply it to the actual situation of the elevated expressway.

Complex structural design problems can be solved by comprehensive simulation of the 3D model.

The team conducted rebar and PT clash detection checks for the pier segments.

Countless modifications for just one segment were made, which largely improved the efficiency of the entire project, with over 50,000 segments.

The BrIM model with all engineering information was used for a series of subsequent related tests and tasks, helping the precasting operation and the erection of the bridge segments.

Figure 4: BrIM Rebar Layout of Pier Segment

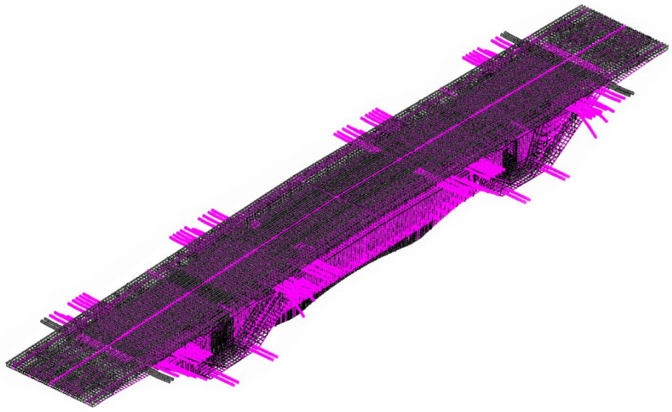


Figure 5. BrIM Rebar & PT Layout of Pier Segment

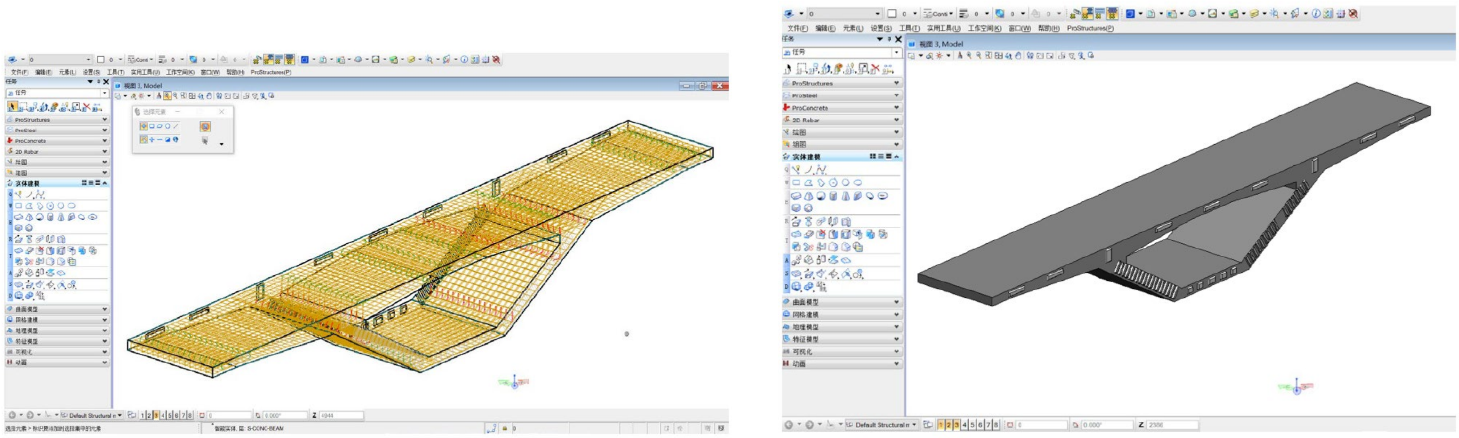


Figure 6: BrIM Platform to Develop PC Segment Shop Drawings

2.1 Precast Yard BrIM Design and Process Optimizing

The design of various precast yards took advantage of BIM technology.

The layout of each functional area and design of equipment, including batching plant, rebar production area, segment production area, storage area, patching area, segment loading area plus portal cranes, office and living area, and transportation access road within the precast yards.

With the 3D virtual simulation roaming of the precast yard, an enhanced layout with consideration of production line optimization was achieved, while the overall footprint of each precast yard was reduced, cost was saved, production speed was increased, and the overall project schedule was reduced.

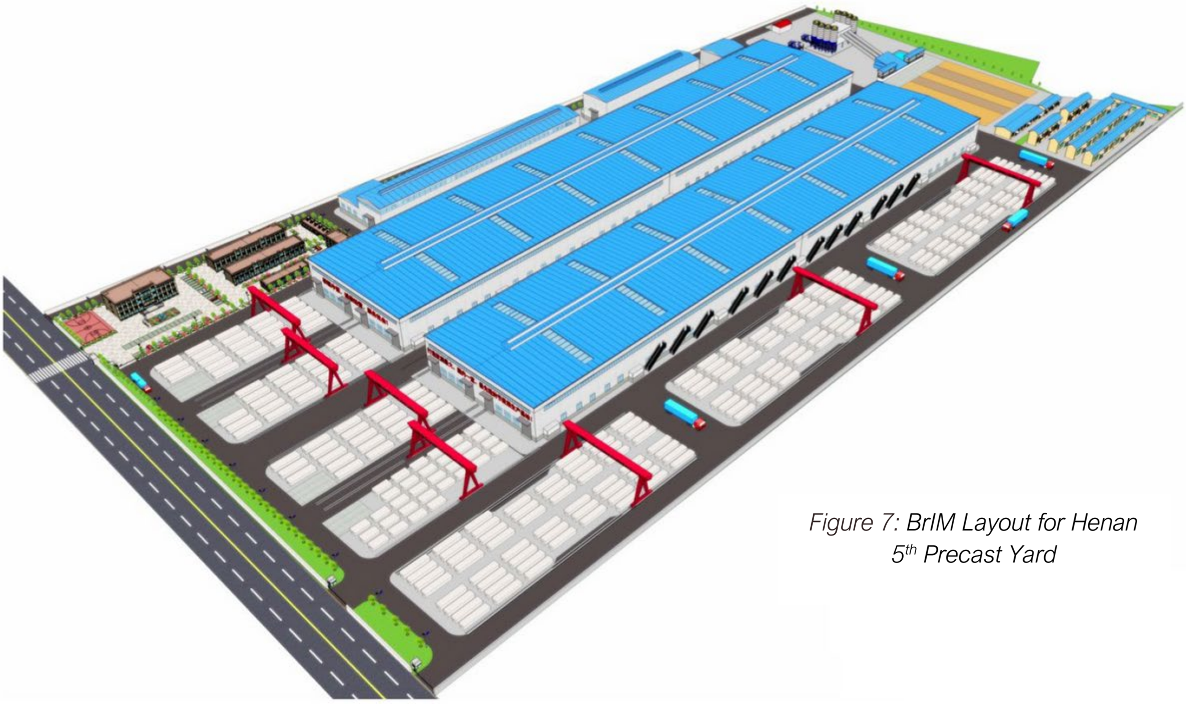


Figure 7: BrIM Layout for Henan 5th Precast Yard

2.2 Precast Yard Management Platform

An efficient and integrated visualization online management platform for precast yards was developed by integrating BIM data and a modern industrial management system.

This SUN-Tech management platform shares the information in real-time and provides cohesive control of the entire process of precast segmental components, from the raw material supply and storage to the segment production, transportation, and storage.

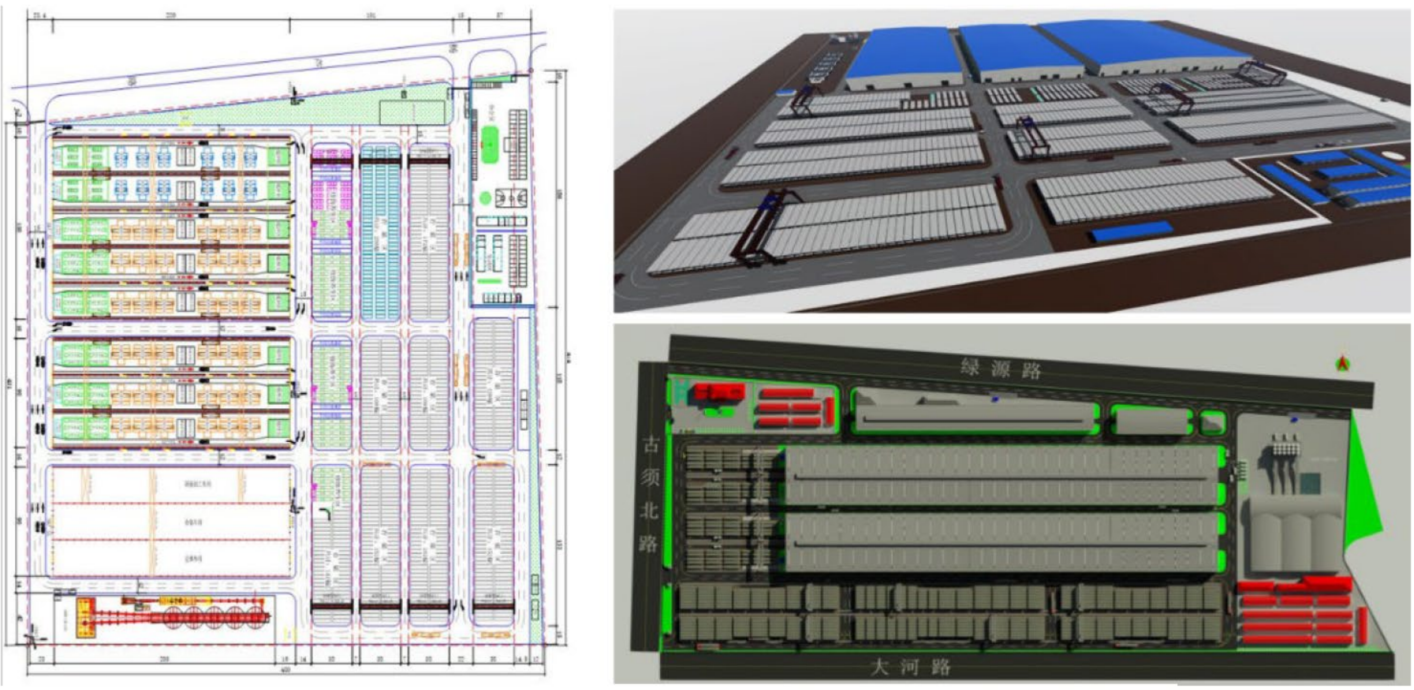
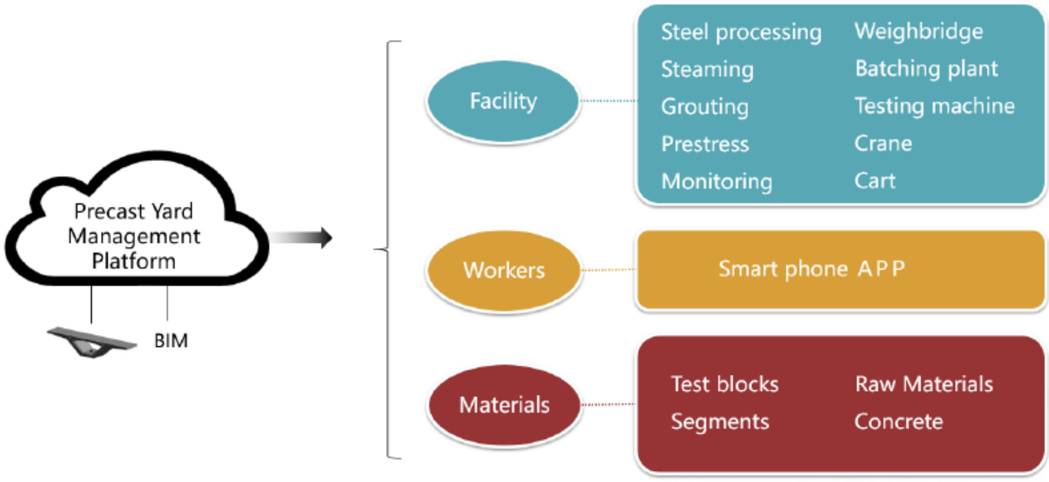


Figure 8: BrIM for Precast Yard Layout Optimization and Design



The SUN-Tech precast yard management platform controls the required material parameters for the concrete production of precast segments (water content, saturated aggregate, cement) precisely, which increases the production quality and reduces waste caused by incorrect material parameter forecast.

The application of intelligent storage and inventory management has changed from a manual recording process, which greatly reduces errors.

The state-of-the-art data management system carries out corresponding big data analysis on a cloud server.

This newly developed process guarantees efficient precast segment production at the highest quality and reduces the overall construction cost while improving work efficiency.

3. INNOVATION OF DESIGN AND CONSTRUCTION

Since the elevated expressway has a total length of 93.3km, its development faced complex boundary conditions, including 27 main interchanges with additional 90.0km, 12 railway crossings, 21 river crossings and underground utility relocations.

From the overall expressway 70%, 65.3km, are elevated viaducts, while the length of segmental bridges is about 45.7km for the main line and 50.0km for the interchange ramps. The elevated viaducts were designed to provide a 100-year service life.

1,200 different bridge frames were designed for the entire elevated expressway.

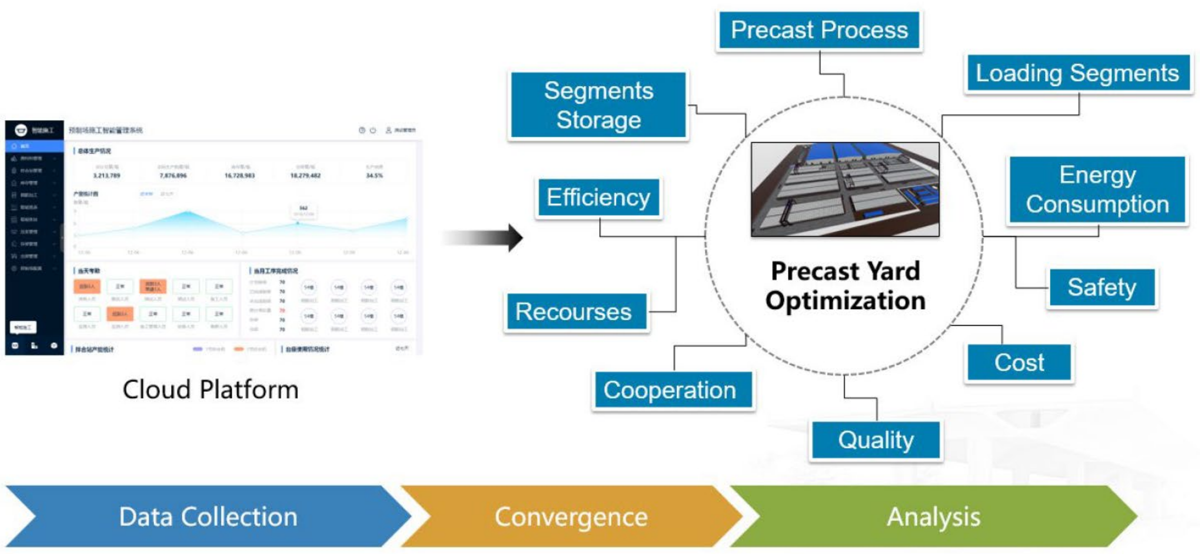


Figure 9: State-Of-The-Art SUN-Tech management platform

Figure 10: Garden Crossing Interchange

Figure 11: Aerial View of Henan 5th Precast Yard Factory

Most of the precast segmental bridges are continuous rigid frame systems without any bearings, consisting of 3 to 4 spans, ranging from 34m to 46m for each span.

Some of the ramps at the interchanges had shorter spans with a minimum span length of 25m and the special precast bridges for the river, rail or road crossings needed longer spans up to a maximum span length of 66m.

With only 4 basic precast segment lengths all required span length combinations could be achieved.

Only 5 basic precast segment forms were used for the fabrication of 50,000 precast segments. Many variations of span length, different widths of the bridge deck, and ramps with a small radius could be produced with this optimal precast template design.

Although only 5 basic forms were used, each of the 50,000 precast segments was unique.

Another challenge was the complicated alignment conditions along the 4th Ring Transportation Corridor, which influenced the layout of the elevated expressway significantly. The general design concept for the elevated expressway was to build the bridges in the center above the existing road with piers in the existing greenbelt.

Where, due to space restrictions or utility line interference, it was not possible to build the bridge in the center, the elevated viaducts were constructed at the outsides of the existing road.

This led to alignments with the elevated expressway transitioning from the center to the outside. The bridge viaduct in the center was erected on two cast-in-place piers with prestressed pier caps.

With this configuration, two single-cell precast box girders were erected using the balanced cantilever method for the center spans.

Figure 12: Aerial View of Henan 1st Precast Yard Factory

Figure 13: Storage Area in Precast Yard Factory

Figures 14 and 15: Inside the Precast Yard Factory

The outside viaducts and most of the interchanges, as well as on and off ramps were designed with a single-cell precast box girder on an integral pier.

Due to the accelerated schedule, these piers with the integral pier segments were cast-in-place.

As an additional research project, some of the ramps were designed and built with precast piers and precast pier segments, in order to show that everything, starting with the foundation, could be fabricated and built with precast elements.

Another remarkable aspect of the project are the precast yards. Eight completely new precast yards (three are precast factories) with over 400 stations were designed and were ready for production within five months.

The locations of the eight precast yards were strategically selected with a cost-distance analysis.

The construction speed for these precast yard factories was about 5 times faster than for a regular commercial or industrial facility.

Not only did the precast formworks need to be assembled, but the entire infrastructure of this operation, office buildings, workers dormitories, concrete mixing plants, row-material storage areas, rebar processing and precast workshops, patching and storage areas for the precast segments, canteens and recreational areas were developed.

The precast yard design and layout itself were a delicate design challenge. All processes needed to be optimized to guarantee an ideal workflow.

The challenge for the production process and segment transportation, while formworks were assembled, led to a more rational and functional layout with independent assembly lines within the precast yard.

Though the overall schedule was driving most of the decisions, there was never a time when quality or safety of the project was sacrificed.

The precast segmental technology allows for the bridge segment production to be in a controlled environment in factories, which is a healthier and safer environment for workers, compared to the cast-in-place method.

The 4th Ring Transportation Corridor in Zhengzhou with the precast segmental bridge technology has made a great contribution to citizens, society and industry.

With 50,000 precast segments and an accelerated schedule, time was the biggest constraint, but the quality was never sacrificed.

The short-line match-casting operation for such a great quantity of segments requires a well-organized, efficient, and accurate data management for the logistics and for the precise geometry control.

A state-of-the-art data management and geometry control software developed by SUN International was combined, implemented, and very successfully used for this project.

The data management system is able to track not only the final precast segment from the fabrication in the precast yard, to the storage area, to the

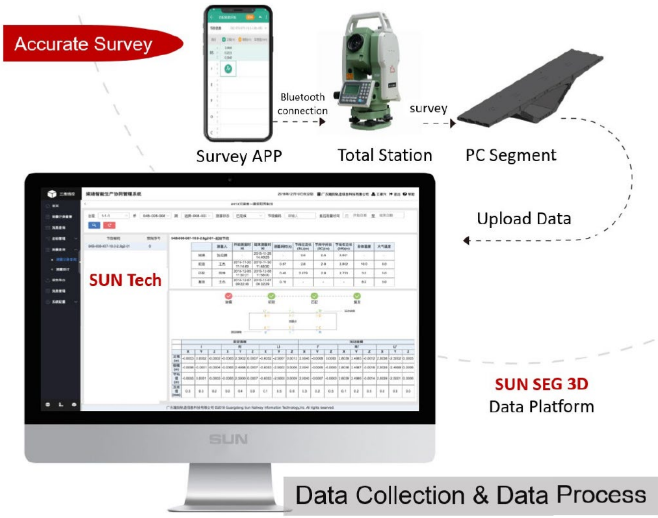


Figure 16: SUN-SEG 3D Geometry Control

Figure 17: Geometry Control Team

transport to the construction site, all the way to the erection of the precast segment, but also able to track the raw material, material testing, and quality control of the used material.

The geometry control part of this software system (SUN-Seg-3D) recorded the data for 6 control points for each precast segment with a total station survey equipment, which was connected to a survey-APP via smartphone, then transferred the data back to the platform, analyzed the data for the current segment and prepared the data, including correction analysis, for the next segment.

This process followed a rigorous quality control procedure, and the target data were submitted back to the survey team, within a very short time frame.

After the survey team received the confirmed coordinates for the new segment via survey-APP, they proceeded to the next step.

With this state-of-the-art data management system, developed by SUN International, millions of data were processed daily.

This entire paperless process was extremely efficient, allowing the production of up to 200 precast segments every day.

Considering the time constraints of this project, the combination of cast-in-place concrete and precast segmental was economically the most feasible solution and the best way to meet the aggressive project schedule.

Foundations and piers were casted on site, while the segments were produced in the precast yards.

Performing this work at the same time greatly improved the efficiency.

However, if the schedule would have permitted, the prefabrication of the foundations and piers would have been a viable option for this project.

To promote the feasibility of complete segmental precast bridges, including the substructure, some of the bridge frames were selected as a pilot research project to utilize the comprehensive (piers & girders) precast technology, and its favorable results showed that this precast technology is a good option for future projects.

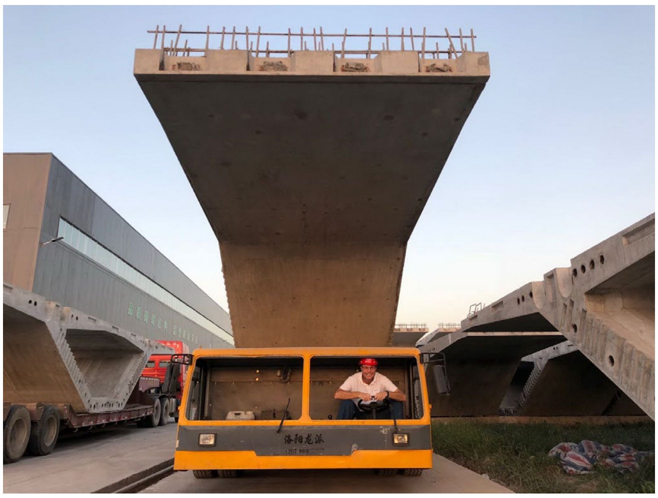


Figure 18: Segment Mover in Precast Yard Factory

Figure 19: PC segment erection with Gantry

Figure 20: PC segment erection with Mobile Crane

4. RAPID CONSTRUCTION

An astonishing achievement of the project is the fabrication and erection of 50,000 precast segments within only 40 months, which are world records for both fabrication speed (50,000 precast segments within 18 months) and the number of precast segments for a single project (50,000 precast segments).

The fast overall project progress benefited from the use of precast segments, which greatly reduced the reliance on concrete delivery to the construction site, and permitted the segment fabrication in a controlled factory setting, while the substructures were being casted on site.

A total area of 1.1 million m^2 was utilized to accommodate the precast yards. At an average speed, the eight precast yards produced up to 200 segments per day.

A fabrication cycle of only 1.5 days per segment was achievable at peak times.

An improved C60 high-performance concrete (HPC) was used to increase the short and long-term concrete strength and fulfill the rapid construction requirements.

Given the large number of continuous bridge frames, interchange on and off ramps with small horizontal curves, and special bridge frame structures on high piers, the balanced cantilever erection method was considered to be the ideal choice.

The contractors were not limited to specific erection equipment but were able to select their preferred construction equipment, varying from overhead gantries, travelers, mobile cranes, portal cranes, or simple falsework.

Figure 21: PC segment erection with Traveler

Figure 22: Construction of West Line

Figure 23: PC segment lifting with Overhead Gantry

Figure 24: PC segment erection with Portal Crane

A segment pair was erected in five hours. This operation consisted of lifting the precast segments, adjusting, and fixing the segment with temporary PT, surveying, applying epoxy at the precast segment joints, and stressing the permanent PT.

A span was completed in only 2 days, which is 30 times faster than the cast-in-place construction method.

With this erection method and the flexibility of construction equipment, the bridge contractors were able to work at multiple locations at the same time throughout the entire project site - at peak times there were 50 bridge erection sites at once.

The erection speed for the precast bridge frames was an average of 800m per day, with a maximum erection speed of 1,500m per day.

The construction process for personnel, material and equipment required strict and continuous coordination with at least 90 stakeholders.

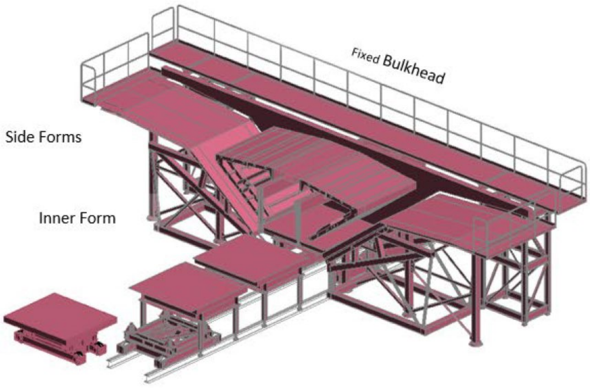
A management platform was utilized to assist the owner to monitor the project schedule and resources at all times.

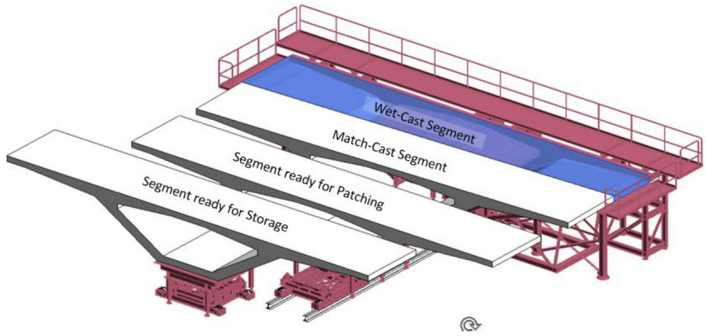
BrIM technology was utilized to support the construction process. The entire erection procedure starting from the precast segment transport, to the segment storage and all steps of the erection process were animated in 3D simulation movies.

These movies helped to develop and check the feasibility during erection with different construction equipment, optimized the efficiency and improved safety during construction.

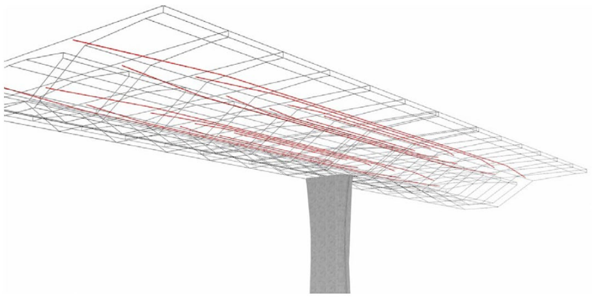
These animations provided the client/owner, the contractor, as well as the designer with a better understanding of the overall production and erection procedure.

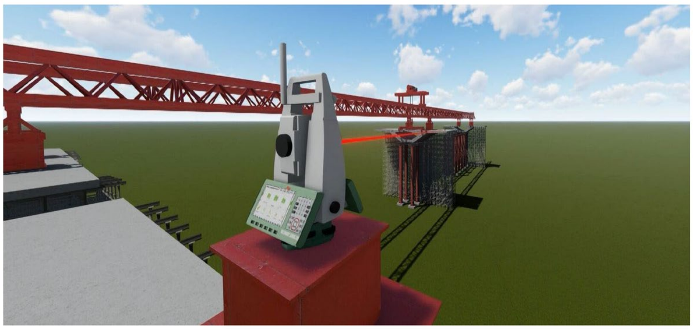
Figure 25: PC segment erection with Overhead Gantries in the Center

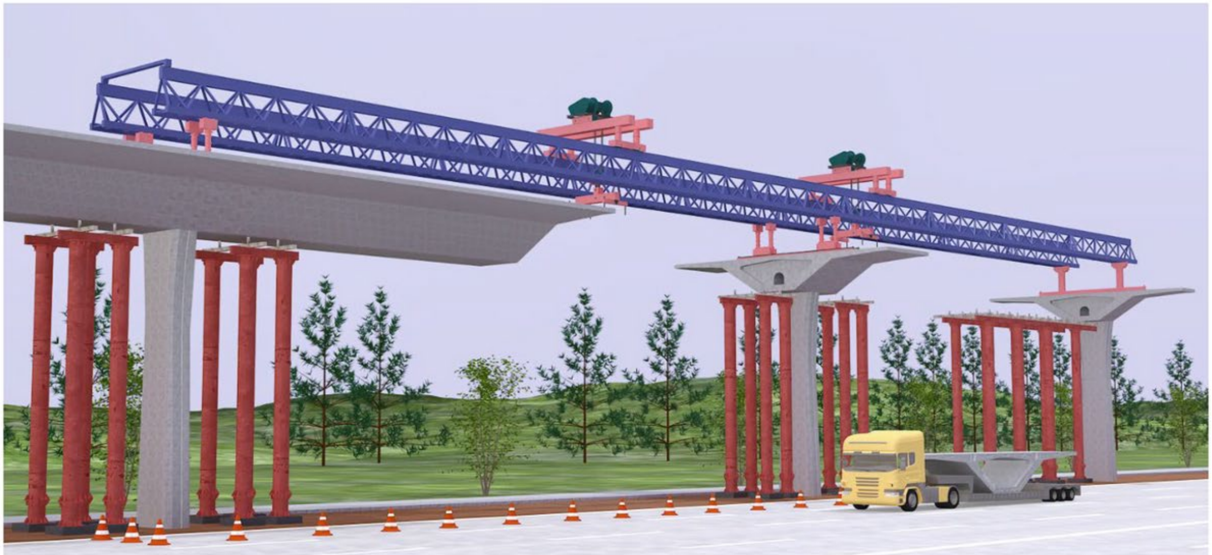




Figures 26 and 27: Short Line Match Casting Operation







Figures 28 to 30: Screenshots from Erection Movies to support the Construction Process

Figure 31: PC segment erection with Overhead Gantry on the Outside

Figure 32: PC segment erection with Overhead Gantry in the Center

5. AESTHETICS AND HARMONY WITH THE ENVIRONMENT

An urban public space was designed along the 4th Ring Transportation Corridor.

The landscape will be cohesive and consistent to integrate the ecological concept of the city.

Service stations were placed in every section and the landscape was adjusted based on various themes.

This transportation corridor is not only designed for the use of vehicles but is also seen as a 93km green corridor which represents Zhengzhou's new lifestyle.

The green belt around the city will enhance the quality of life, including bike lanes, running tracks and recreational areas.

These green areas are also essential to reduce the urban heat island effects.

The superstructure of the elevated bridge viaducts with the constant shallow bridge section presents a simple and slender design, with longer spans and fewer piers, successfully resulting in an aesthetically pleasing and economical solution that accelerated the schedule.

The two piers at the center section of the roads were tapered 1:30 from the bottom up to express a sense of rising strength.

The single piers at the outside section present a slimmer and more elegant shape.

With the aesthetically pleasing combination of the elegant superstructure and unique piers, the bridge design presents a kind of strength and softness at the same time.

The precast segmental technology using the balanced cantilever erection method shortened the construction duration and minimized the temporary environmental impacts.

The innovative design made an extreme effort to save construction material, which translated to a reduction of 560,000 tons of carbon emissions, which made a great contribution to environmental sustainability.

6. COST COMPETITIVENESS

The total cost of the project was $7.1 billion. The design contracts accounted for 4% of the overall project cost, while the construction contracts totaled 75% with an average construction cost for the elevated viaducts of approximately $950/m^2.

Compared with conventional bridge cross-section, this 16.5m wide and 2.2m deep single-cell bridge cross-section with longer overhangs and inclined webs (1:1) reduced the concrete material by 760,000m^3 and the mild reinforcement by 160,000 tons, which is a material saving of 15%.

The structural frame system with fewer bearings was utilized in this project, which reduced the demand for 7,200 large spherical steel bearings, resulting in the reduction of maintenance costs.

Figures 33 and 34: Expressway in the Center

7. CONCLUSIONS

From the onset of the project, the Design Joint Venture team developed elaborate design concepts for the project to save costs, simplify construction processes, improve construction quality, limit the impact on public during construction, as well as taking environmental and aesthetic factors into consideration.

The precast segments were fabricated in the precast yards off-site, which greatly reduced the amount and duration of work performed along the 4th Ring Transportation Corridor.

The elaborate planning of the eight precast yard locations avoided long transportation routes, reduced traffic impact, and led to a decrease of transportation costs.

Due to this accelerated bridge construction process and a state-of-the-art data management and geometry control software, which allowed the construction work at multiple locations at the same time throughout the entire project site, various sections were opened earlier.

With no traffic lights on the elevated expressway, the speed limit could be increased from 60 km/h to 80 km/h reducing the travel time around the whole loop tremendously from 4 - 6 hours to 1 - 2 hours.

Figure 35: Aerial View of Nort-West Intersection

Figure 36: Aerial View of West Line next to the Sports Complex

Figure 37: South Line over existing Intersection

Figure 38: Small Radius on and off Ramps on North Line

INTERVIEW WITH TINA VEJRUM

SENIOR TECHNICAL DIRECTOR, COWI; PRESIDENT OF IABSE; AFFILIATED PROFESSOR AT DTU

Magdaléna Sobotková, Vanja Samec

First of all, please accept our congratulations on being elected as a President of IABSE. We all wish you a lot of success and achievements in your work.

Thank you for your time for this interview.

Thank you for the kind invitation, for your active involvement with the activities in the International Association for Bridge and Structural Engineering (IABSE) and for your contribution to promoting the profession. This is very important and valuable.

As both our magazines, e-mosty and e-BrIM, revolve around bridges, let us ask you about your relationship to bridges and what inspired you to become an engineer.

Since a child, I've always had an interest in math and natural science. In particular in applied science. Therefore, studying engineering was a natural choice for me. I was deeply fascinated with architecture, historical buildings and structures.

I recall as a child passing the New Lillebælt Bridge (opened to traffic in 1970) in Denmark for the first time with my parents and I thought to myself "Wow, this must be the biggest bridge in the world". Which wasn't of course, but this was the first suspension bridge I had seen and for a child, it was pretty impressive.

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

I have been very fortunate and have met many inspiring bridge engineers. Prof. Niels Jørgen Gimsing was teaching bridge building at the Technical University of Denmark and his practical approach and experience were very inspiring.

Later, Prof. Gimsing became the supervisor on my PhD where the topic was cable-supported bridges.

I would also add the many international experts I have met in IABSE. This is an extraordinary community and being a member has provided me with so much opportunity and value throughout my career. It was Klaus Ostenfeld, former CEO of COWI and former President of IABSE, who got me deeply involved with IABSE. I am grateful for his mentoring, which still continues.

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

I think I have been actively involved in over 30 bridges around the world. In the early years it was as a bridge engineer, then as a project manager and in recent years in a more overall role acting on steering committees or as an expert.

You were involved in the design of the Stonecutters Bridge. What were the outstanding moments for you?

I worked on Stonecutters Bridge in Hong Kong SAR for more than 10 years in total.

First, I was involved in the technical assessment of the entries in the international design competition that the Highways Department had launched in 1999 to procure the design of the crossing.

The role was to support the Technical Evaluation Committee. Subsequently, Ove Arup and Partners, together with COWI, won the detailed design and

I took part in the design of the steel superstructure and stay cables. Later in the design phase I also got involved in the project management side of things.

I had the opportunity to spend three years on the construction site in Hong Kong acting as Senior Resident Engineer. Living and working for three years in Hong Kong together with my partner was a highlight in my career and it provided so much valuable feedback on construction and the challenges that needed to be overcome to build a bridge of this scale.

At the end of the day, the international bridge community is not that large and during this period working on Stonecutters I was introduced to a lot of people, who I have subsequently met and collaborated with on other projects and in different roles.

Can you also tell us about your involvement in the 1915Çanakkale Bridge in Türkiye which is currently the longest suspension bridge in the world?

The 1915Çanakkale Bridge connects two continents and holds the current world record with its 2,023m long main span and a total continuous length of 3,563m.

COWI carried out detailed design including specialist studies and construction engineering of the 1915Çanakkale Bridge from 2017 until the bridge opened to traffic in March 2022.*

During this period, I was Vice President for COWI's bridge department, Bridges International. I sat on the Steering Committee, supporting the project team with the necessary resources, setting goals for the development on the project, as well as the financial performance.

In the early phase of the project, there was also some technical sparring on the design of the bridge deck since Çanakkale has an orthotropic twin box steel girder like Stonecutters.

Similar to Stonecutters, COWI had a team on site during the construction of Çanakkale and I am very pleased that they got the same opportunity as I had to learn from the actual construction process.

This gives a unique insight that will be extremely valuable to our clients on upcoming projects.

One of the things that I am particularly proud of was that we made the bold decision to introduce BIM on Çanakkale to get experience with this way of developing and delivering a project.

This was despite the fact that there were no requirements from our client (the contractor) or from the owner to have a BIM model.

It was a steep learning curve and tough for the project team at times, but everybody was committed to the courageous decision we had made as a team and as an organisation we learned so much. As a result, today we have a very well-tuned, automated and powerful process to deliver future projects for our clients.

**You can read about design and construction of the 1915Çanakkale Bridge including an article prepared by COWI in a special edition of our other magazine, e-mosty.*

Other long-span bridges are currently planned or being built. Are you also cooperating on them?

Two bridges with an even longer main span than Çanakkale are currently being designed and constructed in China: The ZhangGao Bridge in JiangSu province with a main span of 2,300m and ShiZiYang Bridge with a main span of 2,180m crossing the Pearl River Delta in GuangDong province.

The latter carries a total of 16 lanes of traffic on a two-level truss girder and the traffic loading is a real challenge.

COWI has acted as an international expert consultant on both these projects bringing in our expertise from detailed design and construction of Çanakkale, as well as from other major suspension bridges before Çanakkale.

The exchange of knowledge and ideas with the Chinese designers, discussing concepts, design assumptions and specific technical challenges has been particularly fruitful.

In recent years, we have seen plenty of record-breaking bridges being planned and already built. The longest main span, the highest towers, the highest bridge, the widest deck, etc. Where do you think are the limits? And what may be the limiting factor?

In my opinion, breaking records is not a goal in itself. The design of infrastructure should always be done respectfully in the service of society and governed by the needs of local communities.

Technically, we can keep pushing the boundaries of technology, but the governing factor should be sustainability in every aspect of the word.

In recent years there have been significant investments in research and concept development of floating structures such as floating bridges.

Floating bridges are being considered for marine crossings where the water depth is so large that it is either not technically feasible or financially viable to install fixed foundations.

The Ferry Free E39 project is an example of a visionary project where these innovative solutions are being investigated and COWI, together with our Norwegian partners, is a central player.

Another area where I think we will see the increased focus is within the existing infrastructure.

Both from a sustainability and a financial point of view there is a lot to be gained by extending the service life of existing structures, rehabilitating it and upgrading it to meet requirements for future use.

This will have to be done in a clever way that causes minimal disruption to normal operation in order to limit the impact on the users.

This will become a major topic for engineers in the future.

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

The construction industry is still fairly traditional. There have been some technical advances in terms of high-strength materials, but the main achievement has probably been in the advanced digital tools that are available for design and construction.

The introduction of BIM models that can be used from design, construction and into the service life phase of a structure in combination with structural health monitoring will give us new opportunities.

We are, however, still relying on concrete and steel and even though there is a push for making these materials more sustainable it is still not enough to make a real change in our industry.

We need intensive research into new materials and also new ways of designing.

Taking orthotropic steel decks as an example, which have hardly changed for the past 40 years or more.

Some of the earlier steel decks are starting to suffer from fatigue and this is a major challenge.

I see a big potential for improvement in this field, and it requires international collaboration to be successful.

How do you see the development of BIM utilisation in the bridge industry?

BIM will become an integrated part of our workflows.

Other industries are far more digitalised than the construction industry and there is a large potential for optimising our workflows and use of structures by adopting tools like BIM and digital twins. More research and development in this field is urgently required. I don't see us going back to traditional 2D drawings anymore.

In what ways has the introduction of BIM changed your work?

The workflow is different and with advantages and challenges of its own. It can provide great value but it is also an investment and if BIM models are very detailed at an early stage, it is also a big task to update and maintain them during project execution when things change.

In collaboration with clients, we are co-creating and gaining more experience with every project.

BIM has also introduced new ways of collaborating on the project teams and the work of engineers and BIM specialists is much more integrated than when we were used to only producing 2D drawings.

You are a President of IABSE for the 2022 – 2025 period, what are your plans? What do you want to achieve?

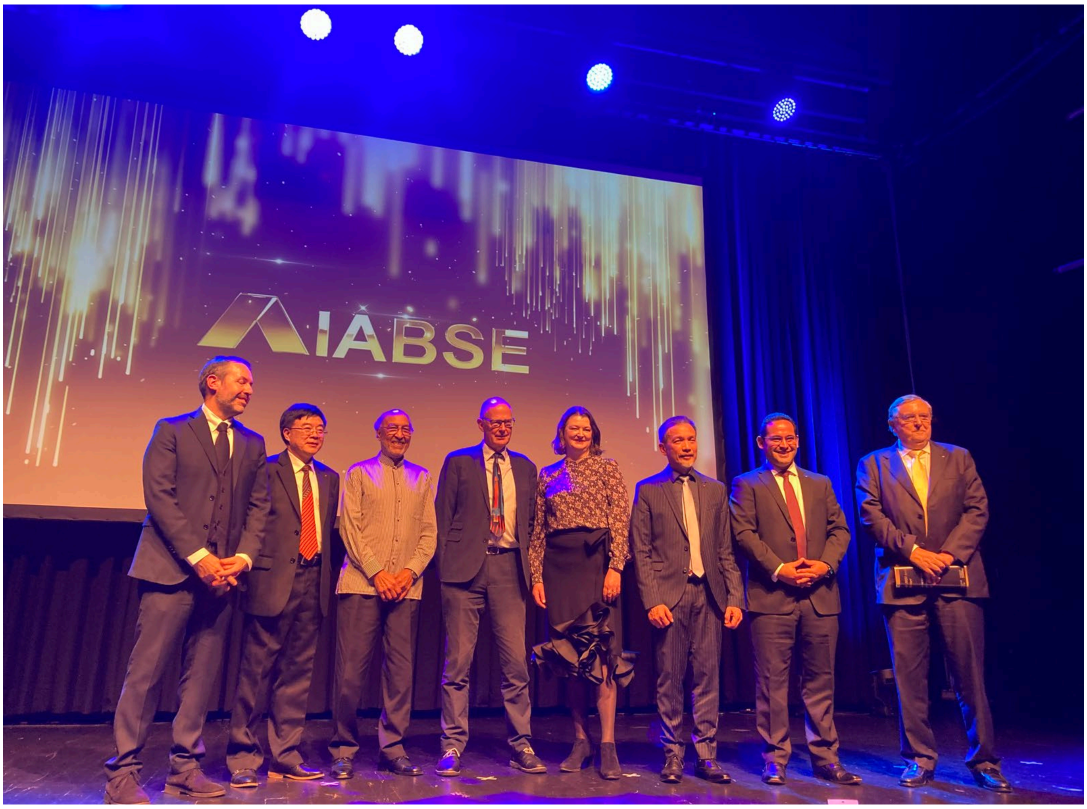
This is a very exciting time to serve as the President of IABSE. Fortunately, the world seems to be opening up after a long period of Covid-19 lockdown.

We all appreciate that we are now able to meet in person again while having learnt a lot about digital platforms that allow us to be more efficient in terms of collaboration.

I look forward to reconnecting with our members and to welcoming new participants at the coming IABSE events: The symposium in Istanbul in April 2023 and the congress in New Delhi in September 2023.

In IABSE we believe in international collaboration, professional dialogue and knowledge sharing to foster understanding and respect between people and organisations across borders. This is the basis on which the Association was founded in 1929.

Engineering is applied science and so that engineers can apply new science with the aim of providing new and better solutions, there needs to be research.



It is of vital importance that universities around the world receive sufficient funding to strengthen their research into identifying more sustainable solutions for the built environment.

A key activity in the Association is the Young Engineers Programme which builds on two fundamental core values of IABSE: The importance of young professionals in pushing for development and the need for international collaboration to achieve real change.

We have an obligation to offer opportunities to young professionals. IABSEs Technical Committee under the leadership of its Chair, Prof. Tobia Zordan, is planning a new IABSE Academy that aims to provide more opportunities for young engineers to learn and develop for the benefit of the societies that our profession serves.

I have great anticipation for this initiative.

What are the tasks and challenges for the future?

A major task for the association is to stay relevant and to continue providing value to our members.

There are so many active members already who share their knowledge and experience for free with the engineering society.

We need many more members who are willing to contribute. I believe that the value grows exponentially: The more members we have and the more diversity in the members' backgrounds, the more we benefit as an Association and as individual members from the broad and deep knowledge and experience anchored in IABSE.

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

I would encourage young engineers to stay curious, to be courageous and seek opportunities actively and to look at what may be of benefit in the long term.

The shortsighted "what's in it for me" approach will inevitably lead to lost opportunity. The highlights of my own career have been when I pursued something somewhat outside of my comfort zone – a new role and responsibility or a position in a new country.

It typically requires some personal investment to pursue new knowledge and skills, and the personal and professional development is the reward.

When the Canadian bridge company Buckland & Taylor Ltd. joined COWI in 1998 I was asked whether I would like to be part of the first team of engineers going to Vancouver on a staff exchange.

I had been with COWI for less than two years at that time and felt that I probably needed a bit more experience to be working with the bridge engineers in this renowned Canadian company.

Furthermore, I had just met my boyfriend. Anyway, we decided to proceed with the arrangements and I got to work on the rehabilitation of Lions Gate Bridge which was a unique opportunity.

The bonds that were formed 25 years ago during my time with Buckland & Taylor (now COWI North America) are very valuable to me and collaboration is seamless.

And yes: the relationship with my – then - boyfriend also lasts to this day.

I would encourage young engineers to seek international experience.

The value of exposure to different cultures, other ways of working and thinking will lead to more collaboration and more trust between people and the organisations we represent.

Finally, I hope for young engineers that they will care: care for the people that they meet on their way; for the people and communities that we build for and last and perhaps most importantly; that they care for the planet – for the climate, the biodiversity and the environment.

Thank you very much for your time.

It has been my pleasure.

Photos Credit: COWI, IABSE, Private Archive

ENHANCEMENTS IN BRIDGE MANAGEMENT INCORPORATING FUTURISTIC TECHNOLOGIES

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Research Engineers; URG

INTRODUCTION

Bridges are vital links in any road network. It is of vital importance to maintain these links. A loss of a bridge can paralyze the overall performance of the road network and cause excessive public and private loss.

Bridges within the network need to be managed in a way that ensures their uninterrupted performance throughout their design life.

Many bridges are affected by deterioration impacts that may occur due to natural disasters, the increase in traffic volumes, weather conditions, and/or material and strength degradation (i. e., corrosion, soil scour, and others), which may have a significant reduction on the structural capacity of the bridge or may urgently require action. [1, 2, 3]

Infrastructure around the world is facing all these problems. For bridges, the situation is compounded by aging, lack of funding for much-needed interventions and sometimes apathy of the owners to maintain the bridge populations.

In this scenario, bridge management teams around the world are faced with the challenge to endure user safety and manage the sustainability of bridges.

Bridge management teams are driven back to the drawing board with the aim to incorporate better efficiency in management principles. They endeavour to bring in innovations that will address the problems in a cost-effective manner.

Bridge management needs to focus on the optimization of fund allocation to address the deteriorating condition of bridges ensuring that sustainability is maintained without compromising the economic potential of the area.

Till recently, most of the decision-making was based on visual inspection by bridge inspection teams. This led to judgment-based conclusions which were used to decide the optimization of fund allocation. This at times may not be reliable because some damage is difficult to detect, quantify visually, or is subject to human interpretation. [4,13]

The search to supplement this system of reaching conclusions brought Structural Health Monitoring [SHM] to the forefront.

Innovations in SHM are playing a significant role in recent times because of their potential to capture real-time performance data, which helps in the reduction of maintenance costs resulting in an overall increase in the reliability of bridge structures.

The focus of SHM is on damage detection which causes distress leading to the deterioration of structures.

SHM applies real-time monitoring under live loads and applies digital techniques for analysis. Using the SHM, it is possible to monitor the bridge for the short term periodically.

It is possible to monitor the response of the bridge structure which reveals modifications to the material and structural properties.

SHM is important for maintenance planning to find a cost-effective solution to reduce costs and extend the life of critical assets like bridges. SHM has been widely used in many bridge structures around the world.

For this reason, a lot of bridge SHM data is available for analysis. This has facilitated the evolution of tools that have been developed to help government agencies manage bridges efficiently. [4, 5, 6, 7, 8, 9, 13]

There is an abundance in the variety of sensors, which are useful to assess the real-time behaviour of the structures.

Historically, monitoring devices were contact based but recent innovations render it possible to remotely monitor the structures.

The evolution of algorithms to link SHM data to modification in a cause matrix provides much-needed solutions. SHM enables bridge management to move the decision-making process to rely on real-time performance-based data.

The research to balance sustainability and economic growth has been the next focus research area of bridge management.

In the **Bridge Management System** [BMS], the key function of fund allocation optimization must be achieved by maintaining the balance between the preservation of sustainable environment and management of the economic benefits due to the prolonged life span of bridge structures.

It should ensure that the sustainability parameters are maintained during the life cycle of any bridge including the period of maintenance, rehabilitation, restoration, and replacement.

Sustainability management during the design and maintenance of infrastructure is ensured with the help of **Life-Cycle Cost Analysis** [LCCA].

The purpose of a Life-Cycle Cost Analysis [LCCA] is to estimate the overall financial cost of project alternatives and to select the design that ensures that the facility will provide the lowest cost of ownership consistent with its quality and function.

LCCA becomes more realistic if the benefits resulting from social, economic, and environmental parameters are also accounted for.

Unified Bridge Management System (UBMS) Analytics considers this management of the balance between sustainability and economics as an important focus area. This ensures the provision of a sustainable life cycle in the most cost-effective manner for the bridges. [10,11,12,13, 17, 21]

Bridge Management System is designed to manage a network of bridges under the constraints of limited budget and resources.

Many BMS have been assessing bridge conditions, modelling future deterioration behaviour, and the decisions making processes of fund allocation optimization, sustainability, economy for maintenance, and rehabilitation.

Various researchers have dealt with individual aspects of bridge management system components such as deterioration models, condition assessment, and life cycle cost analysis [20] that are critical to the optimization of funds.

To perform these functions, AASHTO and other similar guidelines for bridge management suggest that BMS should include the following components: data storage, cost model, deterioration models and optimization models.

Research is focused to evolve a comprehensive system using algorithms to optimize fund allocation, manage the life cycle costs and make it sustainable.

The system represents tools for decision-makers in optimizing bridge maintenance plans and repair strategies over a number of years within a budget limit and other constraints so that feasible and practical plans can be determined and to develop new strategies for managing public infrastructure assets in a way that ensures long-term sustainability under constrained budgets.

The analytics module within Unified Bridge Management System (UBMS) provides a possible solution by ensuring the Sustainability of bridge infrastructure without compromising the economic growth potential of the region in which the bridge is located.

Integration of SHM with UBMS offers data based on realistic observations, delinking it from any bias or judgment. [13, 18]

This integration results in a procedure to modify the Cause matrix whenever the Performance is observed to have decreased.

This ensures a Performance-based decision-making process within UBMS. This when combined, with the usage of Socio-Economic parameters collected in the inventory module of UBMS, ensures maintaining the balance between Sustainability and economic growth. Analytics within UBMS is a potent tool to address the present scenario.

STRUCTURAL HEALTH MONITORING (SHM)– REAL-TIME ANALYSIS OF BRIDGES UNDER LIVE LOAD

Essential information for bridge management is related to the construction and condition of the bridge. The inventory and inspection of bridges on the network is the first step in the process of compiling this crucial data.

The bridge inspection engineer must gather and compile information regarding various types of distress, details of locational, extent, and degree of severity during the inspection of the bridge structure.

Different elements of the bridge exhibit various distress. Normally, failure starts at the element which shows the maximum distress. Such elements tend to fail first. This results in the cascading effect, and ultimately in the failure of the entire bridge.

Location, intensity, and degree of distress are therefore crucial from the perspective of bridge maintenance and management. [1, 12, 13,18]

The Bridge Inspector can focus on identifying the most severely distressed elements after determining the geospatial locational data, the extent, and the severity of the distress in the element.

It is essential to identify the elements that are severely distressed before moving forward with the deployment of SHM. The elements displaying severe distress are subjected to short-term SHM. The performance data is recorded for all such elements.

To record the variation in the performance of such distressed elements under live loads, subsequently, periodic short-term SHM is used.

Short-term monitoring can be carried out using a variety of methodologies and sensors. The cause of the distress will determine the kind of sensors to deploy, the methods, and the parameters to be monitored.

The reason for distress is defined by three main processes as defined by EN 1504.[19, 13]

Two types of SHM are envisaged to achieve the required objectives:

1. **Remote or No contact SHM:** A system where the parameters such as vibration signature, amplitude, acceleration, frequency, and strain are captured by technology that does not require any physical contact with the bridge.
2. **Contact SHM:** System wherein major strain, stress, linear displacement equations, inclination, vibration, frequency, acceleration, and corrosion potential are measured by sensors [Strain Gauges, Linear Variable Differential Transformer (LVDT), Tilt Meter, Inclinometer Sensors, Acoustic Emission Sensors (AE), Fibre Optic Sensors, Corrosion Sensors, Accelerometer] in close contact with various desired components of bridges.

A brief indicative list of sensors, see Figure 1, that can be used, and their limitations are enumerated below. The limitations can be overcome and are indicative. Many other sensors can be used for short-term SHM. [7, 8, 9, 13]

Close Contact and No Contact SHM systems results will show variations in performance if any occur.

Changes in performance imply changes in distress. It is well-known that an increment in the degree and extent of the distress will result in a decrement in the performance of the bridge element.

This behaviour fact is considered for integrating the data of SHM within UBMS.

A data-gathering device connects sensors remotely or by a wire. Measured data is converted to digital form in an AD converter and transmitted wirelessly via a Bluetooth module and Access Point (AP).

The gathered information is kept on a computer's hard drive or in a storage device's (SD) memory.

A signal sender from a computer synchronizes the time of a data acquisition device.

Sr.No.	Sensors	Uses	Limitations
1.	Strain Gauges	To measure strain, to measure resultant stress.	1.Require the application surface to be finished and clean. 2. Sensitive to overload
2.	Accelerometer	For measuring acceleration force, vibration of the bridge.	1. Does not measure constant velocity.
3.	Temperature Sensors	To measures temperature of its environment.	1. Difficult to verify. 2. Non-linear. 3.Recalibration is difficult.
4.	VIDUR & VEDA	Used for Photonic System for vibration and condition monitoring of Structures.	-----

Figure 1: Indicative list of sensors

This system is real-time because the computer manages the sensor nodes (data-collecting devices) and stores data in real-time, see Figure 2.

TYPICAL APPLICATION OF TECHNIQUES TO YIELD ANALYTICAL RESULTS

Research and experimentation at various institutes in recent years have led to several techniques available for analysing SHM data. They can be combined and applied with convenience to obtain the desired results, providing information about decrements in the performance of bridge structures.

A couple of typical analysis procedures are described below:

1. **Operational Modal Analysis** (OMA), which can be Cepstrum-based, was examined in conjunction with Frequency Response Functions (FRF), Principal Component Analysis (PCA), and Artificial Neural Networks (ANN) by V. V. NGUYEN and Ulrike DACKERMANN et al. [5, 6]

   They used the same technique for frequency response function renewal (FRF). The result of this application was the detection of distress zones. The regenerated FRF data allows for the identification of distressed/damaged features. Excitation and transmission-related effects are included in response measurements. Before relevant transfer functions can be found, their separation is necessary.
   Using the Cepstrum approach, which can handle "frequentially smooth" inputs, the applied technique separates the source from the path.
   Following separation, the transfer path Cepstrum is curve-fitted to obtain the transfer function, from which the desired FRFs are produced.
   They can be made smaller by using Principal Component Analysis (PCA) techniques, which can also serve as an input source for ANN training. An Artificial Intelligence (AI) application to predict the likelihood of distress propagation was produced using ANN training. [8]

2. Meisam GORDAN et al. [5] advised the following for applications utilizing ANN, Frequency Response Functions (FRF), the Imperial Competitive Algorithm (ICA), and CFE:
   The operational strategies (Inverse Analysis) and diagnosing approaches (ANN/hybrid models) for input data make up two categories of the methodology used in this work.
   Different scenarios were put on the test structure [1:10] after it had been created. As soon as an FRF is created, it is saved in NVGATE.
   ICATS was used to extract the structural dynamic parameters from the collected vibration data and compute the FRFs using the curve-fitting extraction method.
   The input for an ANN or a hybrid ANN will be this extracted output [7].

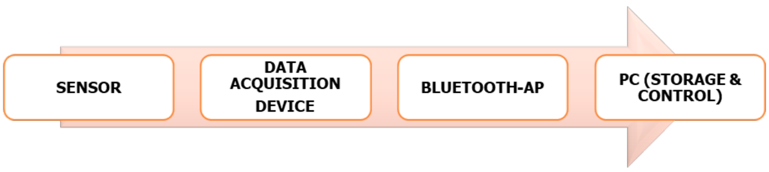

Figure 2: Information flow from a sensor to PC

In the process of Bridge Management, it is critical to identify the cause of distress. When cracks start to appear in the bridge profile, the origin of distress is first recorded.

Most often, crack propagation is the first sign of any visible distress. Integrating Performance with Bridge Management requires several key steps, one of which is connecting the distress symptoms with the cause.

Based on the determination of the source of distress and its correlation with one of the three primary processes - mechanical, physical, or chemical - the Cause matrix in UBMS is evolved [1, 4, 19].

This is primarily done by the Bridge inspection engineer during his long-drawn procedure to record and collate all the information for each element of the bridge from hand touch distance.

This leads to the establishment of a prognosis that defines the cause of distress. Being a prognosis, it is based on the judgment of the inspection engineer and his/her team.

A prognosis based on judgment leads to a scenario wherein such a prognosis must be validated and confirmed by an independent set of procedures and teams. To date, this was done by a non-destructive testing procedure performed at preselected locations by a bridge testing team to accomplish this. [1, 4, 13]

Our ability to accept the prognosis from direct observation of the bridge's performance under live loads is improved by the option of applying SHM. The performance of a bridge component that exhibits severe distress is recorded.

We can obtain time series information about decrements in performance by the application of short-duration SHM over a period of time. We can construct a reasonable logic to characterize the bridge by connecting this decline in performance with an increase in distress. [13, 18]

The application of SHM allows us to access time series data for elements that exhibit severe distress. Analyzing the SHM time series data, we can determine the progression of distress in those crucial elements on which SHM is deployed.

An algorithm that links the decrements in performance to the increments in distress establishes a procedure to modify the Cause matrix. The integration of SHM within UBMS is based on this algorithm.

The probability matrix for modifying the Cause matrix can typically be as below, see Figure 4.

An increment in distress generates a scenario where we can modify the Cause matrix generated by the prognosis of the bridge inspection engineer/team.

From acceptance of the judgmental prognosis, we have a situation wherein the Cause matrix is modified by actual observation of the performance of the bridge and its elements.

Integration of SHM within the analytics of UBMS steers us away from judgment-based to real-time observation and performance-based decision-making procedure. [4, 8, 9, 13, 18]

With the solution to technical needs taken care of, it is now essential to ensure that a balance between sustainability and financial evaluation is established. Life Cycle Cost Analysis enables UBMS to reach this objective.

Figure 3: Various causes of bridge deterioration

Ratings	9	8	7	6	5	4	3	2	1	0
9	0.29	0.21	0.16	0.34	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.21	0.16	0.13	0.51	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.16	0.13	0.11	0.60	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.13	0.11	0.09	0.67	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.11	0.09	0.08	0.71	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.09	0.08	0.07	0.75	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.07	0.07	0.78
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.07	0.86
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.93
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

Figure 4: Probability Matrix

LIFE CYCLE COST ANALYSIS [LCCA] IN ANALYTICS OF UBMS

Detailed financial analysis of a bridge infrastructure is possible with the application of Life Cycle Cost Analysis [LCCA]. Vehicle Operating costs, maintenance costs, and environmental impact costs are considered. Vehicle Operating Costs [VOC] are critical from the user's standpoint because VOC is minimized when bridge infrastructure provides enhanced and improved operational benefits.

The significance of Value of Time [VOT] is critical for both passengers and freight shipments as it is a measure of the saving in time due to the presence of the bridge. Benefits from VOC and VOT savings are direct [tangible] and considered in normal LCCA. [10,11,12,14, 15,16,18]

Generally, this method is adopted to evaluate the Benefit-Cost ratio for any infrastructure including bridges. Apart from these direct costs and benefits, there are not many hidden or indirect (intangible) impacts due to the presence of the bridge.

One classic example of a negative intangible impact is increased gaseous emissions. A few bridges exhibit this negative impact on their surrounding environment, forest, or greenery areas.

The positive impacts arise from the growth in the economic activities within the areas connected by the bridge.

The positive impact appears also due to the increase in connectivity the bridge offers, and the impact on the social life of the populations that use the bridge by offering more opportunities for employment due to ease of travel. [16, 17,18]

The estimation of all such intangible benefits and costs is dynamic and varies over a period. Unless observations and records are available within bridge management to link the dynamics of such changes, it is difficult to estimate and account for such costs and benefits.

Within UBMS, the existence of the Socio-Economic parameter records the changing scenario of the social and economic aspects due to the existence of the bridge. Such records are updated every time an inventory-level inspection is carried out.

Linking the Socio-Economic parameter to evaluate the intangible costs and benefits was overcome by a review of the records and technical review of various previous studies. [1,6,7,8]

Intangible costs and benefits within LCCA calculations and the resultant Internal Rate of Return [IRR] and Benefit-cost ratios are found to be more dynamic and realistic in the UBMS system.

The benefits are enhanced due to the inclusion of intangible benefits for the bridge infrastructure accrued from socio-economic aspects, which represent all benefits arising indirectly from social, economic, and environmental aspects that are considered in the financial calculations.

The bridge structure brings economic benefits from the transport of people and goods across the network. The accessibility, safety, and movement on a bridge are dependent on the population which uses the bridge. It essentially increases the social importance of the bridge. LCCA of such bridge structures must be based on dynamic, robust, and real-time information. UBMS regular updates of all maintenance and rehabilitation activities, real-time increments in distress and its impact on the cause matrix, and resultant dynamic alterations in risk estimation are recorded.

LCCA which is an integral part of UBMS is based on updated records and data in real time. Such a financial evaluation ensures that proper financial due diligence is also included within the bridge management decision-making process.

One such application of LCCA results is illustrated below, showing an enhancement in the IRR evaluation of more than 80%. [18]

IMPORTANCE OF SUSTAINABILITY IN BRIDGE MANAGEMENT

The **objectives of any sustainable bridge** are as follows:

Reducing virgin material use; Optimizing waste stream; Reducing energy use; Reducing emissions to air; Maintaining or improving hydrologic regime characteristics; Maintaining biodiversity; Engaging community values and sense of place; Improving safety; Improving access and mobility; Improving local economy; Increasing lifecycle efficiency; Promoting innovation.

The following **sustainability practices** are related to the planning stage of a bridge:

Addressing scour; Bridge aesthetics; Importance of safety for bridge users; Maintaining or improving access for bridge users including pedestrians and cyclists; Maintaining or improving access for transit; Maintaining or improving aquatic ecosystems; Embracing public participation; Reducing bridge greenhouse gas emissions; Maintaining or improving terrestrial ecosystems; Resilience; Durability; Reducing noise pollution.

The final goals of sustainability are ensured by proper evaluation and implementation as derived from Bridge LCCA.

Reduced cost of construction by increased use of local raw materials, reuse of material, and ensuring recycling of waste generated during the life span of the bridge are a few examples of efficient LCCA management.

Such practices result in less consumption of fuels during the entire life span of the bridge from construction to decommissioning of the bridge.

> *"Sustainable development is a development that meets the needs of the present without compromising the ability of future".*

The sustainability analysis provides direction for improving the sustainability of bridge infrastructure projects and the rationale for undertaking specific actions. [14, 15, 16, 18]

In the bridge engineering community, sustainability means planning, designing, constructing, and managing bridges that maintain a balance between the three pillars of sustainability: social, economic, and environmental considerations.

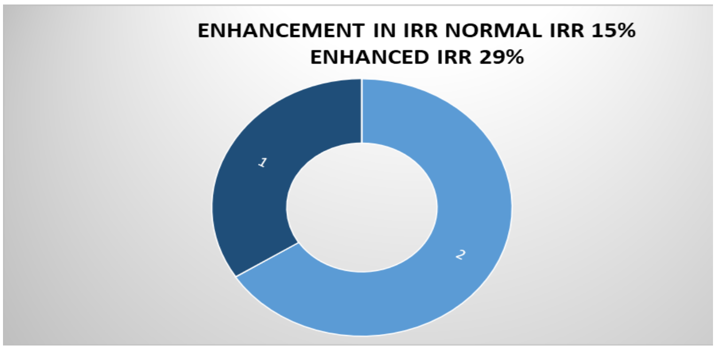

Figure 5: Enhancement in IRR evaluation

While there are many definitions for sustainability, which means supporting the natural, social, and economic systems upon which we depend now and will depend in the future.

A bridge constitutes a large investment of natural, material, financial, and human capital and thus has the potential for significant positive and negative effects on the environment and society throughout its long service life.

If prompt and timely interventions are provided, using a bridge management system it is possible to maintain, strengthen, repair, or rehabilitate a bridge throughout the entire designed service life. This guarantees that bridges will last as designed without needing to be replaced prematurely.

Judicious control of the following factors: cost-effective design application, detour travel time, congestion and traffic jam delay, productivity loss and resultant GDP reduction within the influence area of the bridge results in avoidance of premature collapse needing replacement, increased and stable social benefits, increased network reliability and resultant economic growth and increase in GDP within the influence area of the bridge and finally most important the enhanced safety of the uses [16,18, 20].

LCCA enables the owners to foresee and plan investments in a very cost-effective manner, ensuring sustainability and delivery of the best level of service securely to current and future bridge users in the most cost-effective way. Investments in assets most in need can be prioritized based on the LCCA score. LCCA also permits the cost-optimization necessary to guarantee the bridge's functionality for the duration of its service life.

A risk-based analysis is used to find cost-effective expenditures during the conceptualization, design, construction, and complete operating life of the bridge, ensuring this optimization.

The charts in Figure 6 and Figure 7 show the impact on the financial calculation due to positive and negative socio-economic scenarios.

The main intangible negative impact arises from the negative impact on the environment in the close vicinity of the bridge due to pollution from emissions due to the increased movement of vehicles. Construction of Bridges with high negative impact can be avoided due to LCCA.

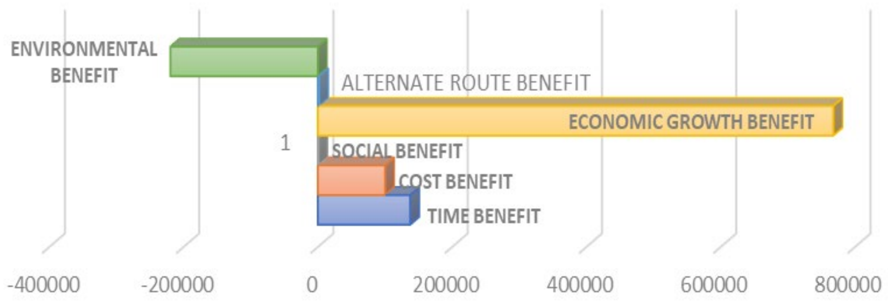

Figure 6: Comparison of Benefits: positive Socio-Economic Scenario

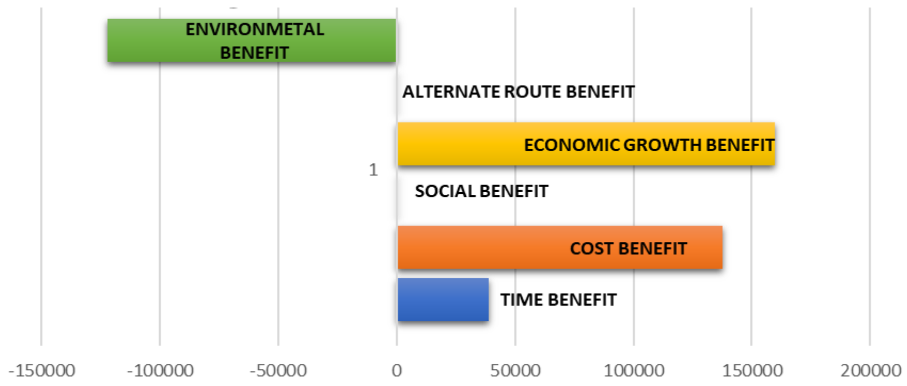

Figure 7: Comparison of Benefits: negative Socio-Economic Scenario

Optimization of fund allocation which is the key fundamental function of any Bridge Management is better governed under the decision-making regime of UBMS.

The priority and ranking process in UBMS Analytics defines the priority accorded to a particular bridge from a set of bridges that need rehabilitation intervention.

The impact of LCCA on the ranking process is seen by an actual example of a set of bridges numbered from 1 to 14 for ease of understanding. [18] The ranking when LCCA analytics is not applied, and ranking is based on a conventional process which is determined by W_{sum} is different when the ranking is subjected to analytics using LCCA where the impact of socio-economic parameters and the importance of the type of road are accounted into the ranking process.

The two tables on the following page, Figures 8 and 9, signify the impact of LCCA on the ranking process.

Figure 8 depicts the results when Fund allocation incorporates the finding of LCCA including tangible and intangible costs and benefits resulting in a focus on Sustainability and Economic Growth whereas Figure 9 shows the results without incorporating the LCCA.

CONCLUSION

Since its inception in the United States in the early 1970s, Bridge Management has undergone significant changes. A fully digitized IBMS introduced the digitization process within the Bridge Management system in 2014.

The definition of the Deterioration model is the first step in the Bridge Management process. The risk involved, when remedial interventions are not provided, for a specific bridge is determined using the deterioration model.

Deterioration model aid in choosing the right kind of cause affecting the structure which in turn help in the definition of the precise corrective action to be adopted for that bridge.

The model enables us to deliver pertinent data for the optimization of fund allocation through the ranking and prioritizing process.

Within the Bridge Management system, this results in deterioration model become extremely important. To characterize the symptom and the process of deterioration, an engineer conducting a bridge inspection must use their professional acumen.

It emphasizes the need to define the deterioration model using a strong, objective and scientific methodology.

Bridge No	Cost of Repairs	Wsum	Rank Bridge	Cumulative Cost	Action suggested
2	10,000,000	120	1	10,000,000.00	Rehab recommended
3	14,000,000	110	2	24,000,000.00	Rehab recommended
4	17,000,000	110	3	41,000,000.00	Rehab recommended
7	10,000,000	110	4	51,000,000.00	Rehab recommended
1	12,000,000	100	5	63,000,000.00	Rehab recommended
5	18,000,000	100	6	81,000,000.00	Rehab recommended
8	12,500,000	100	7	93,500,000.00	Bridge Under Observation
14	16,000,000	100	8	109,500,000.00	Bridge Under Observation
9	16,000,000	90	9	125,500,000.00	Bridge Under Observation
10	17,500,000	90	10	143,000,000.00	Bridge Under Observation
11	14,000,000	90	11	157,000,000.00	Bridge Under Observation
12	18,000,000	90	12	175,000,000.00	Bridge Under Observation
13	11,500,000	90	13	186,500,000.00	Bridge Under Observation
6	13,500,000	70	14	200,000,000.00	Bridge Under Observation

Figure 8: The results when Fund allocation incorporates the finding of LCCA

	Modified ranking and priority					Impact of ABSL, SEBR, and Type of road on Ranking process			
Bridge No	Cost (10M)	Wsum	ABS L	SEB R	BSFR N	Road Type	Ranking/ Priority	Cumulative Cost [Cr]	Action Suggested
2	1.0	120	3.08	3.75	5.5	09	8.81	1.0	Rehab recommended
3	1.4	110	5.71	4.5	5.375	08	7.89	2.40	Rehab recommended
11	1.4	90	3.35	4.25	4.875	08	7.69	3.80	Rehab recommended
12	1.8	90	4.06	4	4.875	08	7.69	5.60	Rehab recommended
6	1.35	70	4.57	4.75	4.625	08	7.52	6.95	Rehab recommended
4	1.7	110	4.47	4.5	5.125	07	7.03	8.65	Under Observation
8	1.25	100	3.04	4.75	4.625	07	6.93	9.90	Under Observation
7	1.0	110	4.03	4.25	5.25	06	6.18	10.90	Under Observation
1	1.2	100	4.22	3.75	5.625	06	6.09	12.10	Under Observation
5	1.8	100	2.43	4.5	4.625	06	6.07	13.90	Under Observation
13	1.15	90	4.13	4	4.625	06	5.99	15.05	Under Observation
14	1.6	100	5.55	4	4.125	04	4.39	16.65	Under Observation
9	1.6	90	7.37	3.75	4.125	04	4.31	18.25	Under Observation
10	1.75	90	4.48	4.5	5.125	03	3.45	20.0	Under Observation

Figure 9: The results without LCCA

Early BMS used the Deterioration model based on symptoms of distress that are recorded. Today, as the depth of knowledge expanded, Bridge Management has switched to an approach, focused on the cause of distress.

This transition from a Symptom-based approach to a Cause-based one took place as a result of EN1504.

This transition was captured and incorporated into UBMS in 2017. Even then the bridge inspection engineer's assessment served as the foundation for the definition of the Cause matrix.

The requirement for a method, independent of judgment, was strongly inspired by the fact that the entire decision-making process was reliant on the judgment of a single person.

The freedom from judgment-based methods was offered by performance monitoring of bridges utilizing SHM.

A barrier in its adaptation stems from the fact that performance needs to be linked to the Cause matrix and resulting Deterioration model to be used in the decision-making process leading to optimization of fund allocation.

The solution was the evolution of an Algorithm linking performance decrements to increments in distress.

Based on SHM raw data, a variety of algorithms are currently available for determining the severity of distress. By employing this definition of degree of distress, its scope, and severity, we can change the Cause matrix.

The modification of the Cause matrix is based on the fact that a decrement in performance implies increments of distress. As a result, the Deterioration model is dynamic, reliable, and impartial.

It is free from the bias resulting from a judgment-based process. The decision-making process is now defined by a real-time model.

Costs are controlled during the whole service life of the bridge.

It makes sure that this takes into account the use of accurate and realistic data for the generation of deterioration models, the inclusion of socio-economic parameters to assess the benefits - Tangible (direct) and Intangible (indirect) that accrue to society as a result of the presence of bridge infrastructure, and the use of the LCCA tool to analyze the costs and benefits during the service life which then is applied to the decision-making process.

Data is regularly being updated under UBMS on a number of socio-economic factors. Application of this data within LCCA ensures the inclusion of a sustainability focus within the decision-making process.

Through this approach, sustainability objectives are also safeguarded. This process ensures that Bridge fulfils present requirements without jeopardizing the ability of future generations to satisfy their own. A sustainable Bridge preserves the harmony between social, economic, and environmental issues.

Using UBMS's Bridge Management Analytics, we ensure that the various economic and sustainable objectives are achieved.

The key strength of UBMS Bridge Management Analytics is that it can be used within any existing Bridge Information System/Bridge Management system.

Minimum requirements of essential data records are either accepted from the existing BMS or the user is allowed to input the data. Analytics of UBMS offers a versatile solution to the existing problems within any Bridge Management.

Further research is not focused on providing a solution that can correlate the distress with the geospatial data which can be provided by BIM or UAV videography.

The goal of future research projects needs to integrate technologies that can provide geospatial information about distress and the ability to create a 3D model of the key components that exhibit severe distress.

Research continues to bring advantages from emerging innovative technologies that encompass our horizon within the folds of Bridge Management.

This ensures the sustained importance of the application of Bridge management in the society we have inherited and shall pass on to the future generation.

Irrespective of who conceptualizes the bridge, who designs the bridge structure, who supervises or who constructs the bridge, bridge structures will continue to be exposed to the vagaries of nature, possible human abuse, and degradation of material from the day they are commissioned.

When the clouds of recession are hovering over the entire world, it is important that Bridge Management delivers more efficient results.

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GEOMETRY AS A COMMON GROUND FOR BMS AND BIM

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ABSTRACT

Bridge Management Systems (BMSs) are sophisticated software tools, widely used for managing bridges. Comprising a centralized database of all relevant information for the entire bridge stock and analytics to forecast bridges' condition and maintenance cost, BMSs are irreplaceable tools, used by all the National Road Authorities (NRAs) around the world.

These powerful tools, although different from one another, all lack adequate visualization of bridges. Recently, numerous researchers proposed using the Building Information Models (BIMs) to address this issue.

This paper presents a geometric approach of introducing BIM to BMS. Rather than trying to thoroughly connect these two robust systems on the object definition level, this approach focuses on geometry.

The paper firstly shows how all the inventory information from BMS can be associated with corresponding BIM objects, and afterwards, the ways to include the condition assessment data into BIM are proposed.

Once the basics of the geometric approach are explained, the example of connecting BIM with BMS is presented. The example is based on KUBA, the Swiss BMS.

Finally, the feasibility, as well as the challenges of the presented approach, are analyzed. The analysis focused on two important questions.

Firstly, it considered if BIM is capable of making workflow changes in the Infrastructure Asset Management (IAM) the same way it did it in the construction industry.

Secondly, it evaluated the BIM capability to describe all the condition assessment information relevant to IAM.

Keywords: BIM, BMS, IAM, Catalog, Ontology, Decomposition

Reference: IABSE Symposium Prague 2022. Proceedings ISBN: 978-3-85748-183-3

1. INTRODUCTION

1.1 Bridge Management Systems (BMSs)

Managing a bridge stock means managing various activities, such as inventory and inspection data collection, bridge condition assessment, special transport administration, and allocation of funds for maintenance interventions.

To do this, majority of the road agencies in the world are supported by BMSs [1]. There is a variety of different BMS solutions on the market, however, a common BMS consists of the following modules: Inventory, Inspection, Maintenance and Planning module [2].

Inventory module includes administrative and technical bridge data (e.g. bridge and road IDs, geolocation, bridge type, etc.) and an optional bridge photo.

Inspection module enhances the bridge data according to the inspection findings, i.e. ratings of the structural (e.g. deck, piers, abutments) and nonstructural elements (e.g. safety rail, pavement, drainage system).

These element ratings are stored in the inspection database as alphanumeric entries. Maintenance module records a historical log of all performed maintenance interventions for each bridge in the network with regard to the type and extent of the works, as well as the cost.

Additionally, this module is used to schedule maintenance actions. Planning module uses the inventory and inspection data, as well as the assigned set of constraints and available budget, to propose the optimal allocation of maintenance funds. This is based on predicting the future bridge condition.

To do this, the module uses various prediction models based on the current condition as well as the determined deterioration process [3].

BMS data repository is mostly a rigidly structured relational database, easily used by the Maintenance and Planning modules to generate various analytics. However, in such a kind of a database, every piece of information is represented by an alphanumeric value of a table cell.

This prevents the spatial perception of the bridge. Besides, this data format is incapable to properly represent the inspection finding data, thus causing the imprecise descriptive positioning of inspection findings and a loss of the spatial inspection finding information (e.g. damage extent).

All the described issues indicate the need to introduce the bridge geometry to BMS, and thus improve the spatial perception of the bridge and its elements. According to Mirzaei et al. [4], none of the existing BMSs include geometric representation of bridges.

1.2 Bridge element classification in BMS

In the BMS database, the bridge is abstracted as a combination of elements of predefined types. Similarly, the other spatial and non-spatial information referring to the bridge elements (e.g. inspection finding) is represented by a limited set of predefined terms (e.g. damage type, extent, and severity).

All those terms are specified in a form of a hierarchically structured list, named catalog. Lately, some National Road Authorities (NRAs) have upgraded their catalogs by developing so-called “ontologies”.

As opposed to a rather simple form of catalogs, the ontologies are formal explicit descriptions of concepts from a certain domain (e.g. bridge management), using relations (or roles).

These can be further specified by restrictions, rules, and constraints applied to the relations, (see Gruber [5]).

Whether a catalog or an ontology, for the sake of clarity, both will be referred to as classification.

The examples of such classifications are the German ASB-ING (catalog of civil engineering structures, also converted to the ontology) [6], the Dutch CB-NL (general ontology for the built environment) [7], as well as the catalog for Swiss BMS, named KUBA [8].

Apart from the national classifications, there are also international efforts to standardize the infrastructure asset management terms used around Europe.

Within the scope of the research project INTERLINK [9], a unique ontology, named European Road Object Type Library (EUROTL), is established. It is envisioned to be general enough to correspond to various BMSs.

These various classifications significantly differ one from each other.

The differences particularly concern the way bridge is decomposed into elements, sub-elements, etc., but it also concerns the number and type of parameters for the bridge condition assessment.

The establishment of the universal solution for the relationship between BIM and BMS needs to address those differences.

1.3 Building Information Model (BIM)

BIM is an object-oriented model of an asset, capable of complex modifications, sophisticated analysis, automatic generation of drawings and reports, as well as various 3D visualizations.

It is an exhaustive repository of various information about the asset.

BIM includes information from multiple domains (i.e. structural, architectural, mechanical, electrical, etc.) and it is structured in an object-oriented manner. This means that each tangible element is represented by an object, which is an instance of a specific object class, defined by certain properties (i.e. attributes).

Besides tangible elements, object classes representing various types of relationships between them are also defined. The feature by which BIM is best known is the 3D visual representation of each tangible element.

Although potentially highly beneficial, the utilization of BIMs by BMS is currently hardly possible. However, at the moment, there is an intensive research activity on bringing together these two concepts to describe a bridge.

One of such activities is the AMSFree project [10], funded by Conference of European Directors of Roads (CEDR). This paper presents one of the concepts resulted from this project.

2. PROPOSED CONCEPT

Theoretically, there are two general concepts which can lead to the successful relationship between BMS and BIM. The first is the “hard” one, and it means a full integration of a comprehensive BIM into the extensive and and often inflexible BMS.

The other concept, the “light” one, would establish a direct relationship between the BIM elements on one hand, and the listed bridge elements (taken from the element classification) from the BMS inventory module on the other.

The hard concept, certainly the more robust one, would require complex changes of BMS, in terms of software architecture and database structure, maybe even the classification that is widely used in practice.

Although this is possible, according to the experience of the authors of this paper, NRAs around the world are not likely to take this step, considering the investment in their current BMSs as they are custom-made to accommodate their needs.

It should be also noted that the date collected over years in these BMSs are of high value and need to be maintained.

Furthermore, this solution would potentially require a very strict BIM structure and content in order to be in line with the BMS. This would put a significant pressure on the bridge design bureaus, since the BIM creation is expected to be mostly their job.

The light concept, on the other hand, would require significantly less effort and money as it would not require significant change of current practice.

Actually, the storage for BIM models and a few extra columns in the existing BMS database tables would be enough.

The core of this concept is addressing the element geometry. Once every bridge element from the BMS is linked with the corresponding BIM element, all the other element-related information from BMS can be easily addressed to the corresponding BIM element, or referenced to the location relative to the BIM element.

For the explained reasons, the research team of the CEDR project AMSFree proposed the light concept. The full description of the proposed concept will require the ability of the BIM model to decompose in a certain way.

The proposed concept will be addressing BIM by means of Industry Foundation Classes (IFC) [11], a vendor-free format for the exchange of digital building models.

2.1 BIM decomposability

For the proposed concept to work, the only requirement for the BIM model is to be reasonably fine-grained disassembled.

The extent of disassembly should be in line with the used element classification hierarchy. In simple words, a single bridge element classified by the type according to the national classification should be represented by a one or several BIM elements.

By the same token an BIM element of a dissembled BIM should be chosen in such a way so that it can be assigned to a national classification with finest granularity.

This particularly applies to the concrete elements which are monolithic in reality, such as the abutment shown in Figure 1.

Obviously, the abutment in Figure 1 can be decomposed into: a single element representing the entire abutment, the bearing blocks, and the

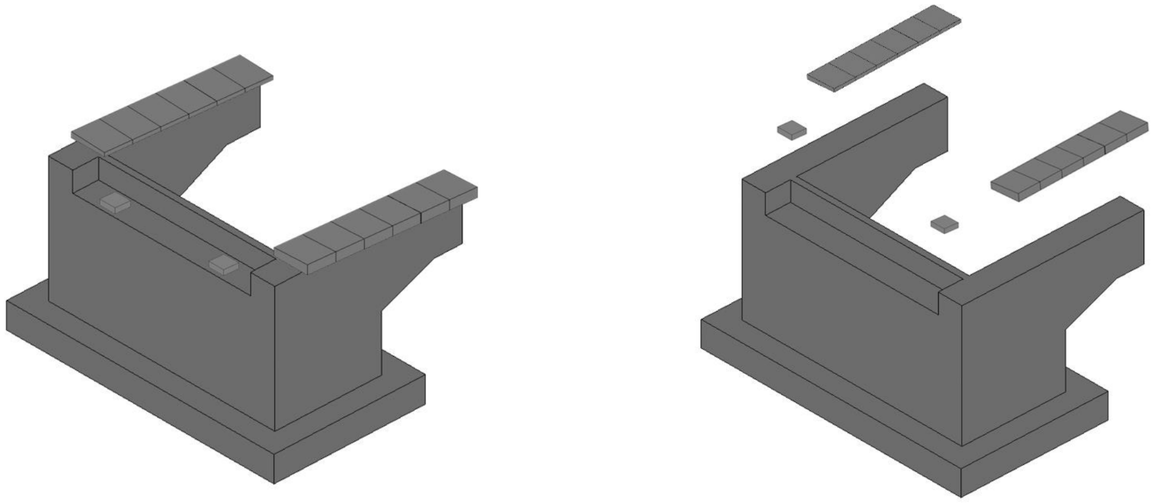


Figure 1: Common abutment element in a BIM model: Composed (left), and Decomposed (right)

cornices. This would work only for the BMSs with a very simple element classification, however, this usually is not the case.

To illustrate a more realistic scenario, Figure 2 graphically represents one possible classification of an abutment sub-elements.

Here, each smallest part of the abutment is labelled and needs to be addressed in the BIM model.

Figure 3 shows the model of the same abutment as in Figure 1, but this time significantly more disassembled.

Considering the differences in the geometry of two abutments (Figure 2 and Figure 3), the extent of the decomposition of the model, Figure 3, is quite satisfying, as each element of the model is easily related with the corresponding element type from the classification, Figure 2.

The orange labels in Figure 3 are the IFC entity types representing the abutment sub-elements.

They are shown in the figure only to indicate that each sub-element is an easily referenced separate BIM element.

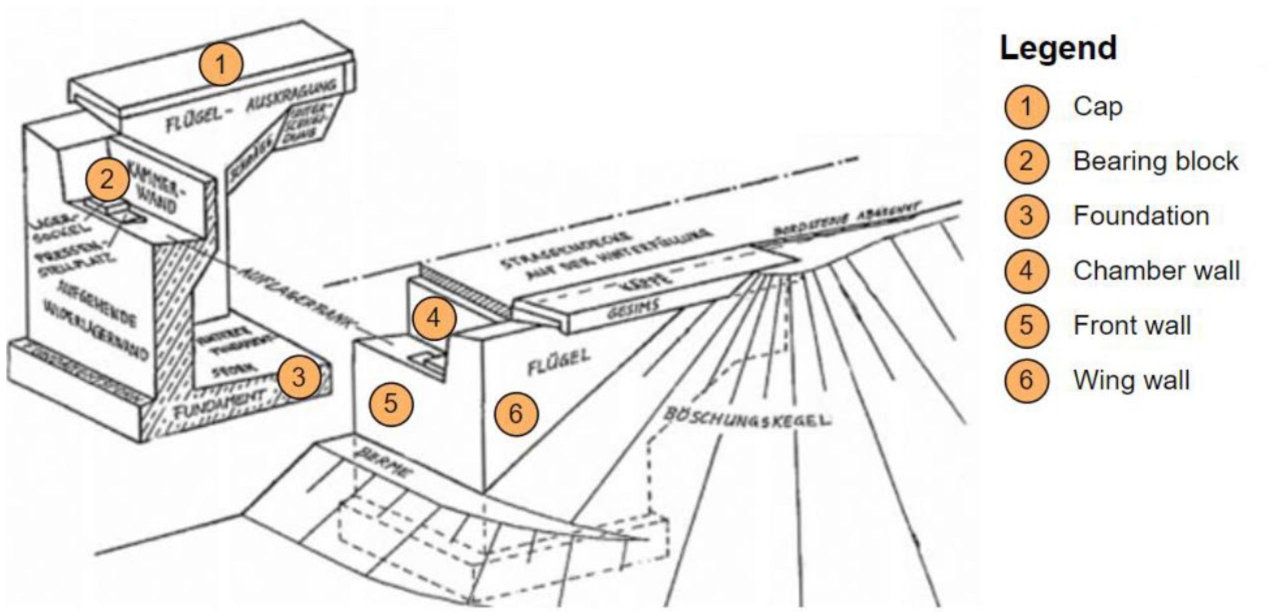


Figure 2: Graphical classification of abutment sub-elements. Adapted from [12]

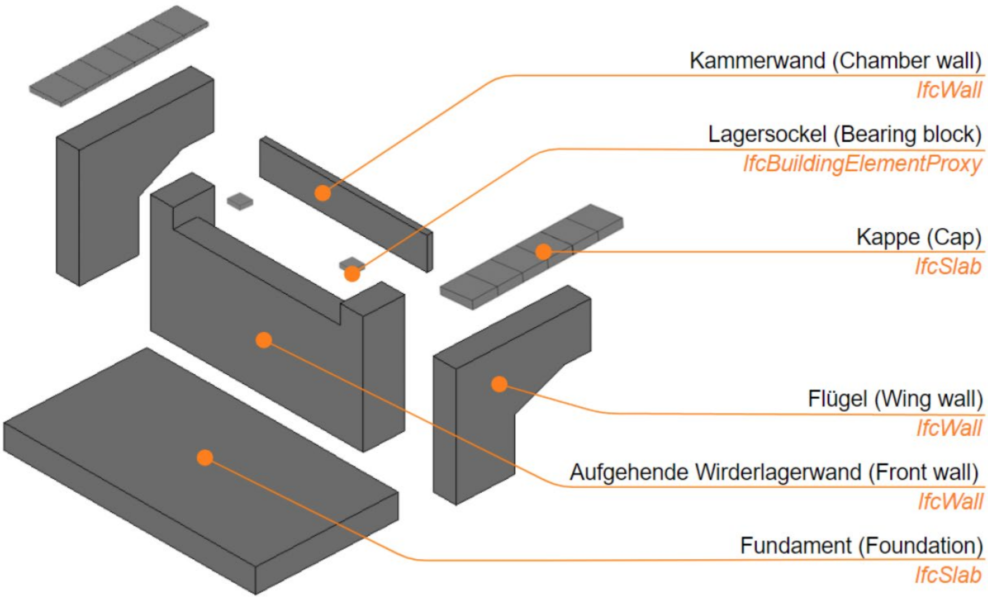


Figure 3: Decomposed abutment into sub-elements labelled according to Figure 2

2.2 Which information stays outside BIM?

In the proposed "light" concept, the inspection findings are not inserted into the BIM model, but just externally referenced.

For instance, the inspection report is stored externally (in the BMS database) and referenced in the BIM model only by location information (URI). The IFC schema offers two options for external referencing.

The first one is by using IfcDocumentInformation (offers various attributes for the storing the linked document metadata) and URI. The other option is using IfcDocumentReference. This option references the document without a metadata.

3. EXAMPLE

To show how the proposed concept applies on a real asset, the Swiss BMS, KUBA, is used. KUBA's object classification is a hierarchical catalog with 450 object type categories. Catalog entries are identified by two attributes: HierarchyCode, a numerical unique identifier of the catalog item, and SelectionCode, which defines the selectability of the entry.

Here, "-" indicates a generalization of a group of entries, and thus cannot be selected, "+" indicates that the object is on the lower hierarchical level and can be selected, and "*" indicates that the object is on the lowest level in the hierarchy an it is selectable.

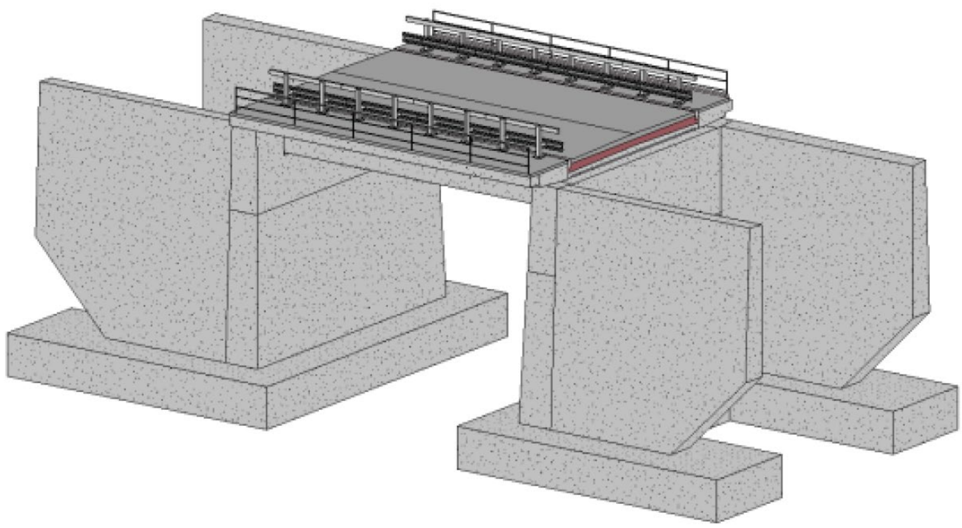
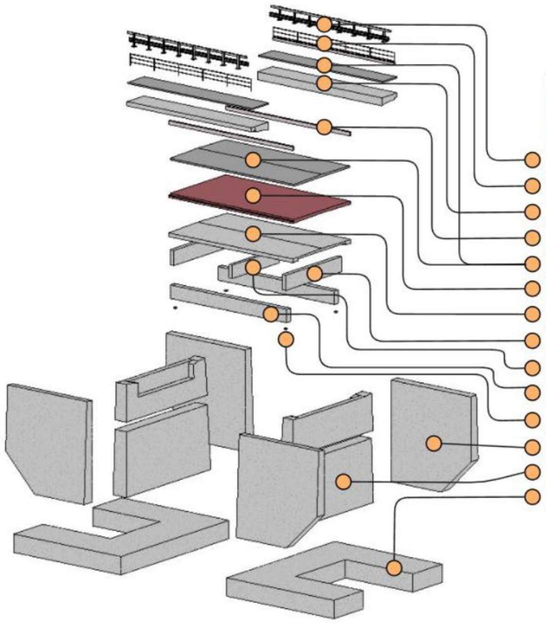


Figure 4: Exemplary BIM model of a bridge



CAT_ NM	CTK_ SEL	xCTK_ HIERARCHY CODE_VL	xLCK_NM_de	*English*
ITYP	+	665	Zaun	*Fence*
ITYP	+	664	Geländer	*Handrail*
ITYP	+	374	Kragplatte	Cantilever
ITYP	+	641	Randstein	*Curb*
ITYP	+	634	Tragdeckschicht	Wearing layer
ITYP	+	633	Tragschicht	Base course
FBTG	+	14	Fahrbahnplatte	*Deck slab*
ITYP	+	3312	Stützriegel	Support crossbeam
ITYP	+	3311	Riegel	Crossbeam
ITYP	+	33	Träger	Girder
BA	+	1201	Stahllager	Steel bearings
ITYP	+	3806	Flügelmauer	Wing wall
ITYP	+	3805	Widerlagermauer	Abutment wall
ITYP	+	3012	Streifenfundament	Strip footing

Figure 5: Decomposed bridge model (left), with its elements associated with the corresponding objects from the KUBA catalog (right)

The model used as an example is BIM of a 12.5 meter spanned simply supported double girder bridge, shown in Figure 4.

The model is disassembled and each bridge element and sub-element is associated with the corresponding KUBA catalog type, Figure 5.

4. CONCLUSION

The proposed concept for establishing the relationship between BMS and BIM aims to be a simple answer to a great challenge.

The importance of the classification of terms used in Bridge Management is emphasized.

Based on this classification, a disassembled BIM is to be created, so that each element in the classification, relevant for the subject bridge, can be referenced in the BIM.

Without going into technical details, it is shown that the established relationship between BIM elements and classification serves also as a framework for linking the condition assessment information from BMS with the BIM elements.

Perhaps the greatest quality of the proposed concept is the fact that it does not require almost any changes of the existing BMSs and related practise.

Except from an additional place (i.e. extra column in the database table) for storing the information about the reference to the BIM model, the data structure, as well as the functionalities and logic of various BMS modules remains intact.

The BIM models are created in the bridge design phase by consultants and are intended for use in the next phases, such as construction and operation.

The information required by the Bridge Management can be provided by so-called as-built BIMs.

Although the creation of as-built BIMs is neither regulated, nor supported by appropriate software solutions, they will be certainly generated by adjusting the as-designed BIMs.

This means that, except from the geometric imperfections occurred during the construction, the structure and the content of the as-built BIM will be almost the same as the one of “his predecessor”, the as-design BIM.

This will, accordingly, bring more responsibilities to consultants, the creators of the original, as-designed BIMs. In this context, the proposed concept requirements towards BIM models are minor.

Rather than demanding the exhaustive asset information to be stored in BIM, the only requirement is to make the elements disassembled enough.

Last, but not least, the technical quality of the proposed concept is that it does not require the accurate BIM export to IFC.

It does not matter which IFC classes are used for BIM elements mapping.

Therefore, to use this approach, it is not necessary to wait for the official release of the latest IFC extensions.

5. ACKNOWLEDGMENTS

The research presented in this article is a part of the research project AMSFree, funded by CEDR (Conference of European Directors of Roads).

The authors thank to the consortium AMSFree for the collaboration in the researching the ways to utilize BIM in the Infrastructure Asset Management.

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IMPLEMENTATION OF DIGITAL TWIN AND MULTIPLE LINEAR REGRESSION IN SHM OF BRIDGES: A CASE STUDY

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ABSTRACT

The authors of this research aimed to create an automatic damage identification technique for reinforced concrete traffic bridges using machine learning algorithms. A digital twin of the bridge was created using a verified 3D finite element model based on plans and actual environmental conditions and loads.

The digital twin was used to analyse the bridge's performance under different loads, and the data from sensors installed on the bridge was used to train a machine learning algorithm to find the relationship between the bridge's performance and monitored quantities.

The technique was tested on a case study bridge over the Danube River in Hungary, where additional strain gauges were installed to improve the monitoring system. The results showed the technique's potential for continuous monitoring of the bridge's condition and early detection of any deterioration.

Keywords: SHM of bridges, Machine learning, Multiple linear regression, digital twin.

Reference: 13th Central European Congress on Concrete Engineering, 13 – 14th September 2022, Zakopane, Poland

1. INTRODUCTION

The great significance of bridge structures results in high requirements for their reliable and long-term use [1].

Over the last 15 years, concerns about the deterioration of bridges increased significantly as the existing bridge structures are subjected to various environmental and operational loads in daily function.

The influences of these external loads are unfavourable and prone to accelerated structural damage, the probable reduction in bridge performance as the load capacity and the remaining life of the structure can arise from various causes such as weather, overloading by traffic, poor design work, strong motion excitation, fatigue cracking, construction deficiencies, and material deterioration [2], [3].

Besides, extreme events like earthquakes may also be encountered throughout the bridge service life; for example, Baihua Bridge, a reinforced concrete (RC) multi-span girder bridge, collapsed in the curved spans and was damaged significantly in the straight spans during the Wenchuan, China earthquake of May 12. 2008 [4], where five spans collapsed utterly. Some columns suffered from shear cracking, crushing concrete, and destruction of collar beams.

Deterioration rates of different RC bridge elements are influenced by the combined effects of several complex phenomena such as reinforcement corrosion, concrete degradation, creep, shrinkage, cracking, fatigue, etc. [5].

Finding and controlling the deterioration factors that damage bridges are as crucial to efficient bridge maintenance as repairing the caused damage.

Identifying these factors will certainly help in the cause-and-effect analysis, damage diagnosis, etc., and the modelling of bridge deterioration, improving prediction accuracy and reducing bridge life cycle cost [6].

Traditionally, visual inspection played an essential role in detecting structural surface defects and assessing the structural condition.

However, visual inspection is labour-intensive, time-consuming, and subjective even for well-trained inspectors, hence is unable to track condition variations in real-time.

Structural health monitoring (SHM) techniques were proposed and increasingly used in bridges in past decades to address the problem [2].

At the core of a well-designed SHM system is a data acquisition system that relies on deployed sensors to initiate the information workflow from which ultimate decisions about operations, maintenance, and other life-cycle actions will be made [7].

Sensors are generally divided into two types, namely wired and wireless sensors. Wired sensors are usually limitedly applied since they require installation during structure construction.

The wiring could impact the function of the structure with a limited number of sensors. Nevertheless, assessing civil structures is a complex task caused by the stochastic nature of the underlying deterioration processes and the loading demands.

Yet the contradiction is that this situation can lead to difficulties if, for example, no relevant information is extracted from monitored data. Hence, the critical issue associated with SHM techniques nowadays is how to extract relevant information that can be incorporated into the decision-making process relating to managing and maintaining civil infrastructure [8].

Several mathematical alternatives may be able to account for the environmental and operational effects, with regression analysis being a suitable tool in the Machine Learning (ML) field when there is a large quantity of data obtained under varying conditions [8].

Since modern monitoring systems provide large amounts of data, regression analyses have been explored in several SHM applications.

Within a local approach to SHM, Guo et al. [9], [10] carried out a linear regression analysis to describe the pattern between monthly-averaged S-N fatigue damages (number of cycles to failure, N(S), when a material is repetitively cycled over a given stress range S), monthly-averaged temperatures, and traffic flow.

Furthermore, SHM systems can predict further damage or the bridge's collapse if an alarm system is established with the help of a Digital Twin (DT).

They can give the comparison phase threshold values for stresses and internal forces. DTs have two essential characteristics, interactive feedback, and self-evolution.

They can realise intuitive observations and predictions of the working state, making operation and maintenance work more efficient, timely, and intelligent.

Machine learning algorithms are needed to drive the analysis and processing of the twin data platform. By analysing the data, a DT can diagnose and predict the bridge's status [11].

The fusion mechanism of the DT and machine learning is now becoming the core of SHM monitoring.

Its primary function is to collect, process, and analyse data and then output diagnostic and predictive results to support the decision-making of related work and predict or even prevent further damage or collapse of the bridge [12].

2. METHODOLOGY

In this research, the authors aimed to create an automatic damage identification technique for RC traffic bridges, which can be done by understanding the relationship between the effects caused by different loads on the bridge and the information measured by the installed monitoring system using a proper machine learning algorithm.

Two fundamental components of this technique are the digital twin of the bridge and the measurement collecting devices, namely, sensors as part of the monitoring system, feeding the system with the necessary data.

A digital twin of the real structure was created in the form of a verified 3D finite element (FE) model, based on the implementation plans, actual environmental conditions and loads, validated by the results of a loading test. The digital twin was used to analyse the bridge's performance under different load scenarios.

At the same time, the information corresponding to the sensors installed on the real structure could also be acquired from the model.

The performance of the bridge could be measured as the utilisations of variables describing structural behaviour (e. g. strains, stresses, deformations, crack width) in relation to the relevant limit values.

Using this information, a proper machine learning algorithm was trained to find the connection between the bridge's performance and the monitored quantities.

With the help of the relation revealed using the digital twin, the actual bridge performance could be predicted using the data measured by the installed monitoring system. In case of inappropriate performance, a warning could be given to the bridge operator.

To test the above technique, the authors chose a reinforced concrete box girder bridge above the river Danube in Hungary as a case study.

The creation of a digital twin and numerical modelling of the bridge was carried out using AxisVM finite element software. Initially, only two types of sensors were installed on the bridge to measure temperature and longitudinal elongation at some of the supports, Figure 3.

To acquire more suitable information about the superstructure, seven additional strain gauges were recently installed on the bridge at different locations inside the box section, Figures 4 and 5.

Sensor instalment was performed with the help of Hungarian Public Roads Company as the bridge operator and the Structural Laboratory of Budapest University of Technology and Economics, Faculty of Civil Engineering.

A brief description of the analysed bridge, the installed monitoring system and the corresponding digital twin could be found in the following chapters.

To test the machine learning algorithm before it is applied to the large-scale bridge structure, the theoretical procedure was tested on a simple concrete beam.

The results of this analysis are briefly introduced in chapter 5.

3. DESCRIPTION OF THE ANALYSED BRIDGE

The bridge in question was constructed over a branch of the Danube River in Hungary in 1990 and is called the Soroksári bridge.

The superstructure consists of two variable heights reinforced concrete box girders with side cantilever plates for the pavement.

The total width of the cross-section is 20.638 m, and the length of the investigated part is 148.55 m. Figure 1 represents the bridge's side view and cross-section.

A monitoring system has been installed in the bridge as part of an earlier repair of the bearings.

The task of long-term monitoring was to continuously measure the structure's condition, evaluate the structure's condition based on the processing of the measurement data, detect possible deterioration as soon as possible, and help with maintenance activities.

The monitoring system built into the structure was suitable for measuring temperature and longitudinal elongation characteristics using Rhodium type 30305 temperature gauges and ASM PCQA24 type magneto restrictive distance meters. The measurement was carried out at each pier in the longitudinal direction of the bridge.

The geometry of the design might be different for each pier due to the different pier dimensions. Still, the layout was the same: the sensor body was attached (i.e., moving) to the upper half of the pier with a stainless steel-curved bracket, and the actuator head was connected to the frame by a hinged rod at both ends (i.e., does not move).

The measurement accuracy was 0.1 mm, and the sampling frequency was 5 Hz. The synchronisation between the sensors on the same pier was ensured.

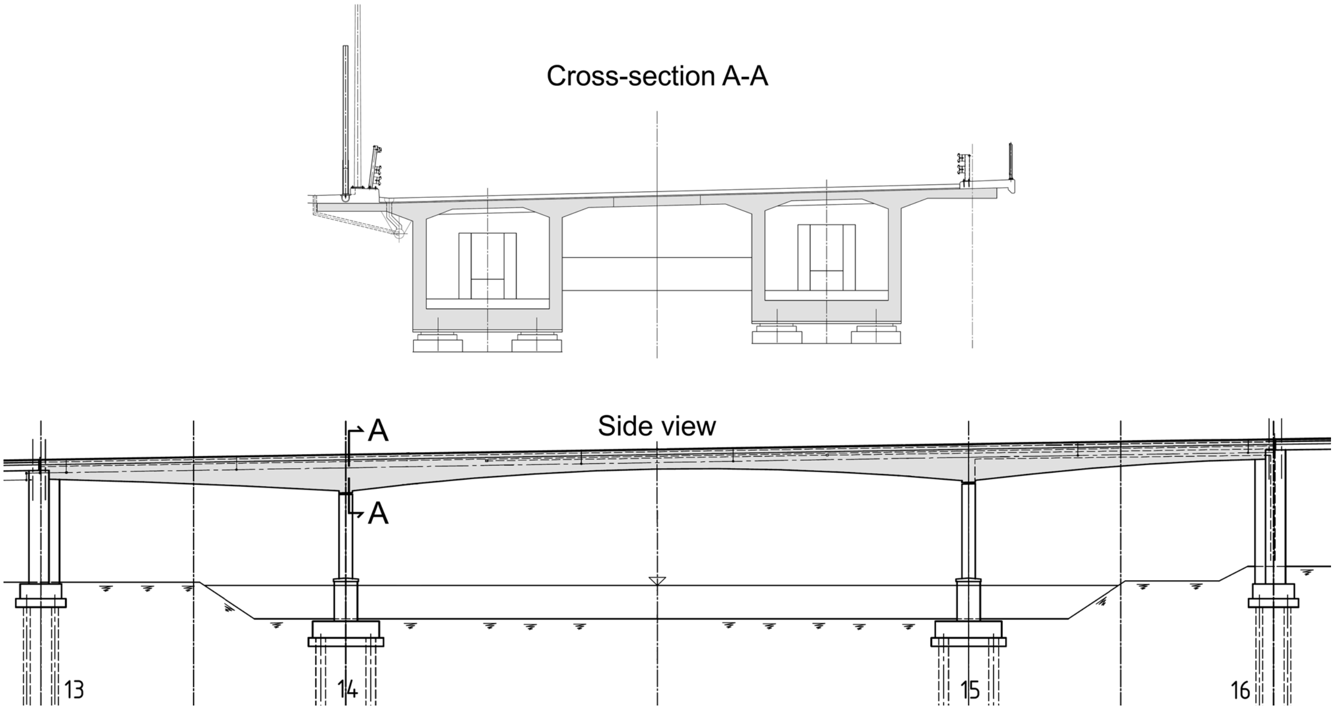

Figure 1: Side view and cross-section of the analysed bridge section

The connection between the sensors and the measuring centre on the bridge structure was achieved through the existing drainage pipes; the wiring did not collide with the temporary lifting points or other supporting structural elements.

Temperature measurements were recorded using Rhodium 30305 type Pt100 sensors with temperature gauges. The signals from the sensors were connected to the HBM PMX PX455 measuring cards.

The measuring range was –30…+85 °C, the accuracy of the Pt100 sensors was class "A", the display resolution was set to 0.1 °C, and the sampling frequency was 1 Hz.

Synchronicity between the signals of the temperature gauges and the pillar displacement gauges was ensured. Figure 2 shows the sensors mentioned above inside the box section.

No element of the measuring system required continuous management or user intervention on the bridge.

The measuring centres had an Ethernet connection, through which the data was transmitted to the computer controlling the measurement.

The computer controlling measurement was an HPE (Hewlett Packard Enterprise) type EL300

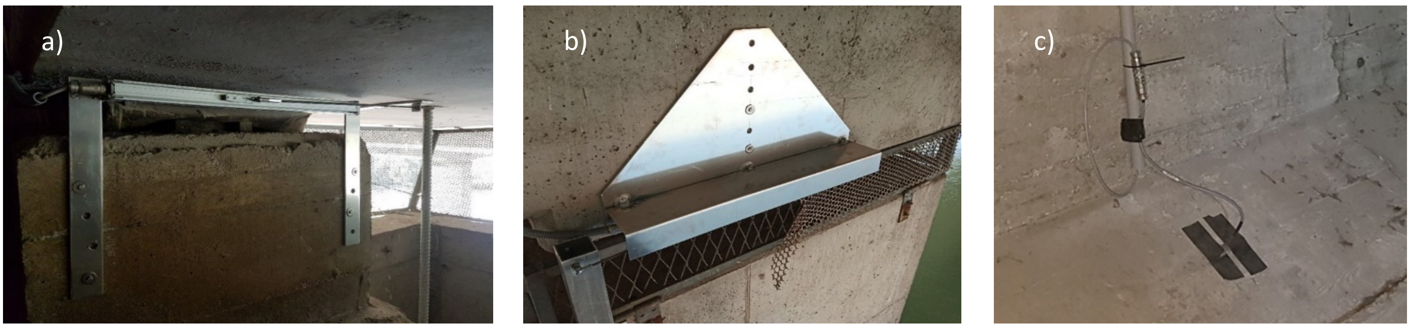

Figure 2: Pier longitudinal displacement measurement devices a) at piers 13 and 16; b) at pier 15; c) temperature gauges at pier 14

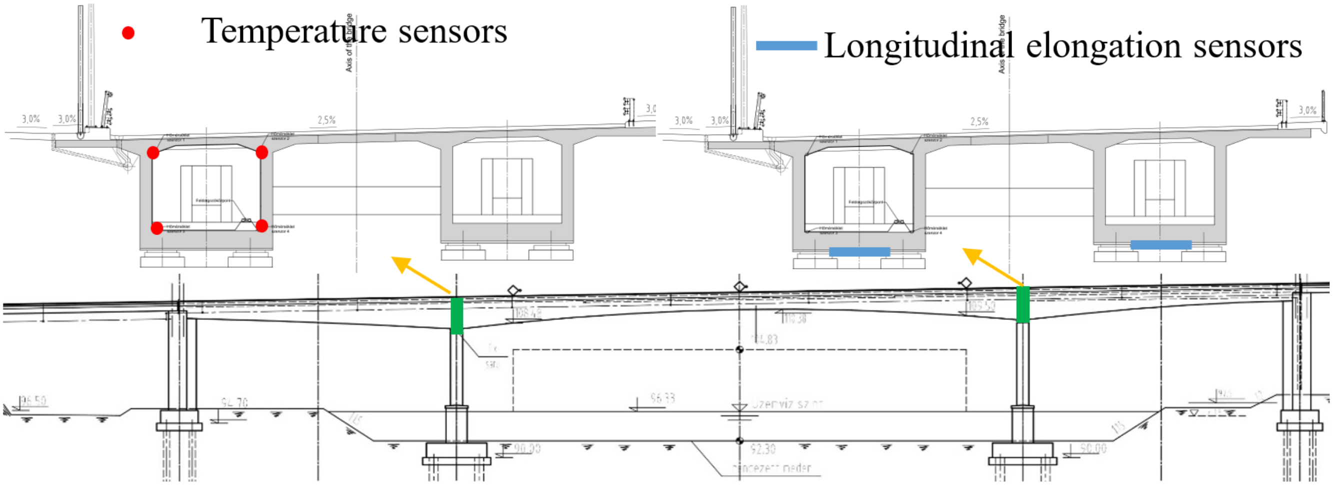

Figure 3: Temperature sensors in cross-section 14, pier longitudinal displacement sensors at sections 13, 15, 16

industrial PC running Microsoft Windows 10 Professional operating system.

The measurement was controlled by HBM's CatmanEasy measurement data acquisition program.

Although the condition of the bridge currently was sufficient to withstand the imposed loads and environmental conditions, it should be monitored continuously, as it is prone to further degradation.

In order to improve the existing monitoring system, the authors proposed installing additional sensors on the bridge.

The information provided by these new sensors might also form the basis of the SMH system described in chapter 2.

For these reasons, 7 strain gauges were installed on the bridge in December 2022. Locations of the new sensors are illustrated in Figure 4, while Figure 5 shows the new sensors inside the box section after the instalment.

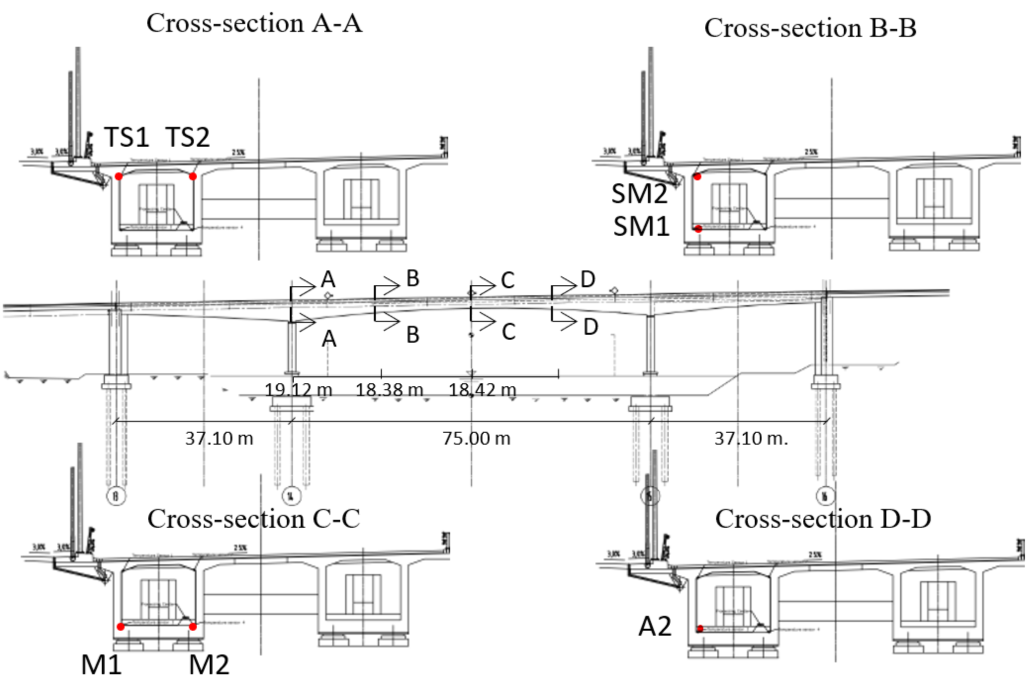

Figure 4: Locations of the newly installed strain gauges in Soroksári Bridge

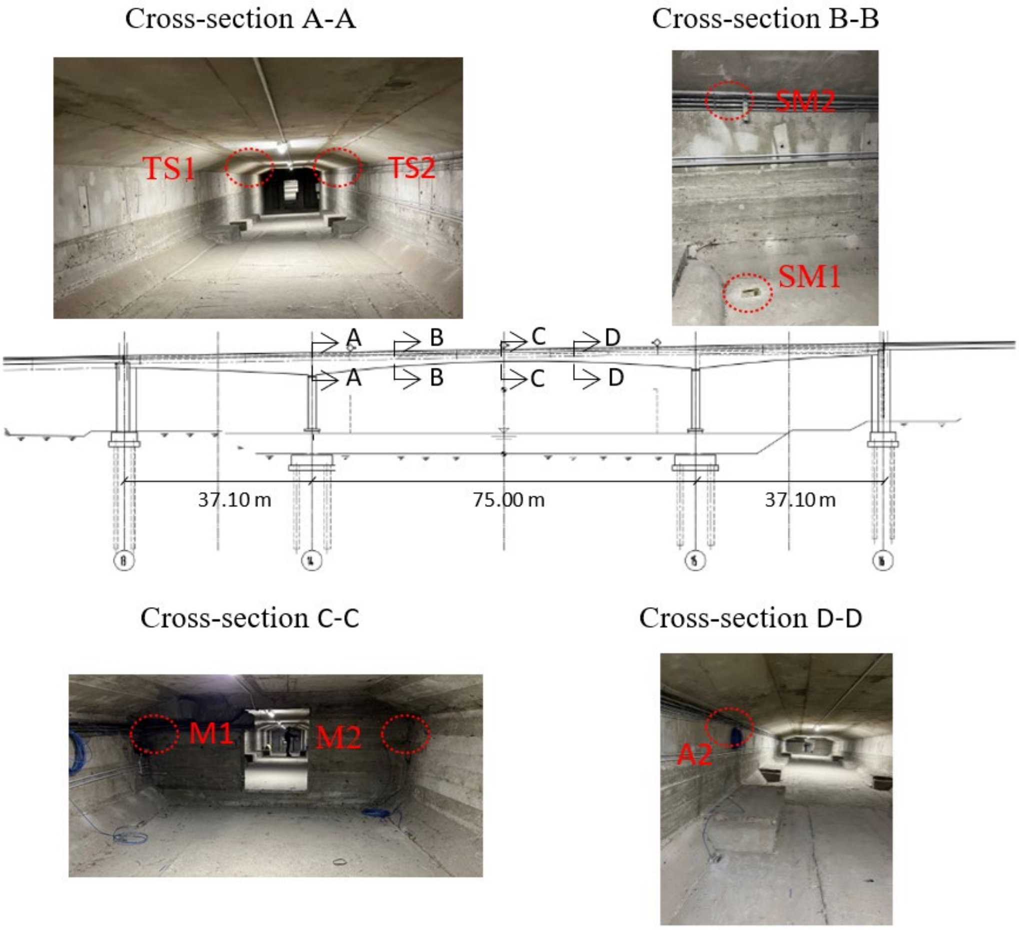

Figure 5: Pictures of the newly installed strain gauges inside the Soroksári bridge

4. DIGITAL TWIN OF THE BRIDGE

There are several methods for the numerical analysis of engineering structures. These methods can be linear or non-linear (in terms of material laws and geometry) as well as static or dynamic loads may be considered [13].

In the context of condition control and damage assessment of civil engineering structures, static load tests are widespread [14], [15]; and FE modelling can perform global damage detection and can even predict the possible damage that can appear due to various causes [16].

FE analysis is also essential as it verifies the structural elements by examining their load-bearing capacity to withstand the applied dead and live loads; for example, an FE model can predict residual deflection [17], and they can also be used for research studies to explore the progressive collapse behaviour of structural members and sub-structural structures under severe deformations [18].

For instance, M. Scamardo et al. [19] used FE models to approximate the directions of in-plane tensile cracks, and D. Foti [20] developed a 3D model of the Normand tower to evaluate its structural behaviour. 3D Modelling is the first step in creating a digital twin, see Figure 6.

A digital twin is a digital replica of actual physical objects (processes, systems, etc.) in computers. It is considered a conceptual digital model of data and behaviour for structures of interest, attributing, and operating through their life cycle [19], [20].

Digital twins must be the most realistic virtual representation of physical entities, including the digital model and all relevant information, and must be synchronised with those entities. One important characteristic of digital twins is self-evolution; they must change and evolve according to the actual situation while maintaining the contrast between physical and virtual spaces [11].

Digital Twins are not just pure data; they contain algorithms that describe their real counterparts and decide an action in the production system based on this processed data [21].

A digital twin operates as a virtual representation of the physical bridge, which can be updated in near real-time as new data is collected, provide feedback to the physical twin, and achieve 'what-if' scenarios for assessing risks and predicting performance.

A part of this research focused on creating a suitable Digital Twin (DT) of the Soroksári bridge by developing a 3D FE model using AxisVM software, Figure 7a.

The numerical bridge model consisted of shell elements, and the geometry and material properties were taken from the implementation plans. The latter was planned to be refined later by in-situ measurements.

The FE model was validated by the results of the loading test performed by the Budapest University of Technology and Economics in 1990 [22]. The accuracy of the applied triangular finite element mesh was also verified.

Determination of internal forces and stresses based on geometric nonlinear (second order) calculation. Deformations, Figure 7b, and crack widths were calculated by considering the planned reinforcement.

The created numerical model must follow the actual behaviour of the structure as closely as possible [23]. Therefore, it is also planned to include the damage (e. g. significant cracks) spotted during future field inspections in the FE model.

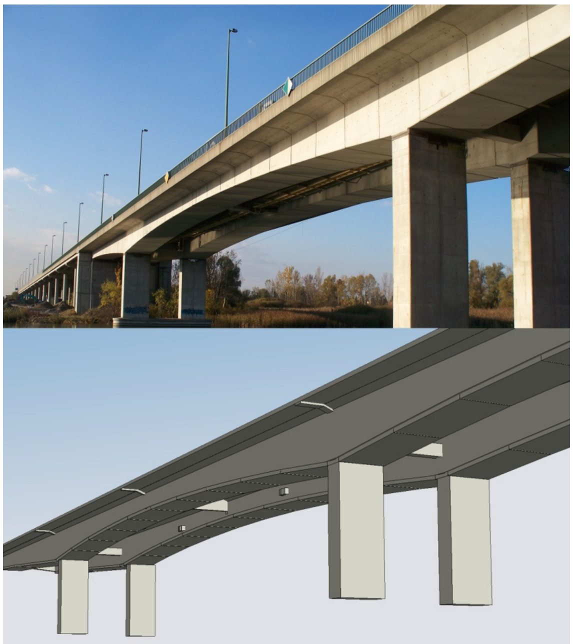

Figure 6: The Soroksári bridge – original structure and its digital twin

Tensioning forces inside the post-tensioning cables in the top plate were modelled by appropriate concentrated forces at the ends and at the breakpoints of the cables. For the purpose of strength control several loads according to Eurocode standards were applied on the bridge, including self-weight and permanent loads, wind load, thermal loads and traffic loads.

Based on the calculated internal forces, the designed reinforcement of the bridge was satisfactory for ULS in bending, torsion, and shear. The bridge was also satisfactory for SLS, including deflections, crack width and stress control.

Deflections were calculated by considering actual reinforcement and the effect of cracks using nonlinear calculation.

(a) (b)

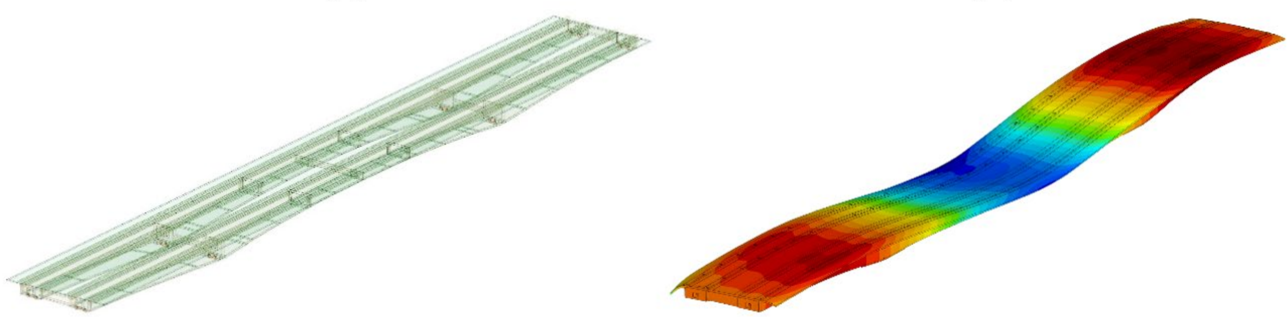

Figure 7: 3D FE model of the bridge (a); deflected model (b)

5. DAMAGE DETECTION BY MULTIPLE LINEAR REGRESSION

In our research, we looked for a correlation between possible damage related to structural behaviour and the data measured by the monitoring system.

Generally, structural failure was defined as an exceedance of a limit value for a certain quantity related to the structure (e. g. stress, strain, deformation, crack width).

Statistical methods describe the behaviour of a set of observations by directing attention to the observations themselves rather than the physical processes that formed them. One of those statistical methods is regression.

Regression plays a vital role in statistics [24], it is a technique for analysing raw data and searching for the messages they comprehend. Even where no sensible physical relationship exists between variables, we can relate them by a mathematical equation.

While the equation might be physically meaningless, it can be extremely valuable for predicting the values of some variables from knowledge of other variables, perhaps under certain stated restrictions [25].

In SHM of bridges, most probably the relationship between the input measurements and their effects on the behaviour is not linear, but as a trial for this method, authors tried linear regression, in later stages of the research, nonlinear machine learning algorithms will be used.

Multiple linear regression analysis is the most straightforward statistical tool to relate the observed environmental and operational factors with the observed structural responses and behaviour.

This statistical tool can be used to predict one or more responses (dependent variables) from a set of predictors (often called the predictor, the regressor, or the independent variables) and to evaluate the influence of the predictors on the dependent variables [26].

Worden and Cross [27] used linear regression to learn a predictive model from the data for Tamar Bridge in the southwest of the UK. Data were acquired from a vibration-based monitoring system installed on the bridge. This data was passed to a computer that performs an automated modal analysis to extract the structure's natural frequencies. The use of non-linear regression is possible at a later stage of the research.

The linear regression model was obtained by the least-squares fitting of the training data [28]. This involves the initial assumption that a specific type of relationship, linear in unknown parameters, holds.

The unknown parameters were then estimated under certain other assumptions with the help of available data to obtain a fitted equation.

The method of analysis used was the method of least squares, simply a minimisation of the sum of squares of deviation of the estimated values from the actual values.

Figure 8 represents the coding steps of the applied regression method that will be used for the SHM of the bridge in question.

After the instalment of the new sensors on the Soroksári bridge, a set of independent variables was included, and simple linear regression was extended to multiple linear regression as expressed in the following equation [26]:

$$Y = X\widehat{U} + E \qquad (1)$$

where Y is an n-by-m matrix of the dependent variables, being n the number of observations and m the number of dependent variables, X is an n-by-(r+1) matrix with the corresponding n values of r designated predictor variables, $\widehat{U}$ is an (r+1)-by-m matrix with the expected model parameters that weigh the contribution of each predictor variable, and E is an n-by-m matrix with the random error of the multiple linear model.

As mentioned before, new strain gauges were recently installed on the analysed bridge. While the data collection phase is ongoing, the regression model was tested on a simple structure.

A simply supported reinforced concrete beam, Figure 9, was loaded by randomly generated imposed load (q_m) and concentrated loads ($F_{m,i}$) representing traffic loads.

The span of the beam was l_{eff} = 9.5 m. The applied tensile reinforcement was 6Ø20 in the middle of the beam and 4Ø20 at the supports.

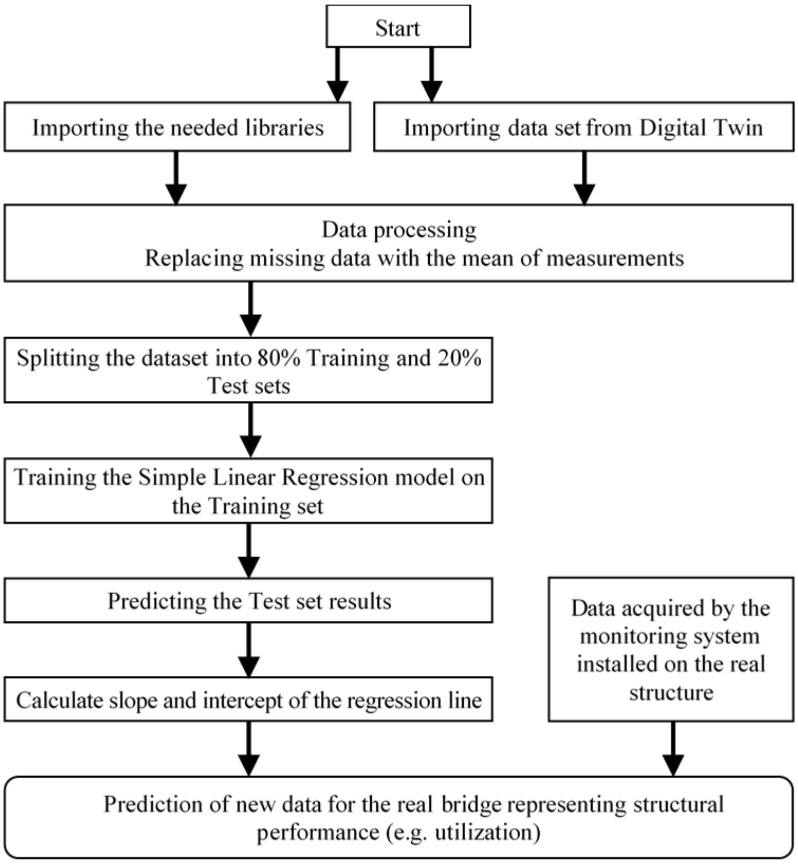

Figure 8: Steps of linear regression for SHM

Shear reinforcement consisted of Ø8/150 stirrups at the supports and Ø8/280 stirrups in the middle.

The applied concrete grade was C30/37 and S500B steel grade was used for the reinforcement. Utilization of the beam was calculated on the mean level, for any generated load case in each cross-section for ULS and SLS (bending moment and shear capacity, deflection, crack width).

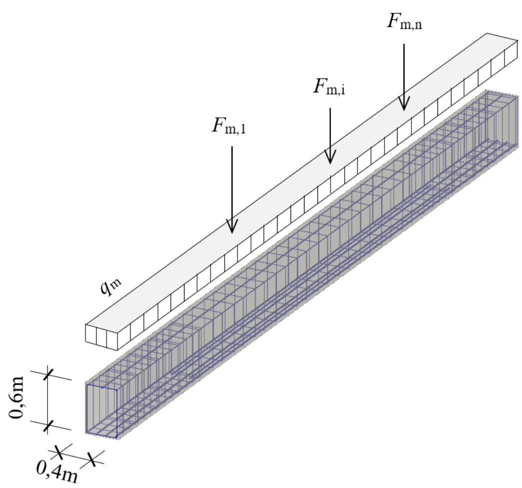

Figure 9: Simply supported beam model used for testing of the regression algorithm

Figure 10 illustrates the maximal utilisations of the beam for 300 randomly generated load cases.

Certain points of the beam were considered as 'monitoring points' where corresponding results were recorded at each run.

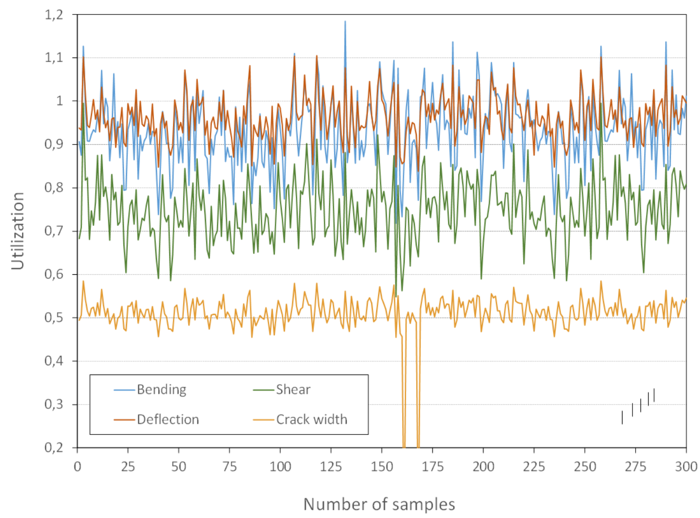

Figure 10: Maximal utilization of the beam for ULS and SLS for 300 generated load cases

Accordingly, the longitudinal strain was recorded in the bottom flange at midspan and in the top flange at a quarter of the span, vertical (shear) strain was recorded in the web at the support.

The connection between the recorded 'monitoring' values and the performance of the beam (represented by the magnitude and location of maximal utilizations for ULS and SLS) was analysed using the proposed regression algorithm. In the presence of multiple characteristic values, we had one dependent variable and a set of independent variables.

As an example, for the multiple linear algorithms, the deflection was chosen to be a dependent variable or the regressor, which represented the failure mode.

Based on the trained system, we could predict new deflection values and detect values exceeding the given limit (typically $l_{eff}/400$ in the case of a road bridge) based on the monitoring information only.

The multiple linear regression splits the data into a training set with a size of 20% which was used to build the regression model by fitting the regression line to it, and a test set of the size of 80% of the data which was a separate dataset that is used to evaluate the performance of the trained model by comparing its predictions on the test data to the actual values.

The goal was to assess how well the model generalizes to new, predicted data.

Figure 11 shows the comparison of calculated and predicted maximal deflections for the sample concrete beam.

For the prediction, the regression algorithm was trained using results of 316 beam analyses.

According to the given diagram, the prediction of the deflection is sufficiently accurate even in the case of a relative low number of training data.

The maximal difference of calculated and predicted deflections was less than 1%.

This was a consequence of the simple structural geometry which makes the distribution of internal forces relatively simple, and the selected 'monitoring' values are suitable of the accurate prediction of the variable in demand.

The next step of the research is the application of the multiple linear regression model to the digital twin of the Soroksári bridge, and the prediction of the bridge's performance based on the data provided by the installed sensors.

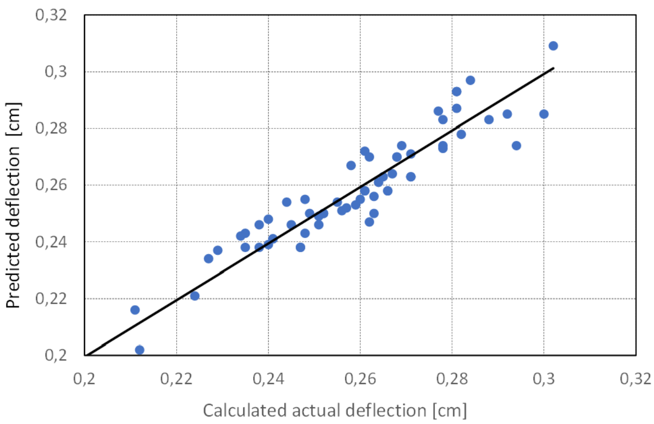

Figure 11: Comparison of calculated and predicted deflections for the sample beam

6. CONCLUSIONS

A new automatic damage detection identification technique for RC bridges was proposed.

Its foundation was the implementation of digital twins and multiple linear regression to form an innovative closed system that can, with the help of sensor measurements from the actual bridge, be trained to predict further damages.

The authors planned to test this technique on the Soroksári bridge, where only two sensors were originally installed, therefore, new seven strain gauges were installed on the bridge to improve the existing monitoring system.

In the meantime, authors tested this theory on a simply supported beam assembled using Mathcad, and multiple linear regression was applied to find the connection between deflection and other parameters like bending moment, shear stress, and crack width.

The results of the study showed that the digital twin and machine learning algorithm could be effective in predicting the bridge performance and detecting possible damage. In the future, an alarm system will be developed to give warnings about possible damage.

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APPLICATIONS OF AR/MR TECHNOLOGY FOR THE VISUALIZATION OF FUTURE BRIDGE CONCEPTS – PART 2

Muhammad Fawad[1], Marek Salamak[2], Asseel Al-Hijazeen[3], Kálmán Koris[4]

INTRODUCTION

With the boom of industry 4.0, the construction sector has equipped itself with amazing technologies such as Building Information Modelling (BIM), Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) [1].

All of them are digitizing and automating the construction processes by improving the information management and visualization of in-service and future structures.

Among them, MR technology is taking the lead while showing reality-virtuality combinations.

It goes beyond the augmentation and virtuality of realities and by combining their features it provides the real and virtual world continuum, Figure 1.

In this way, 3D drafts of projects which are prepared in a virtual world can be seen in the real world and real sized models of these structures can be visualized.

MR technology is not only 3D visualization of structures but also deals with project information management and its collaboration among users [2].

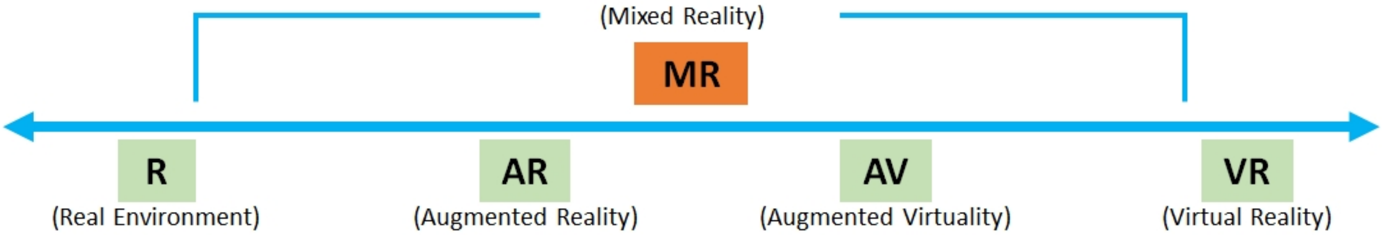

Figure 1: The real and virtual world continuum

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The bridge industry is taking the maximum benefits of these promising technologies and making the bridge structures smart enough to be visualized even before their construction and managed in terms of their health and serviceability.

MR can revolutionize the whole process of bridge construction. Starting from the design phase, it manages the construction processes, providing the 1:1 scale visualization of each structural element, dealing with a detailed comparison of 3D designs and built structures, and offers its services for bridge health monitoring after the bridge construction [3].

It enhances the data accessibility for decision-making in project management such as design checks, construction simulation and monitoring, especially for operation and maintenance.

The MR environment is fully immersed in user interaction and virtual motions. The user uses certain gestures, voice commands and gazes in the MR environment and operates the device with these commands.

The only problem faced during the implementation of MR is the display contract, especially in the sun. Therefore, MR devices are needed to display the 3D models with high resolution and contrast [4].

The dynamic development of this technology and the exponential progress of computing power make it more and more common, and new concepts and solutions are emerging that allow users to explore different areas of the real and virtual world continuum [1].

To implement the MR application, several cyber-physical devices are in practice, but the handiest and most suitable gadgets are Microsoft HoloLens and Trimble site vision.

These devices are using certain applications like Trimble Connect (TC), which provides a database of 3D projects from where the bridge models can be directly visualized in the MR [5].

These devices allow users to implement the 3D project model into the real world and show them at the exact location and scale.

There is also a possibility to collaborate with other users of the design team or stakeholders by using the gestures and voices [6] commands of HL.

The implementation of industry 4.0 concepts in bridge engineering depends on the use of Bridge Information Modelling (BrIM) in connection with AR/MR which helps to visualize all the relevant information in such a way that gives a real picture of bridges even before their construction.

This technology is not only providing the visualization of future structures but also allows the users to see the progress of construction phases, modelling of the HVAC system and their visualization during the construction to avoid any clashes, management and collaboration during construction, and verification of all the structural designs after construction [7].

This article is the second part of a series, focusing on the field applications of digital technologies in structural, especially bridge engineering. The first part analysed the use of VR for the assessment of bridge concepts whereas, in this part, the authors are implementing the use of MR for the assessment of bridge concepts.

Taking the advantage of MR applications, authors implemented this technology to visualize the future bridge concepts. In this article, BIM models of a future bridge are presented in a MR environment using Trimble Microsoft HoloLens (THL) and Trimble Site Vision (TSV).

EXPERIMENT DESCRIPTION

This study is pioneering the concepts of MR implementations not only for the selection of futuristic bridge designs but also for their visualization onsite with a 1:1 scale.

It is one of the first attempts in central Europe that uses such decision-support techniques for the construction of new bridges.

The said concept is used in this study to help the designers and clients at the design phase of a bridge construction planned in the south-eastern part of Poland. In this way, the authors provided additional support to the client in selecting the variant to be used in subsequent and final design stages.

It consisted in visualizing the variants proposed by the designer in the VR and MR. The aim of these activities was to facilitate decision-making by the client and to indicate the preferred solution to the designer.

Figure 2: Selection of bridge design concepts using VR

Complete descriptions and details about two different bridge concepts were discussed in the previous article [8], where VR concepts were used to draw a comparison between two different variants of the bridge design, Figure 2.

The authors presented these variants using Oculus Quest-2 (VR device) in front of the client, and one of the variants was selected for the final design of the bridge. So, in this way, VR helped in the selection of bridge design.

After the selection of the bridge design, the major concern was the visualization of the selected design in the real world at a 1:1 scale. For this, the authors used the applications of MR and visualized the future bridge design in the real world at a 1:1 scale.

USED DEVICES AND TECHNIQUES

Several MR gadgets are serving the purpose of MR implementation, but Trimble HoloLens (THL) and Trimble Site Vision (TSV) are the most useful MR devices when it comes to Architecture, Engineering and Construction (AEC) industry.

Both devices are provided with several inbuilt sensors which constantly map the user environment and implement the MR using gestures, voices, and gaze motion, Figure 3.

These devices are equipped with an on-board computer and android system that enables them to connect to Wifi and cloud databases.

Using the project-oriented specific applications, Trimble Connect (TC), both devices can self-implement the 3D models generated by the BIM platform into reality.

These models are saved in the Autodesk Revit (RVT) format or in an open format such as OpenBIM (IFC).

However, mainly open formats were used for this study. The models are made fully interactive using the device's gestures and voice commands.

Autodesk Revit and Trimble Connect (TC) are the major software used to supplement MR devices. Using the TC plugin in Revit, the BIM model of the bridge can be uploaded directly to the TC database.

a. Microsoft HoloLens-2

b. Trimble Site Vision

Figure 3: MR devices used in this study

So, in this way every uploaded model is available in the database of TC in each device, therefore, it becomes very easy to load these projects in MR medium and augment them in the real world.

So, different structural elements and utilities of the bridge structure can be visualized at their exact locations.

WORKING METHODOLOGY OF THL

In order to implement the MR using THL, the BIM model is assigned the actual ground coordinates of reference points from where the MR is implemented. After uploading the model, the next task is to develop a QR code for the respective reference point by using the "View Online" tab of the TC application.

After connecting to the online web server of the application, several functions like cloud data, QR code generation, adding URLs, and writing some notes for other collaborators of the project can be performed here. So, from the QR code tab, QR at the selected locations can be generated.

In the field, a model can be visualized in the real world after loading from the TC database. The model can be visualized at full scale in VR if the street view is turned on from the "Explore" tab. Besides this, several collaborators can be called instantaneously to show the progress of work on site and certain clashes can be eradicated right there.

To implement the model in MR at a true scale, the "Align" tab is navigated. It offers two functions to implement MR.

One is model alignment, in which the user can scan the walls of structures and align them with the same walls of the model (only workable with existing structures).

The other one is using a QR code, for which a QR code is placed at the exact location of the reference point and scanning of the code generates a mesh in the surroundings and the model is placed at an exact location with the actual size of the structure.

WORKING METHODOLOGY OF TSV

Similar to THL, TSV is also a very useful device to implement AR/MR. It not only takes over the distance limitations of THL but also resolves the visual problems of the 3D model in the sun because the visualization is carried out using a smartphone so quality visuals can be obtained.

The device is equipped with several smart features which are compatible with AR-supported android cellular devices.

These features include the GNSS receivers, GNSS positioning system, EDM/AR positioning system, and EDM distance measurement. The hardware system of the device contains an antenna which is also the head of the device and connects directly with the satellites. It uses the cables providing integration to the mounted cellular device which can also use its own GPS for satellite connection.

The overall hardware set of this device includes:

1. Trimble Site Vision equipped with a mounted antenna.
2. AR-supported mobile device.
3. Cable connecting antenna and mobile device.
4. Batteries to provide power to SV setup.

After mounting the mobile device onto the TSV, it can be connected to the antenna using a cable. The device can be turned on; the catalyst is needed to be connected to the mobile device using the Bluetooth function of the mobile.

There will be a confirmation sign of connectivity with the green light on the antenna which shows the successful connection between the mobile device and TSV. This whole connection can be established using the TSV app installed in the mobile device.

After establishing the successful connection, the device must be connected with the external satellites. Here lies a drawback of TSV as it cannot be fully functional inside the building, under the bridges, or in any shade. To make it fully functional the antenna must be clear to the sky.

There are two main steps that should be completed before the implementation of MR at the exact location which are:

1. Connection with at least 10 satellites.
2. Orientation synchronizations as per SV surrounding environment.

The successful implementation of both functions is guaranteed by the green signals for satellites and the orientation symbol on the mobile device. If they are orange, it means the implementation is not yet successful so TSV instructions should be followed.

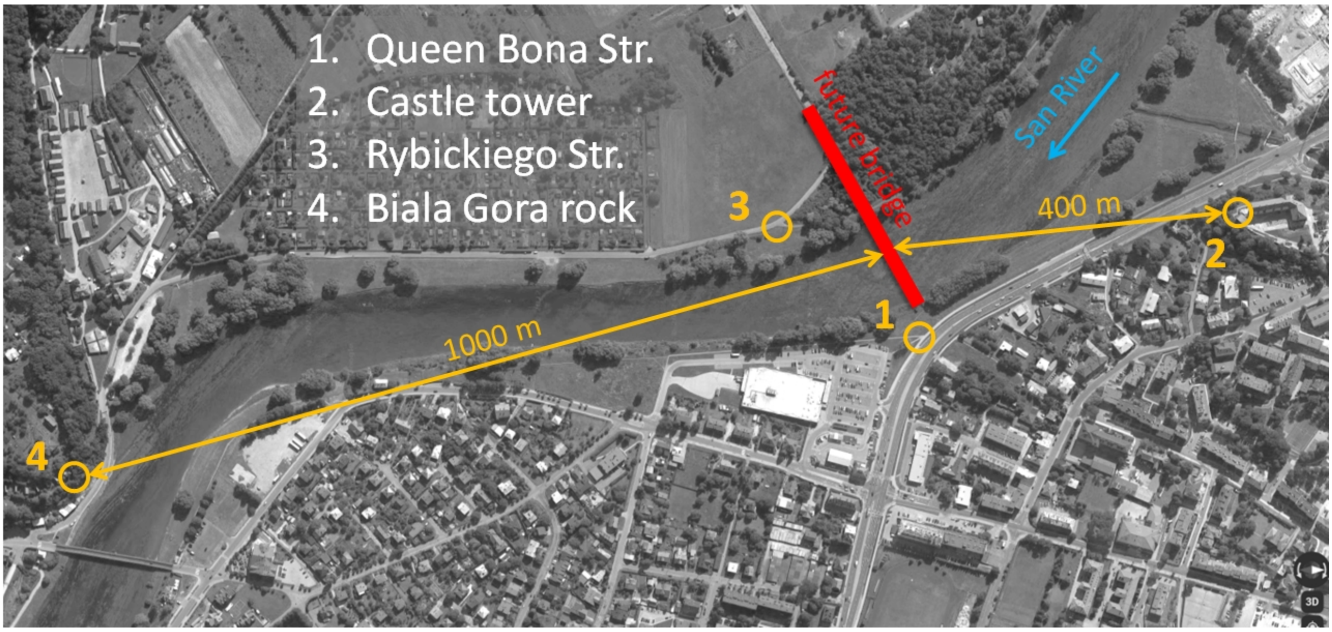

Figure 4: Location and marking of the indicated observation points

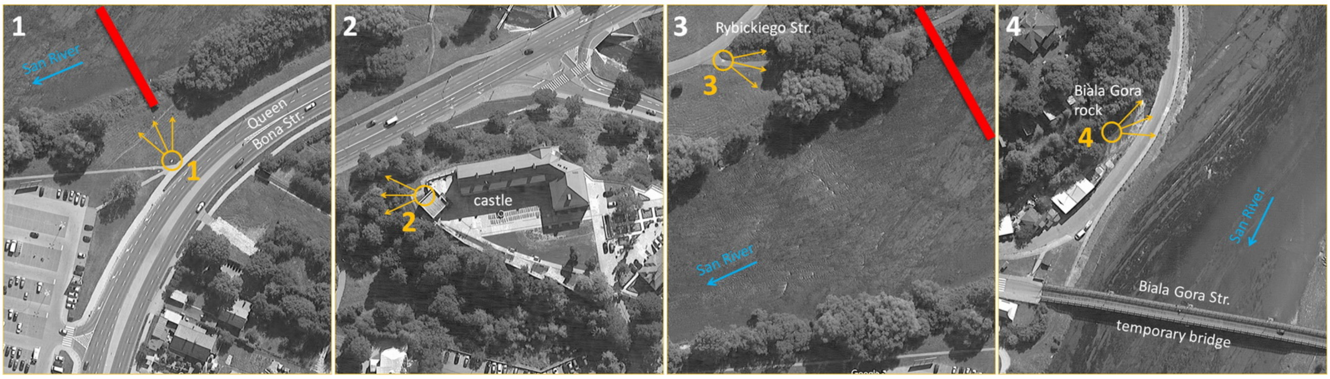

Figure 5: Detail of the terrain around the indicated observation points

MIXED REALITY DEMONSTRATION OF BRIDGE

Demonstrations of the MR for the selected variant of the bridge started with the selection of the locations of observation points in the field. Four places were initially proposed; they are shown in Figure 4.

Details of the terrain and viewing directions around the adopted observation points are shown in Figure 5.

On the left side of the San River, there were two points marked with no. 1 and 2.

1. Queen Bona Street located in the immediate vicinity of the planned roundabout, the entrance to the bridge, and the shopping center nearby. It is a place with a high intensity of road and pedestrian traffic, which will be used even more after the construction of the bridge and intersection.
2. The castle tower, where there is a viewpoint often visited by tourists. The tower is located 400 m from the future bridge and at the same time more than 30 m above the ground on the right bank of the river, where the cable-stayed bridge pylon can be erected.

Figure 6: An attempt to visualize the model in the MR space around point no. 3 at Rybickiego Street

The next two points marked with no. 3 and 4 have been proposed on the right side of the San River.

3. Rybickiego Street at the intersection with the bicycle path going along the river. The point is located approximately 50 m from the planned pylon of the cable-stayed bridge or the abutment of the arch bridge.
4. Biala Gora Rock, where there is a characteristic vantage point to admire the San River valley. This place is located almost 1000 m from the planned bridge.

Points no. 1 and 2 are of the greatest importance for the entire project. They are the easiest to access and the most frequently visited (due to the shopping mall nearby and the renaissance castle with a view of the San River valley).

Therefore, a major portion of this work was carried out at these points.

However, the MR implementation trials started from point no. 3 at Rybickiego Street, Figure 6. The possibility of displaying the model in the MR space in both TSV and THL devices was first checked there.

The established reference point was located at the intersection of the street and the bicycle path branching off it.

After several attempts, however, it turned out that the area on this side of the river is too densely covered with trees and shrubs.

The visualization of the model was therefore poorly visible. In fact, only the pylon in the THL goggles was able to be displayed.

The user could stand right next to it and imagine its height and dimensions, Figure 6.

At point no. 1, Queen Bona Street, closest to the crossing, the experiment was fully performed with both devices. First, it was THL goggles where the operation in the field is carried out using gestures and a virtually displayed menu.

Such a menu is usually shown after recognizing a raised wrist, Figure 7. After loading the model from the TC project database, the process of its localization and calibration started. The prepared QR marker with exact coordinates of the bridge was used for this purpose.

The model of this marker was first placed in the virtual space, and its real image was placed in the real terrain at the same coordinates as in the model by scanning the QR code through the marker scan technique.

Users without the THL helmet had the opportunity to preview the MR views cast on the tablet from the THL.

The tablet, used for this purpose, was connected to THL via the http protocol over a local WiFi network. The surroundings were mapped by the built-in cameras of the goggles.

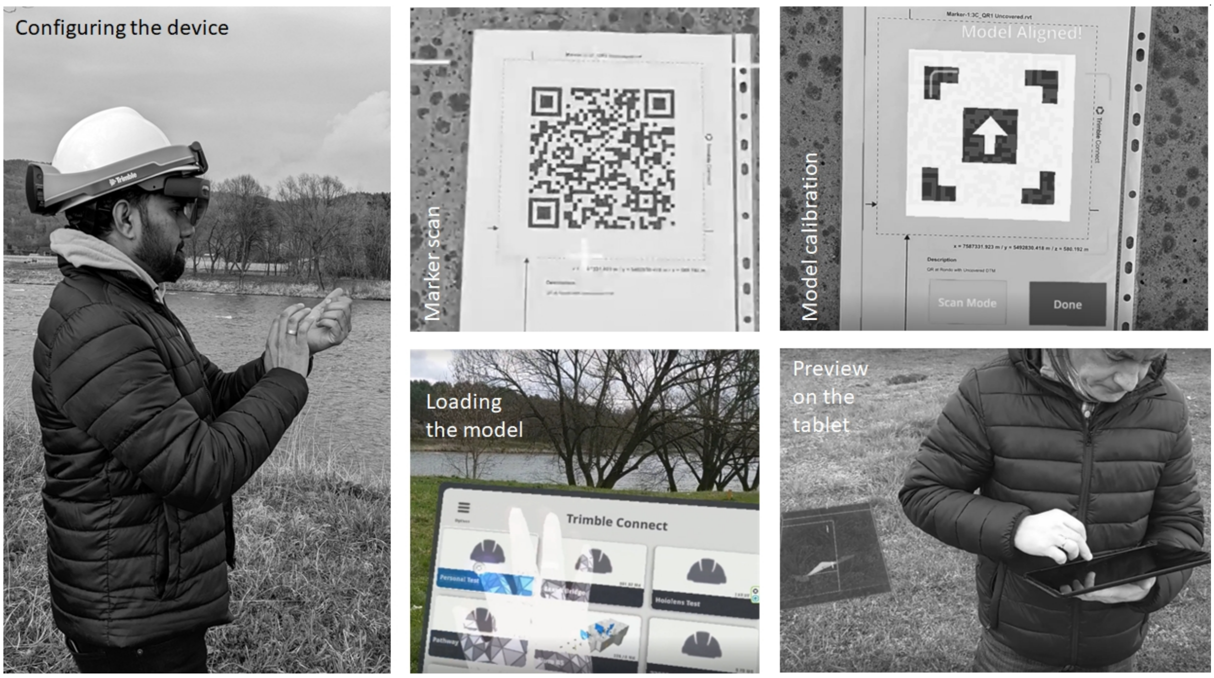

Figure 7: Experiment with Trimble XR10 + MS HoloLens at point no. 1 at Queen Bona Street

The image visible on the tablet screen demonstrated the visualization of the real environment and the virtual model.

This way not only the user of THL was immersed in the MR but the people attending this demonstration were also able to see the MR implementation of the future bridge.

Figure 8 shows the virtual menu of the TC application and the main menu of the THL goggles. The navigation function that is used in mixed reality can be observed by recognizing the movements and gestures made by the user with his hands.

In the end, a view of the model in its natural setting was shown, but unfortunately, a part of the bridge was visible due to the distance limitations of THL.

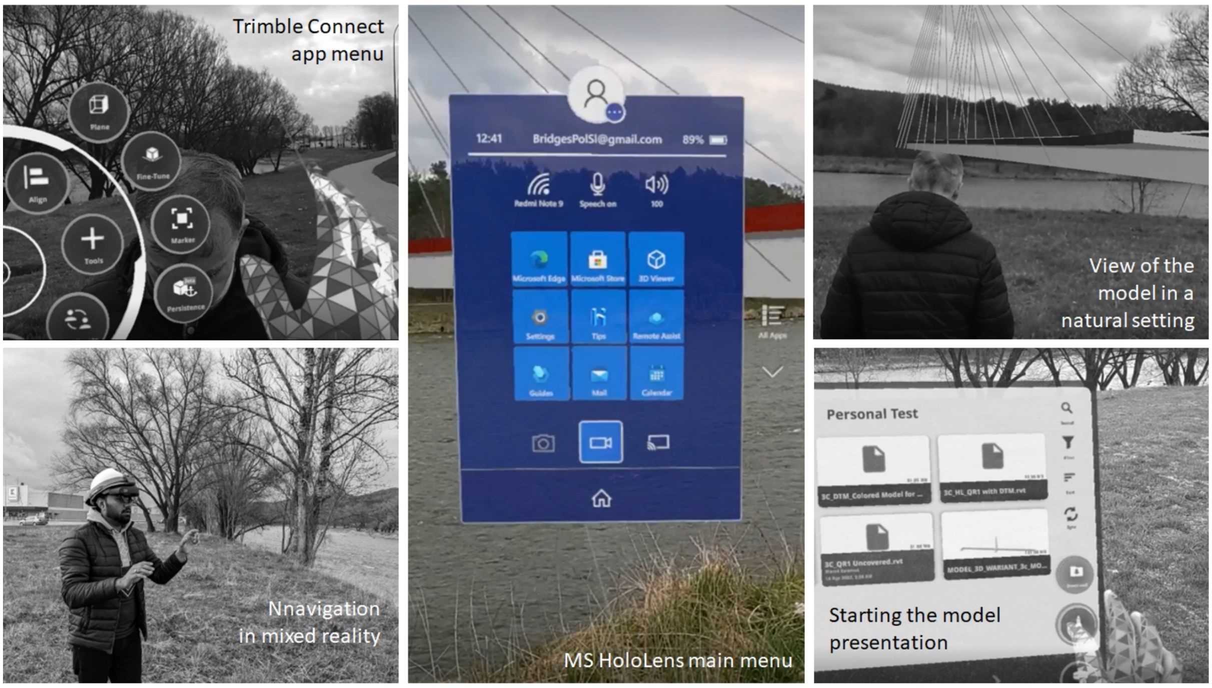

Figure 8: Model visualization with the Trimble XR10 + MS HoloLens device at point no. 1 at. Queen Bona Street

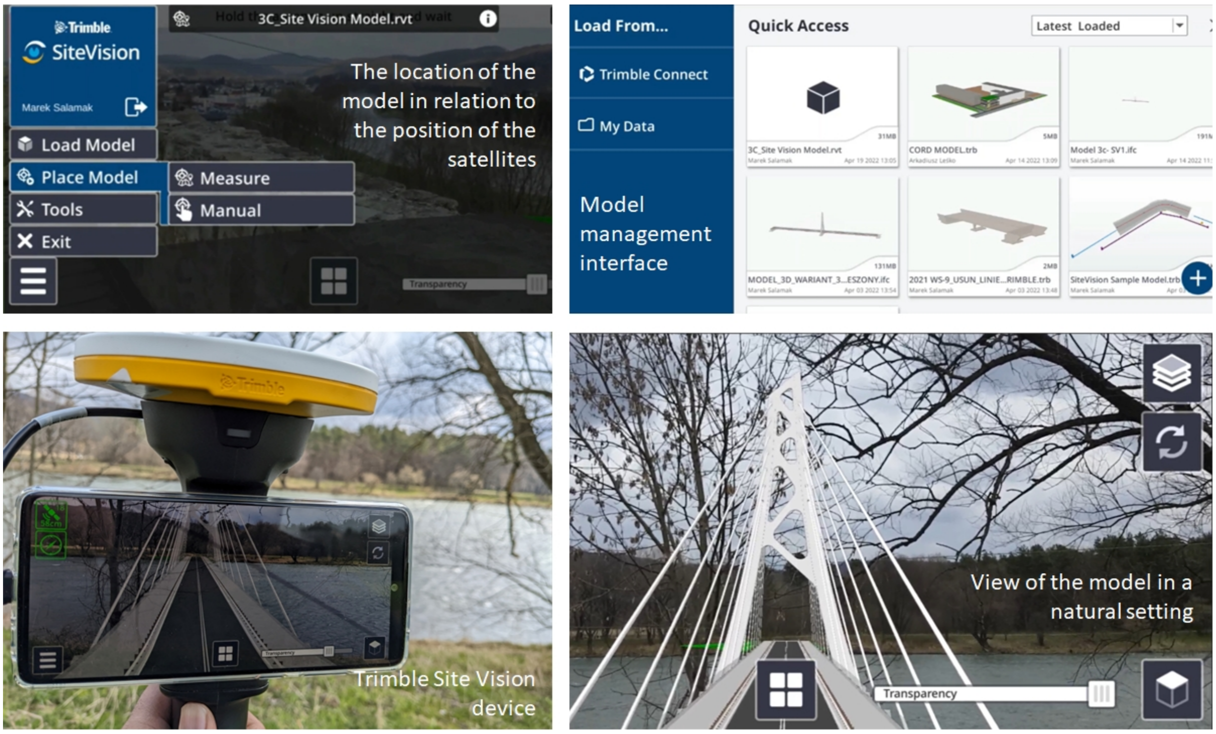

Figure 9: Model visualization with the Trimble Site Vision device at point no. 1 at Queen Bona Street

These limitations resulted from the large dimensions and a large number of details of the bridge model.

Users could see that the model of the bridge span is above the ground in the way it will eventually be built.

As the user approached the model, other details could be displayed.

It can therefore be assumed that the THL device does not work well in the case of work in the open area and with longer span structures.

Such an open area without any characteristic objects with flat surfaces does not allow for full visualization of a large model and its precise display.

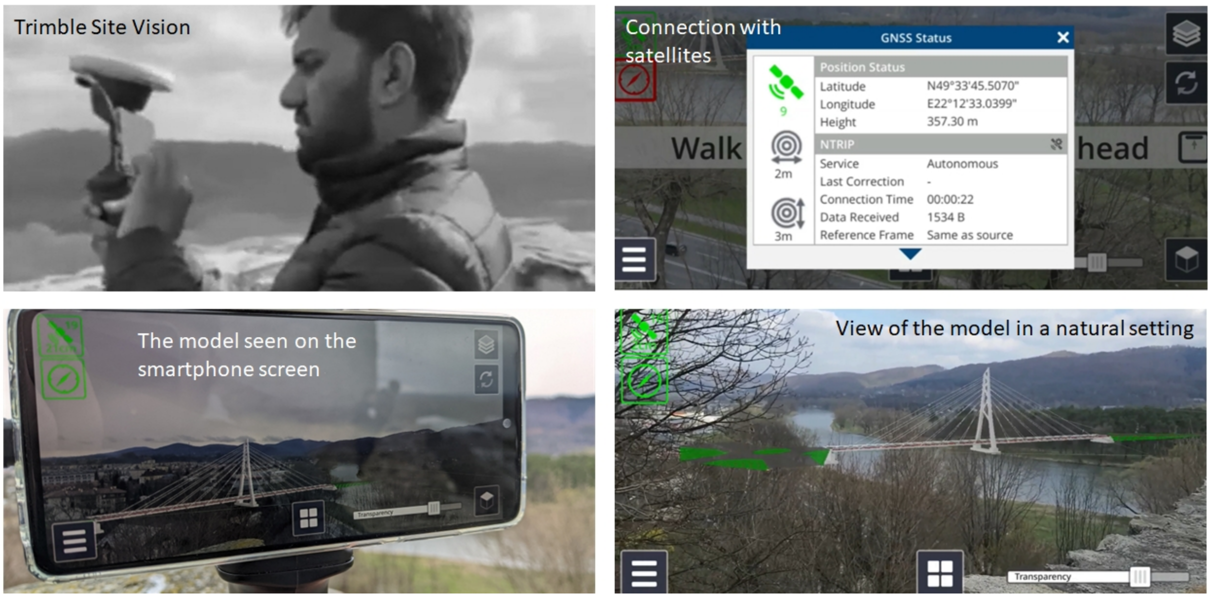

Figure 10: Visualization of the model with the Trimble Site Vision device at point no. 2 on the castle tower

Certainly, THL is better suited for operating in closed rooms of cubature type, such as buildings.

A TSV device with a smartphone was also used at the same point in the terrain.

It served not only as an interface to support dedicated TC applications, but also to display the projection of real and virtual objects on the screen, Figures 9 and 10.

The surrounding terrain was recorded by the smartphone's built-in camera, and virtual objects of the bridge model were placed on this image. This device worked better in open spaces and with large objects.

It was easy to display the entire model with all the details, and the display was stable too, Figure 9.

Even moving the user with the antenna did not interfere with the displayed view of the bridge. The model was continuously updated in real-time.

An attempt to visualize the access road to the bridge and the roundabout allowed for a general idea of what the terrain will ultimately look like at the site of the planned crossing.

Participants of the experiment could see that the plane of the road was above their eye level.

The roundabout will be raised almost two meters above the existing terrain.

Unfortunately, the models used did not have sufficient accuracy to reproduce the embankments and roads planned by the designer.

This will be supplemented only in further design stages when a complete model with true coordinates will be prepared by designers.

In the immediate vicinity of the roundabout (point no. 1 at Queen Bona Street), it was possible to retrieve the planned longitudinal axis of the bridge using TSV.

Unfortunately, the coordinates and parameters adopted during the calibration turned out to be insufficiently precise.

Consequently, the precision of bridge mapping was not very accurate but still a full length of the bridge with its pylon was visible on the screen, Figure 9.

However, from a greater distance (point no. 2 on the castle tower), the model had proportions closer to the designed ones, and landscape behind the bridge was imagined to be true as it will look like after the construction of the bridge.

The orientation of the bridge from this location was still not fully accurate as it was from several dozen meters, which can be seen in Figure 10.

There are several factors which were influencing the placement, especially the connections to GNSS satellites and the orientation parameters of the device.

Besides these limitations, the implementation still worked well from a long distance and was found to be very close to the real placement of the bridge which was also acknowledged by the audience.

WORKING LIMITATIONS AND SUGGESTIONS

Both THL and TSV are no doubt amazing devices, but their full capacity is still in operation.

As mentioned earlier, THL has the major limitation of distance mappings as it can map the surrounding up to 5 m.

Besides this, its functionality and visualization reduce in the sun so a cloudy environment is best suited to perform such types of experiments.

Moreover, in very cold weather sometimes the device hangs and shuts down automatically.

Similarly, TSV has the limitation of its use only in the open air as it needs direct connections with the satellites.

Moreover, during the orientation settings devices require some adjustment of the antenna by walking on the ground, so, it is very challenging in case of limited space availability.

Other issues involve the accurate measurement of designated coordinates, which takes longer time for their adjustments, therefore, bigger marking points with enough space availability can reduce the limitations and help to achieve better results.

CONCLUSION

This study involves experimentation and demonstrations with the use of techniques and devices operating in a mixed reality continuum.

This study provided additional support to the concerned authorities in the process of selecting the final variant of a future bridge.

Visualization of the models in VR was described in the previous article of this series which made it easier to talk about the advantages and disadvantages of both designs of a bridge and the selection of the final design.

Thanks to this, the participants could more easily imagine the real height of the pylon and the full length of the bridge which was shown by switching to street view.

MR implementation using the THL is carried out by uploading the BIM models of the bridge into the database of the TC application. QR codes of the actual coordinates of the bridge were assigned to the virtual model of the bridge.

So, these QR codes were placed physically at the same locations and scanned using THL, which placed the bridge structure at the exact location and scale.

Similarly, TSV was also used at designated locations to implement MR.

First, the model was uploaded to the TSV applications connected to different satellites and then orientation was set as per the embedded coordinates of the real ground location.

In this way, the bridge was placed at its exact location and scale.

The benefit of using SV is that it overcomes the distance limitations of MR and structures can be seen even in the sun with better-quality visuals.

Field trials using mixed reality proved to be more difficult to implement but it was possible to display the models in natural surroundings and make the client's representatives aware of what the surroundings would look like after the bridge is built.

However, device limitation brought some precision concerns in the study.

However, it must be considered that the whole project with the practical use of mixed reality was very experimental, which no one has tried in the infrastructure industry in Poland so far.

The authors plan to repeat this project after the designer completes the model and obtains corrections to the GNSS satellite signal.

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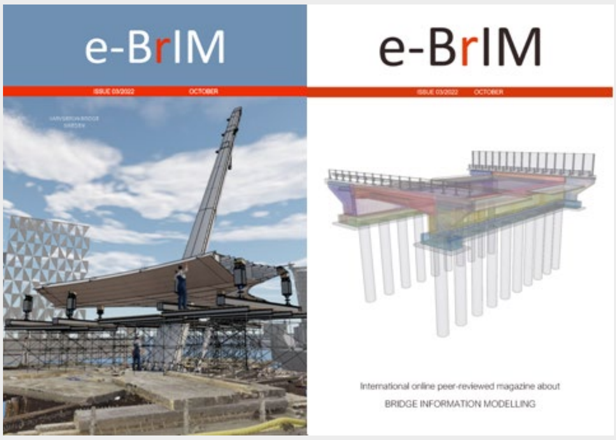
e-BrIM

ISSUE 01/2023 FEBRUARY

ONE YEAR OF THE e-BrIM MAGAZINE



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