DOCTORAL DISSERTATION

in the discipline: Civil Engineering, Geodesy, and Transport

BIM-based Framework of Bridge Health Monitoring Supported by Immersive and 3D Reconstruction Techniques for Analytical and Asset Model Updates

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:

June 2024

Gliwice (Poland), Budapest (Hungary)

Extended abstract (EN)

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1. Introduction

Bridges as a critical component of modern infrastructure, facilitating the mobility of goods and people across geographical regions. Despite the technological revolution in the engineering domain, bridges remain prone to deterioration over time, caused by several factors such as environmental conditions, vehicular loads, material fatigue, etc. It causes bridge failures that go beyond simple inconvenience; frequently resulting in disastrous outcomes that include everything from economic disruptions to the loss of life. Even with the increased bridge resilience, the frequency of incidents highlights the need for proactive monitoring and maintenance techniques. This is where a Structural Health Monitoring (SHM) system offers its services and provides robust solutions to mitigate such problems. Such systems help us to understand that disasters—which are often attributed to structural damages—are today's issues rather than historical events. It puts a greater emphasis on employing technological developments to avoid tragedies in the future. As an aspiring researcher, the prospect of contributing to the development of solutions that reduce the risks associated with bridge collapse serves as a motivation for my engagement in this domain. This is where my dissertation serves as a paramount in integrating the BIM, 3D reconstruction, and immersive technologies to ensure the safety of bridges. The transformative potential of these technologies over the traditional methods of structural assessment and maintenance is the motive of this research to go deeper into this multidisciplinary research.

1.1 Aim and objectives of this research

The major aim of this research is to provide a foundation for the development of an Immersive automated bridge Structural Health Monitoring system by utilizing the applications of Building Information management (BIM), Internet of Things (IoT), and Augmented/Mixed Reality (AR/MR) technologies and 3D-reconstruction methodologies. The proposed framework addresses the automation of bridge health monitoring systems, the specificity of bridges, and their practical adaptation in the civil engineering industry. Novel use cases of the methodologies specified as components of the proposed immersive SHM framework support the practical adaptability of the suggested solutions.

To reach the above-mentioned aim of this dissertation, four major objectives have been defined.

1. Development of bridge asset management framework using Analytical and Bridge Information Modeling (BIM) tools,
2. Proposal of advanced SHM system and their validation,
3. Integration of SHM, BIM, and IoT technology for smart infrastructural health monitoring,
4. Development of an Immersive Bridge Digital Twin Platform (IBDTP) using Mixed Reality and Digital Twin technologies.

To achieve the above-mentioned objectives successfully, this research provides a comprehensive review of the literature on Structural Health Monitoring (SHM) of bridges. This review discusses the evolution of Bridge Management Systems (BMS) and their advancements in detail. It further explores the use of BIM technology for SHM, highlighting its applications in data collection, management, and predictive decision-making. It also discusses the use of Virtual, Augmented, and Mixed Reality (VR/AR/MR) for visualization of future bridge design concepts. The study also explores the integration of VR/MR tools with BIM technology, leading to the development of an immersive bridge digital twin platform, utilizing IoT-based wireless sensors for monitoring and maintenance.

1.2 Research gap

The state-of-the-artwork underlines the challenges related to traditional methods of bridge inspection and monitoring, focused on static data collection and processing. The BIM and MR technologies emerge as a transformative technique to automate the generation of the BIM reality models and enable real-time detection of structural irregularities, providing proactive data flows to bridge safety and reliability. On such a basis, a fully integrated bridge digital twin model can automate bridge monitoring processes, make autonomous decisions, and perform proactive maintenance, aided by real-time data collection from sensors and IoT technology. Such an integrated and holistic application is not available in the current body of knowledge. Thus, this research is intended to develop the Immersive Bridget Digital Twin Platform (IBDTP) to improve infrastructure management and monitoring and showcase its potential for monitoring future infrastructure projects.

2. Bridge Management Systems

A bridge management system (BMS) is a means for managing bridges throughout the design, construction, operation, and maintenance of the bridges [1]. As funds available become tighter, road authorities around the world are facing challenges related to bridge management and the escalating maintenance requirements of large infrastructure assets. Bridge management systems help agencies meet their objectives, such as building inventories and inspection databases, planning for maintenance, repair, and rehabilitation interventions systematically, optimizing the allocation of financial resources, and increasing the safety of bridge users [2][3].

BMSs have been developed to assist decision-makers in maximizing the safety, serviceability, and functionality of bridges within available budgets. There are four basic components of a BMS, developing the lifecycle of a bridge. These basic components include asset inventory, inspection/monitoring, performance evaluation, and decision-making. All of these components revolve around the asset's lifecycle and help in the management of bridge performance throughout its life. All of these components are illustrated in **Fig. 1**.

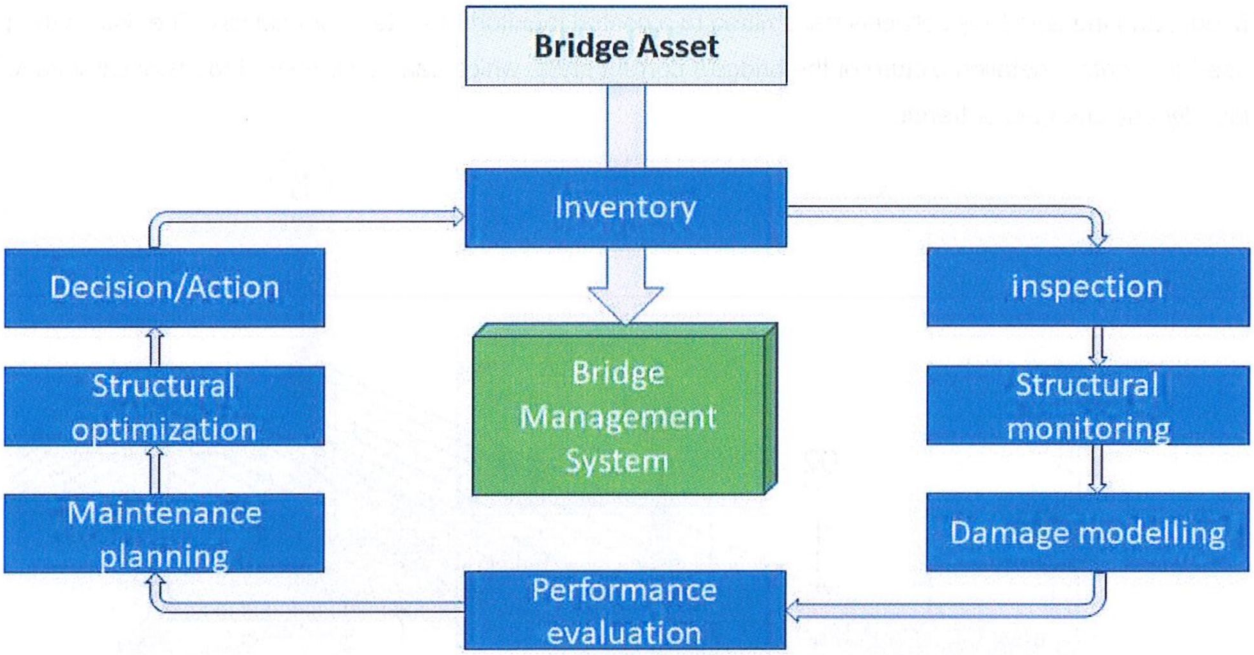

Fig. 1: Lifecycle of Bridge Management System (BMS)

The BMS stands as a comprehensive computerized framework, offering decision support across the design, construction, operation, and maintenance phases of bridge infrastructure. It is recognized as vital for the effective maintenance and sustained safety of bridge structures over extended operational periods [4]. Thus, BMS plays a pivotal role in optimizing management efficiency and reducing unnecessary costs associated with infrastructure management challenges.

3. Structural Health Monitoring of bridges

The Structural Health Monitoring (SHM) framework is utilized to observe and evaluate the existing condition of civil infrastructure, which has broadly evolved to monitor the safety, serviceability, and sustainability of existing structures like bridges [5]. A typical layout of the SHM system on a bridge is shown in **Fig. 2**. Such systems help to identify deterioration and damage caused by the aging and downgrading of the structure. The reasons for this may be environmental factors, improper design, poor construction quality, lack of proper maintenance, and natural disasters like earthquakes, floods, or strong winds [6][7]. The increasing decay of bridges calls for structural evaluation to make them in line with the exact design requisites [8].

Structural health monitoring (SHM) of bridges has been the subject of interest for many engineers and academicians for a long time. Numerous studies have been conducted in the past to improve SHM systems [6]. SHM is the process of monitoring and measuring the structural response in real-time, to detect anomalies in the early stages of damage in structures [9].

SHM of bridges typically involves the use of sensors that measure various parameters such as strain, temperature, vibration, and deformation. These sensors are typically installed at strategic locations on the bridge, and the data they collect is transmitted to a central monitoring system for analysis. The data is then used to create a detailed picture of the bridge's current state, which can be compared to historical data to identify any changes or trends.

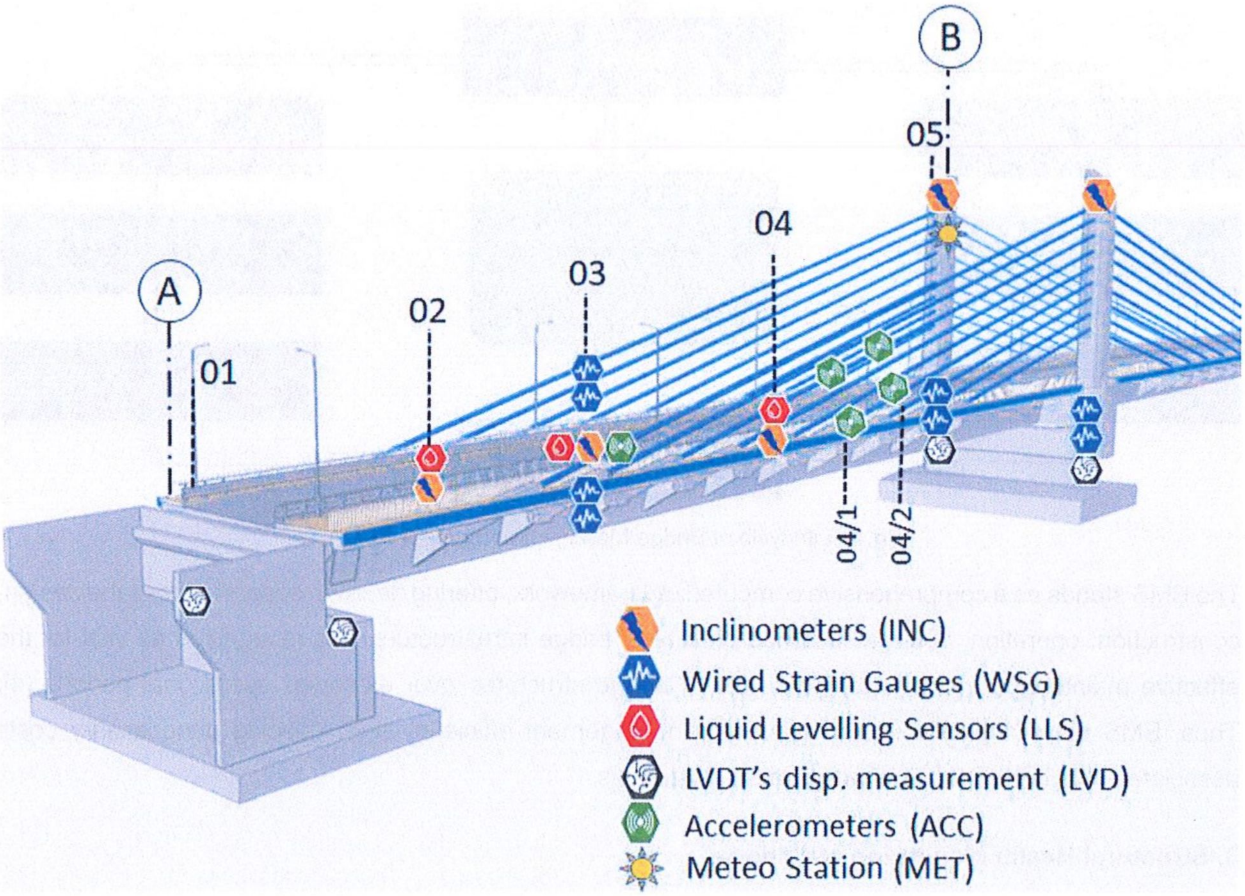

Fig. 2: Typical SHM system installed on a bridge

Structural Health Monitoring (SHM) systems have experienced a tremendous transformation from the conventional bridge monitoring techniques which relied more on direct measurements of bridge response using the traditional sensors on the bridge. These conventional methods involve direct assessment of structural health using visual inspection techniques or simple handheld devices like portable sensors. Nevertheless, these methods exhibit certain constraints, as they are highly dependent on manual intervention, causing several issues such as time-consuming processes, labor-intensive work, involvement of human errors, and challenged quantification of measured data [10]. Moreover, they lack comprehensiveness and detailed damage evaluation in the context of advancements in bridge monitoring. Considering these limitations, these methods were replaced by digitally advanced and robust sensors like wired strain gauges, fiber-optic sensors, acceleration sensors, piezoelectric transducers, and Liquid leveling sensors for accurate and rapid monitoring of bridge health [11]. Even the system using such tools has limitations concerning data management and 3D visualization of structural defects in real time.

4. BIM and related digital technologies used for bridge management and monitoring

Building Information Management (BIM) is an intelligent, smart, and effective multi-dimensioning tool used to manage the information management of construction facilities. This information management is generated using certain software, developing the 3D models of the facilities and managing their assets. Currently, the major focus of the BIM approach is on 3D modeling therefore, it is usually termed as Building Information Modelling, but BIM is much more than just a 3D modeling tool; it is a collaborative process that involves the generation and management of digital representations of the physical and functional characteristics of a project. These digital models are used to inform decision-making throughout the project's lifecycle.

In the digitized world, bridges evolve from static constructions into services providing multidimensional connection: physical – of communities, and digital – of data. This shift results from the requirements of facilities managers and the need to ensure the safety and comfort of users, where the BMS offers its services and people started adopting them. This system forces connectivity and integration of bridges in the more synchronous digital dimension, especially in acquiring, processing, and sharing data. A bridge management system is now enabling bridges to cooperate with other objects to empower global holistic management and to constitute the digital networks of smart infrastructures. To enable that, we need a multi-industrial paradigm – the world is shifting towards BIM tools for BMSs.

In recent years, BIM has become the most flourishing technology in the building industry, and it has been extended to infrastructure engineering. This technology is a promising approach that can be used for the design, construction, and facilities management of structures, wherein a digital representation of the building process is used to facilitate the exchange and interoperability of information [12]. The application of BIM brings about cost reduction, quality control, and efficiency improvement throughout the life cycle of the project. A study [4] conducted by Stanford University highlighted the potential benefits of BIM tools in construction projects. According to this survey, BIM implementation has the capacity to mitigate 40% of additional changes, lower contract prices by 10% through the identification and resolution of conflicts, and shorten project durations by 7%. With these advantages, BIM has also been adopted by commercial software, such as Autodesk Revit, ArchiCAD, and Allplan [13]. Furthermore, BIM has been successfully implemented in many bridge designs [14] and other civil works designs and management. However, the application in the maintenance phase started relatively late. McGuire and Atadero utilized BIM to manage the inspection and evaluate information [15]. Abudayyeh and Al-Battaineh adopted the as-built bridge information model for maintenance and management As-Built Information Model for Bridge Maintenance. Similarly, some research works also combined BIM with the traditional management system to improve maintenance efficiency [16][17][18]. Such studies concluded that the use of digital tools especially BIM technology enables bridge management systems for standardization and maintenance of bridges, as well as processes of processing facilities' data.

In addition to BIM, several other technologies like visual programming, Artificial Intelligence (AI), Scan-to-BIM approach, Virtual, Augmented, and Mixed Reality (VR, AR, MR), Internet of Things (IoT), and Digital Twin (DT) tools hold the promise of revolutionizing the infrastructure management processes. They offer new avenues for data depth, accessibility, and three-dimensional visualization of bridges and their monitoring parameters. Thus, they benefit bridge monitoring in automating data collection, monitoring, transfer, and predictive decision-making for structural maintenance.

Further, the use of 3D reconstruction techniques using Laser Scanning and Photogrammetry techniques helps to collect, process, and integrate bridge health data with the BIM tool. This integration enables real-time detection of structural irregularities and deformations, therefore contributing to the development of safety and reliability programs for bridges. Integration of 3D reconstruction and BIM technologies also plays a vital role when integrated with SHM as it yields a Digital Twin (DT) model of the bridge. This DT model often integrates a virtual model of the bridge with the physical bridge equipped with sensors to monitor and optimize asset performance, utilizing bidirectional data exchange between physical and virtual models. It enables real-time monitoring, prompt anomaly detection, and proactive maintenance of the bridge asset. This integrated framework has proved to be specifically useful in maintaining structural integrity under dynamic conditions.

To enhance the user experience of implementing DT models, immersive technologies such as Virtual, Augmented, and Mixed Reality (VR, AR, MR) have also been explored in this research. For this purpose, Trimble XR10 HoloLens (HL) is focused more that include an intelligent MR-based data dashboard. This dashboard is used to engage construction and infrastructure stakeholders to obtain intuitive information about bridge health in an immersive environment.

The applications of Internet of Things (IoT) technology are emerging as a handy tool in Structural Health Monitoring (SHM) systems of bridges. Ongoing advancements in IoT components, such as wireless sensors/networks and processing software packages, position it as an ideal technology for SHM, particularly in the context of bridges. IoT technology enables real-time monitoring of bridges through strategically positioned sensors capable of collecting data on various parameters like strains, temperature, corrosion, cracking, fatigue, and vibrations. The complete wireless sensor pack includes a sensor node and a microcontroller, which communicates the actual state to the management unit for prompt action, ensuring continuous monitoring of the bridge's health and structural integrity. This whole sensor is then integrated with the web platform unit over the Wi-Fi to facilitate remote data transmission. This platform then controls data collection and transfer for further processing. To ensure a constant power supply, an onsite solar unit connected to standby batteries can be employed.

5. Analytical and 3D modeling of bridges to assess the impact of damage and design of a SHM

5.1 Case study of a damaged RC bridge in Hungary

During the initial stages of development, the computational capabilities of computers and limited virtual space methods led to simplifications in modeling, particularly in mapping bridge geometry. The force or displacement method was initially used for these analyses, but the Finite Element Method (FEM) was introduced, which was better suited for creating algorithms and computational procedures using faster and more memory-capacious computers. Such methods include the analytical part consists of a separate, three-dimensional primitive that represents the computational element and object properties needed for analysis. However, this method often contains geometric inaccuracies and requires user intervention. To overcome these limitations, several analytical modeling tools are directly used to create and analyze analytical models. These tools support the creation of structural systems, complete models of small and medium-sized bridge structures, flexibility in creating bridges with unusual geometry and complex structural systems, parameterization of model geometry, and detection of collisions and geometric inaccuracies.

This research uses analytical modeling tools for the damage assessment and design of monitoring systems of bridges. For this purpose, two case studies are included in this dissertation. In the first case study, a damaged RC bridge situated over a waterbed in Hungary is considered. The analytical methods are used to analyze the existing condition of the bridge and based on the analysis results the SHM system is proposed for the monitoring of the bridge. The proposed SHM system is shown in **Fig. 4**.

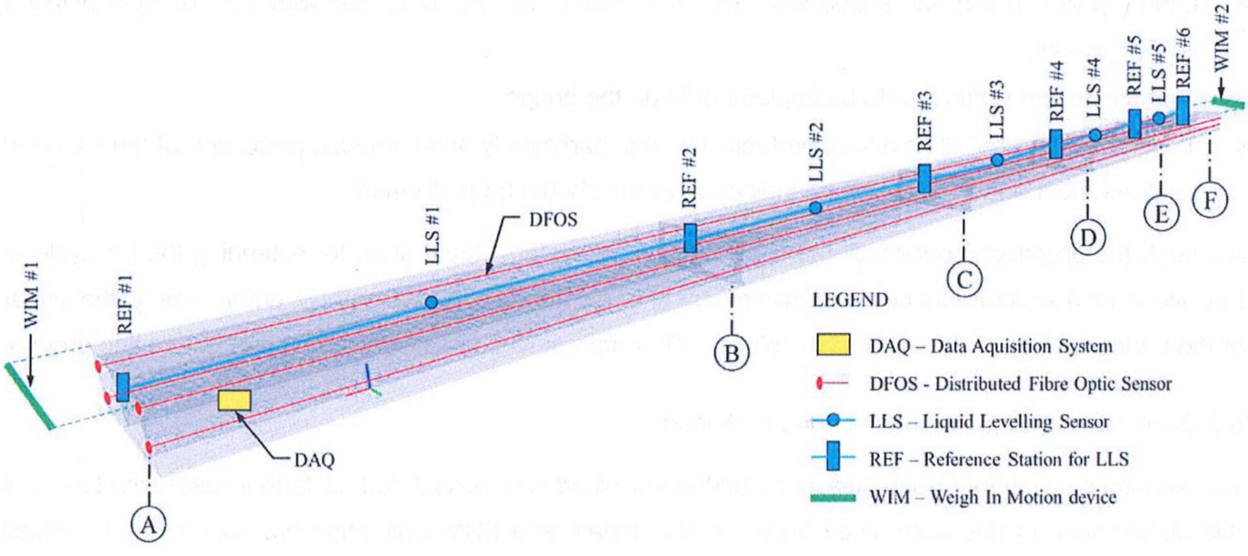

Fig. 4. Location of the essential elements of the SHM system

The findings of this case study can be concluded with the comparison of results extracted from three different types of analysis methods and their recommendations for the development of an SHM system that can be installed on RC bridges having a similar situation as considered in this case study. Analysis results yield the following observations:

- Out of limit crack width, calculated as 0.4 mm in case of in-situ investigations, 1.5 mm in case of static analysis, and 0.6 mm in case of non-linear analysis, exceeds the EC limits (0.3 mm).
- High values of temperature and humidity variations cause cracking and weathering of concrete.
- Extensive corrosion of steel bars was observed which is due to the small concrete cover.
- Bridge deflection is observed in the safe zone as it is calculated to be 6 mm in case of static analysis and 20 mm in case of non-linear analysis, so both values are below the EC limits (69 mm) bridge.
- The bending and shear capacity of the bridge in the Ultimate Limit State and stresses in the Serviceability Limit State satisfy the criteria as per the guidelines of EC.

The above results are more refined in 3D non-linear analysis and have closer values to the in-situ investigation. Hence, a 3D non-linear analysis is highly recommended for the damage assessment and evaluation of bridges. Further, to monitor associated damage and to ensure safer operations of the bridge, a SHM system is proposed in this study. This system includes the installation of a Liquid Levelling Sensor (LLS) for the measurement of vertical displacement, Distributed Fiber Optic Sensors (DFOS) for deformation monitoring, and Weigh in Motion devices for monitoring moving loads on bridges. Installation of this system is subject to the following measures.

- The system will be in operation for 15 years and will alert the authorities when a sudden drop in the load-bearing capacity is observed.
- Load (up to 300 kN) and speed limits (up to 30 km/h) are recommended with monitoring of passing vehicle weight.
- One directional traffic flow to be implemented on the bridge.
- Together with the SHM system, protective works, particularly anti-corrosion protection of the exposed reinforcement and injection of the indicated cracks should be performed.

Although the proposed concept of the SHM monitoring system would allow for extending the life cycle of this overloaded structure (of course, while ensuring an appropriate level of safety), unfortunately, the owner of the bridge did not decide on such a solution. Therefore, it was necessary to find another testing ground.

5.2 Case study of an extradosed bridge in Poland

The second case study of an extradosed bridge in Poland was considered for further research phases of this dissertation. In this case study bridge model update and SHM calibration are done using field load testing. Once the analytical model is created and the associated SHM system is proposed and installed on the bridge, there arises a need for the verification of the generated analytical models and the calibration of the installed SHM system. For this purpose, this research uses the bridge load testing technique to fulfill said purposes at once. This case study is used to show the FEM model of the bridge together with the SHM system and the load test as a process that can be used to update the model, i.e. the birth of the digital twin.

In this case study the Static and Dynamic load testing methods were used. The static load testing helped in the validation of the FE model by comparing the results of the field test with the numerical output, especially displacements. These results were further compared against the code limits and measured values of load tests which satisfy the FE analysis results. Further, the consistency of the stiffness values was also checked, which was also in the range of FE modeling results. Additionally, a comparison of permanent and total deflection was checked against the standard condition which was found to not exceed the level of 10% [19], thus validating the FE model. In this way, load-testing results validate the developed FE model and show that there is no need for the FE model updating.

Similarly dynamic load testing helped in the validation of the existing SHM system installed on the bridge, by stating that the dynamic parameters of the SHM system suffice the needs of the existing SHM system whereas there is a lack of the number of sensors, and measurement location for dynamic parameters, therefore existing SHM require more of such devices for reliable monitoring of dynamic parameters.

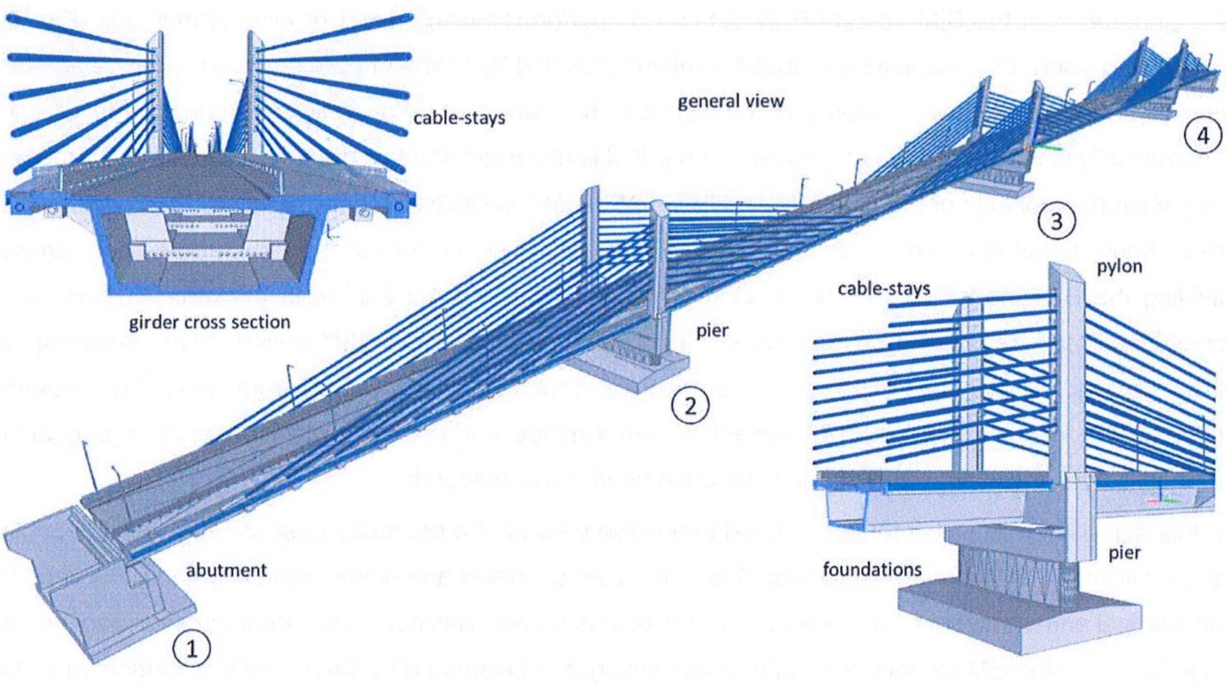

Fig. 5. BIM model of the extradosed bridge in Kurow

The BIM model of the bridge was developed using Autodesk Revit software (Fig. 5). Where all the geometric details were collected from the CAD files of the bridge archival. The 3D geometry of the bridge was developed by incorporating alignment, profile, and cross-section details as shown in Fig. 5. All the structural elements, including pylons, extradosed cables, deck, piers, RC box girder, and abutments, were modeled using the details of the analytical model shown in Fig. 5, and all the materials properties were assigned as per the archives. As the bridge model was quite complex the electrical and plumbing system was not modeled because this way the model could be very heavy which could cross the limits of the number of elements in the MR tools. With all the mentioned geometric details the BIM model was developed (as shown in **Fig. 5**) and exported to the relevant tools for further processing.

This model provides a base for the novel solution proposed in this research. These solutions helped to generate an accurate parametric FE model, as well as suggested efficient visualization of real-time sensor data. Visualization of SHM data is very handy for bridge inspectors as they can use the suggested application during bridge inspection and see the real-time condition of the bridge by interpreting the information provided by sensors regarding the bridge's health. The integration between BIM and FE models ensures a coherent database with the ability to generate and update structural models in an automatic or semi-automatic way.

After the development of BIM model, it is further used to automate the analytical modeling process and to develop the FE models directly from the BIM model. To achieve this goal, the BIM model of the bridge is used as a source file to develop the automated BIM-based FE model, which documents the first new scientific result of this dissertation.

The generation of the BIM-based FE model can be performed using direct or indirect methods (**Fig. 6**). Direct integration (**Fig. 6a**) involves closed solutions provided by BIM and FEM software. Linear elements, including beams, columns, pylons, or cables, can be translated into analytical counterparts created automatically in the structural analysis environment. It is observed that this method generates valid models only when the topology of both the BIM and the FEM models is similar in terms of the number of elements, their shape, orientation, and relations. Moreover, the direct generation of the structural model requires dividing the BIM model into pieces, including elements that are not explicit in the real structure, e.g., longitudinal, and transversal beams. Introducing such a topology in the BIM environment, especially for structural analysis purposes, is not a valid approach, as it requires additional, separate, and virtual elements to the BIM model that can disturb its semantics, performance, and usability in other aspects, e.g., quantity take-offs. Therefore, indirect methods have been used in this research.

In this approach, the VPL interface is used to retrieve data on the geometry of spans, pylons, and cables directly from the BIM model and convert them into a set of curves and points, including additional lines for longitudinal and transverse components of the structural model. This geometric representation can then be used to generate FEM models using additional packages in Dynamo (**Fig. 6b**) or textural formats readable by structural analysis software (**Fig. 6c**). Using a visual script, a file is generated that contains the coordinates of all the nodes. This file is written in the syntax of the CADINP language used in FE software.

The novel Dynamo script outputs a generic list of node coordinates, allowing for universal data exchange between BIM and FEM environments. Visual programming enables parametric model creation through an open, adjustable code. Direct methods are limited due to software maturity and inconsistencies in BIM model topology. In bridge FE models, direct methods may give incorrect output due to irregularity and complexity. Therefore, open indirect solutions are recommended, which can be extended or modified for specific FEA software. This approach saves time, makes it easy to update the FE model based on load testing results, and maintains openness and transparency of source code. This approach can be the basis for BIM-based bridge FEA and may help designers carry out FEA in the future.

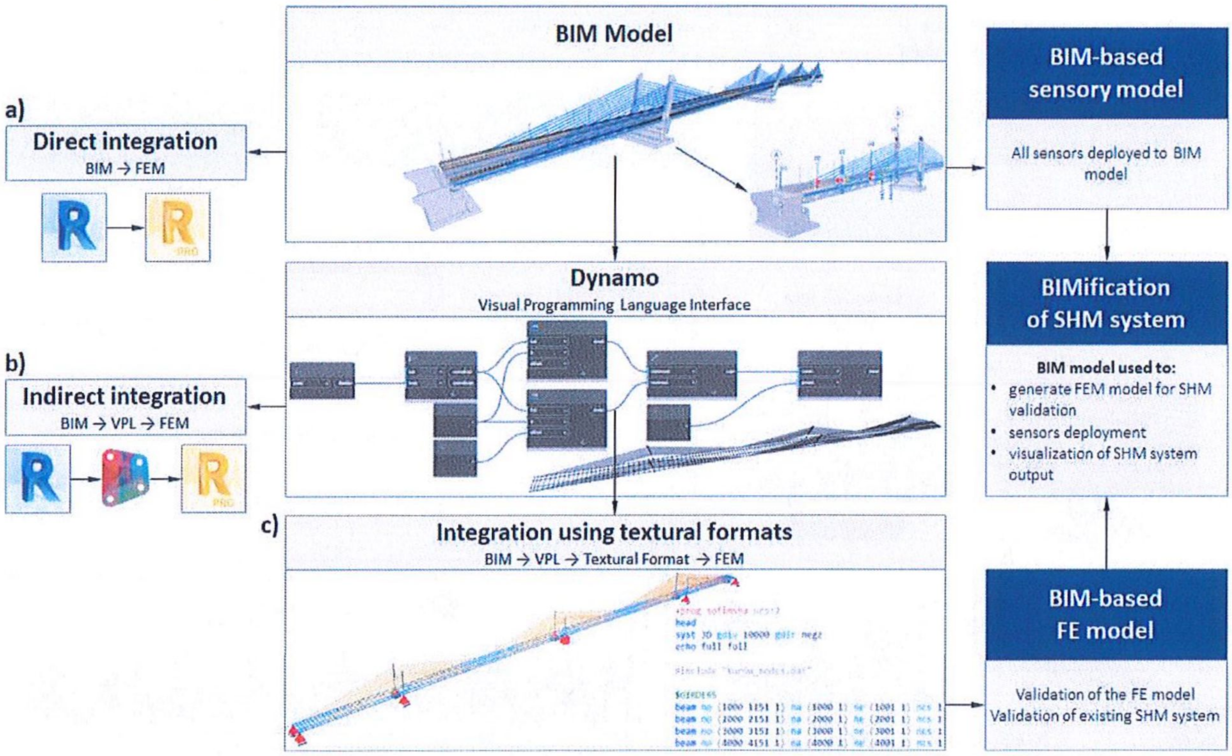

Fig. 6. Methods of the generation of the FEM models based on the BIM model

Considering the importance of IoT-enhanced SHM systems, this research linked the SHM system of the case study with the IoT tools using the BIM platform. To take full advantage of the promising IoT technology, not only the developed IoT platforms are used in this research but a proprietary IoT system has also been developed in this research. This system involved the development of wireless sensors embedded with the free versions of a web platform controlling not only the wireless sensors installed as part of an SHM system but also facilitating real-time data monitoring and management. After the successful development of the wireless sensors and connected IoT-based web platform, the system was tested at a lab scale for the case study of the bridge SHM system. In this study, BIM technology offered a bridging role between the SHM system of the bridge and developed IoT-based wireless sensors. This job is done by developing the virtual sensory model of the bridge SHM system in the BIM model (**Fig. 7**). Here all the sensors developed using the IoT technology are embedded individually where the data monitoring web platform is linked with a click option. In this way, the bridge SHM having the real sensors installed on the bridge is replicated with the virtual replicas of the sensors having real-time communication with the real sensors, whereas clicking each of these virtual sensors opens the web platform where the actual sensors as shown in **Fig. 7** are sending the data in real-time. It ensures seamless remote data visualization, offering various data analyses for continuous monitoring, maintenance, and safety measures, with periodic evaluations and optimizations to enhance system bridge monitoring efficiencies.

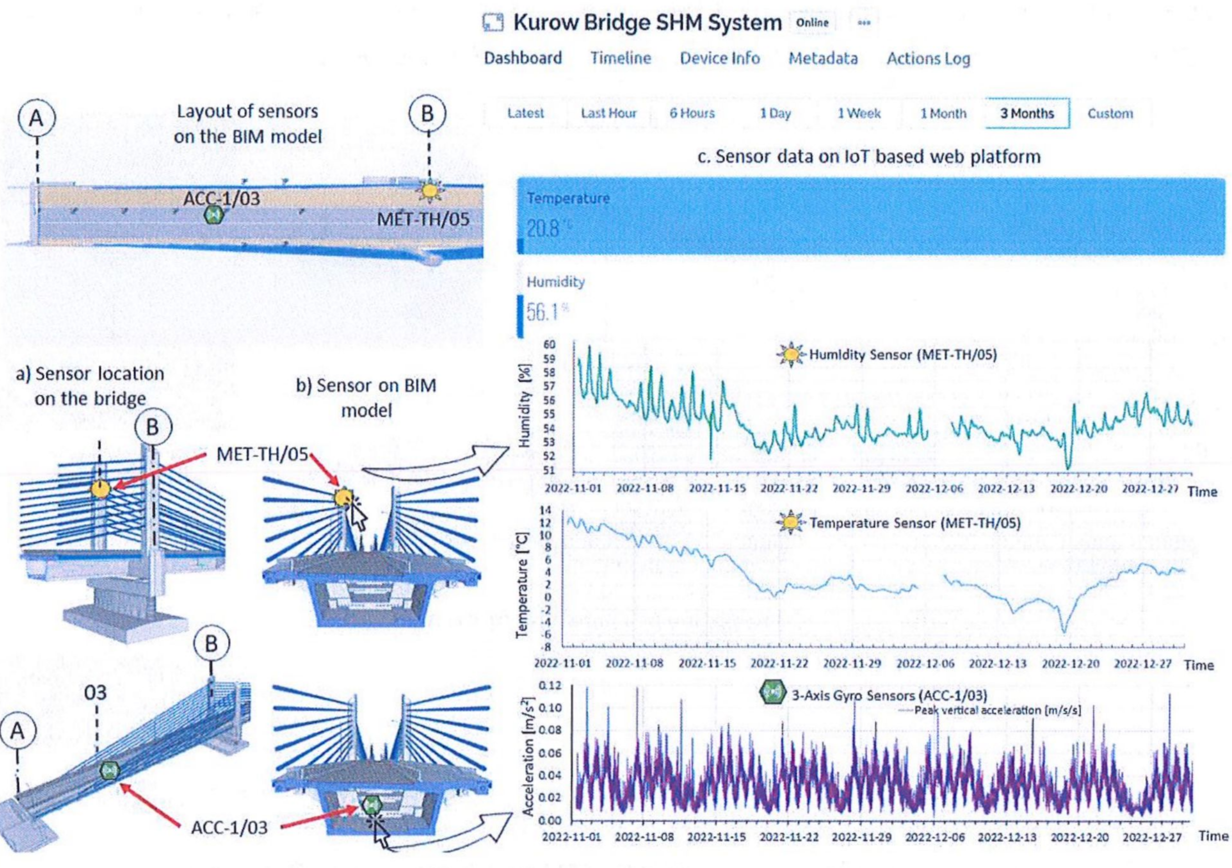

Fig. 7. IoT-based SHM system of a bridge

Further, to effectively utilize the developed IoT-based SHM system it is integrated with MR to develop the immersive SHM system. This MR-enhanced solution increases the potential of a traditional SHM system using the applications of MR. Currently, MR applications in the construction industry are only used for machine control on construction sites, concrete pouring, reinforcement detection, onsite clash detection, and worker's field safety. So far, very limited research is available that tries to implement this technology in bridge monitoring, thus, this section will discuss a novel way of developing an immersive MR-based SHM system.

This immersive SHM system includes developed wireless IoT sensors that integrate real-time sensor data from the installed sensor network and process it through the web platform in real time. The integration of SHM data with MR using MR headsets creates a seamless real-virtual blend. Holographic overlays highlight critical areas and gesture controls enable online data management. This way it helps to manage the technical condition of the bridge with real-time alerts, remote/onsite monitoring, cloud integration, data visualization, system calibration, and maintenance procedures to ensure the system's accuracy, reliability, and functionality while offering an advanced solution for monitoring of bridge health in real-time. To achieve these goals, the VR model of the bridge is created from the BIM model, and the BIM-based sensory model is developed (embedded with the web address of the IoT platform). Clicking the sensor opens the IoT platform where real-time data is continuously monitored and stored. This data can be visualized over a certain period (1 hr., 6 hr., 1 day, 1 week, and 3 months) (**Fig. 8**). Data can also be stored in HL as a .CSV file which can further be transferred to any workstation. This way visualization of SHM data can be performed onsite or remotely and data can be transferred to the project team over the Internet. The schematic layout of this whole process is shown in **Fig. 8**.

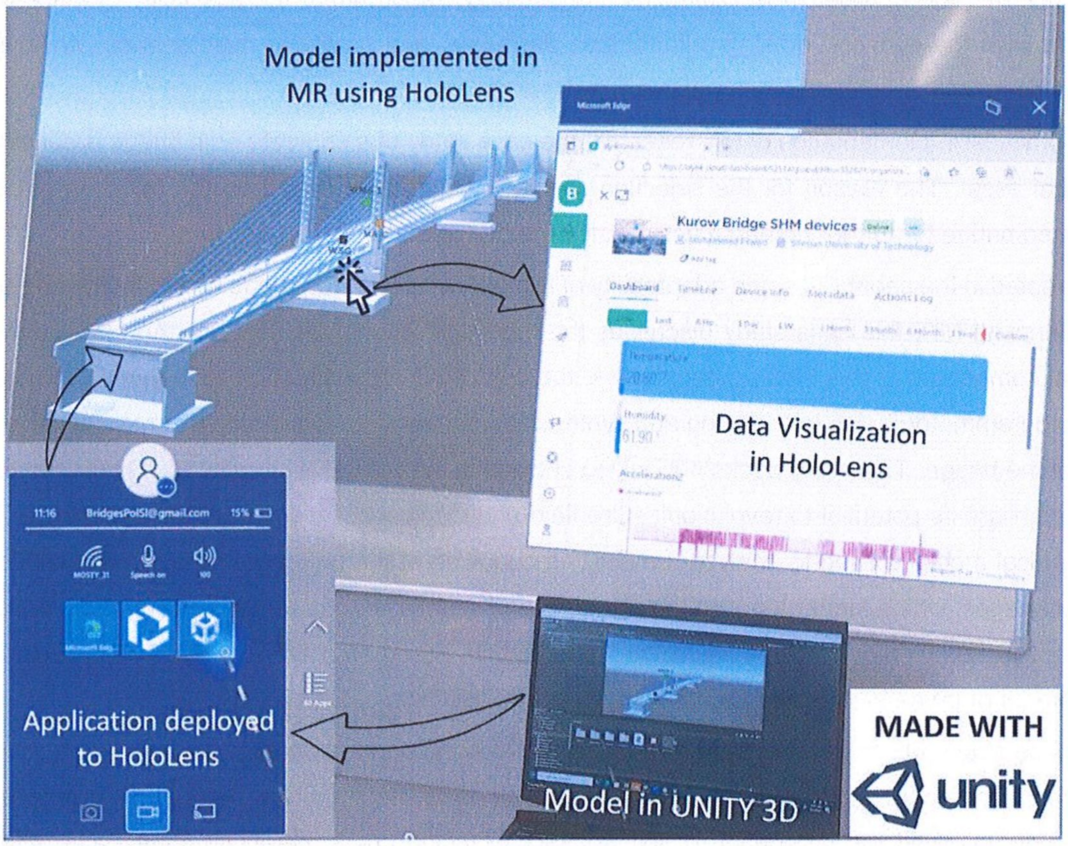

Fig. 8. MR-enhanced bridge SHM and visualization of SHM data in HoloLens

Using such an immersive system helps in the early detection of bridge damages through SHM's identification of anomalies, IoT's sensor network for continuous monitoring, and BIM's data platform for a combination of SHM and IoT data for timely intervention. In this integrated system, comprehensive data integration includes SHM measuring the structural data, IoT collecting diverse data sources, BIM integrating SHM and IoT data, and MR for better visualization of SHM data and bridge damages to provide a holistic view of infrastructure health. Predictive maintenance thus can be performed by such systems in real-time with clear visualization of damages in tabulated and graphical formats. Overall, this integration creates a comprehensive approach, enhancing the safety, reliability, and efficiency of infrastructure while optimizing maintenance efforts and resource utilization for smart infrastructural health monitoring.

6. Development of Immersive Bridge Digital Twin Platform using MR and DT technologies

The major novelty of this PhD research was to develop an immersive automated SHM system. The automation of SHM systems is currently trending in bridge monitoring because of their remote applications but the major aspect of this automation lies in the 3D visualization and on-field assessment of SHM data. For this purpose, Mixed Reality (MR) offers its service. This MR-enhanced solution increases the potential of a traditional SHM system using the applications of MR. The automation part of the immersive SHM system involves the application of Digital Twin technology, which offers the possibility of automatic data collection from the sensors, making autonomous decisions, and proactive maintenance, while aided by real-time data collection from sensors and IoT technology.

For the practical implementation of this research, the case study of a concrete arch bridge is considered as a physical asset. The reason for the selection of this case study is based on the rejection of using the extradosed bridge for further research activities by the bridge authorities.

Deeply rooted in the capabilities and adaptability of Digital Twins (DT) for bridge health monitoring and their integration with MR, this case study discusses the modeling techniques used for the case study. As an essential component of this PhD research work, the use of 3D reconstruction techniques (laser scanning and photogrammetry) helps in capturing and synthesizing spatial data to develop a comprehensive BIM 3D model of the bridge. This study seeks not only to showcase the technical benefits of 3D reconstruction but also to highlight its potential to revolutionize the field of structural assessment and maintenance. Further, the analytical model is used to analyze the existing condition of the bridge along with the identification of bridge damages, which further leads to the proposal and installation of a bridge SHM system, according to which bridge health monitoring is performed and further linked with DT and MR technologies for the development of Immersive Bridge Digital Twin Platform (IBDTP).

In this case study, FE analysis is used to analyze the existing damage state of the bridge which identifies prone zones for monitoring bridge damages [20][8], thus bridge health monitoring system is proposed [21]. This system involved the installation of IoT sensors including crack meter, tilt meter, and optical laser displacement sensors which are used for monitoring longitudinal and vertical displacement, rotation angles of the bridge deck, and monitoring of bridge cracks. An additional gateway sensor is also installed which acts as a data communication network. After the installation of sensors, measured data is compared with the results of FEA to verify the FE model and simulate the results of bridge damage. As buckling of steel hangers is observed as the major problem, FEA is further used to simulate the reason for the buckling, which comes out to be the prestressing of the bridge deck where temperature changes increase or decrease this effect.

Further, this research integrates the proposed SHM system with BIM, IoT, and MR technologies to develop an Immersive Bridge Digital Twin Platform (IBDTP). For the development of the IBDTP, the geometric reality model of bridges based on parametric BIM designs was adopted. For the continuous monitoring of the bridge's health, the SHM system of the bridge was proposed, and sensors according to the proposed system were mounted on the bridge. With the system installed on the bridge, a novel 3D game engine aided by IoT technology was used as part of IBDTP and is deployed using MR hardware to enable an immersive decision-making environment for infrastructure managers and seamless communications between the virtual and real sensors. The developed IBDTP was successfully tested on the real bridge using the MR headset. The successful implementation of the developed IBDTP in the field is shown in **Fig. 9**. Results show that the measurement data collected and presented in IBDTP improves the infrastructure managers' accessibility to major damage data of the bridge to plan for future interventions.

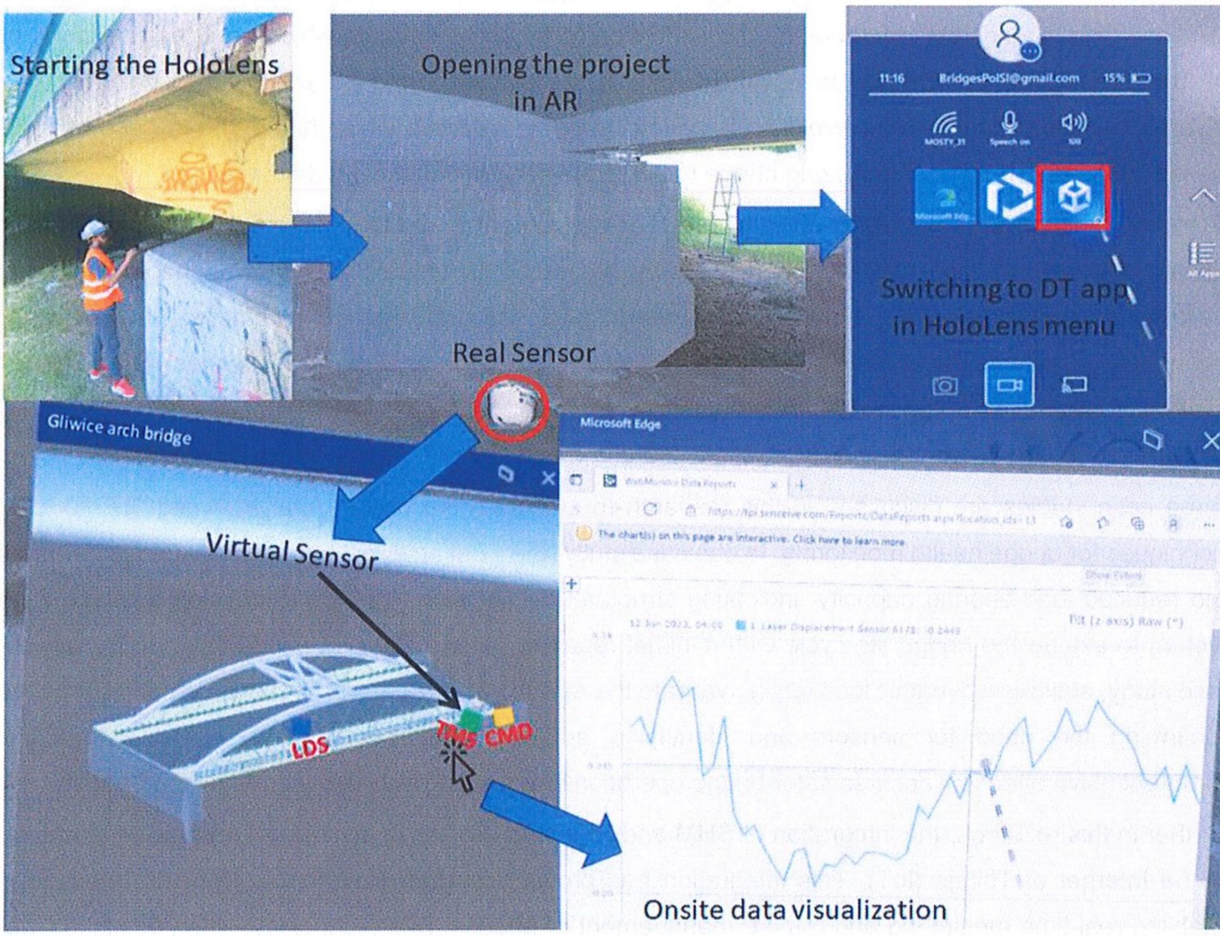

Fig. 9. DT model of bridge SHM system in MIxed Reality as IBDTP

The proposed IBDTP not only pioneers the immersive Digital Twin of the bridge SHM system but also addresses the limitations associated with traditional SHM methods, particularly concerning data management and the visualization of three-dimensional structural data. The developed IBDTP is also documented as the third new scientific result of this dissertation. The IBDTP provides a comprehensive framework as a base to guide future practices of digital twining of infrastructure to enable proactive decision-making of infrastructure managers. Moreover, the functions of the IBDTP can be potentially scaled for different types of bridges and critical infrastructure, substantially improving the traditional SHM in terms of data management and 3D structural visualization.

7. Conclusions

This research has provided a state-of-the-art review of the literature available for Structural Health Monitoring (SHM) of bridges from the design phase to the development of immersive solutions for SHM. The study encompassed the exploration of Bridge Management Systems (BMS) in detail with the details of technological advancement in BMSs over the period. The exploration of the BMSs started with the use of traditional bridge inspection methods for the extraction of bridge health data which were then replaced by the dedicated SHM system due to advancements in the analytical and 3D modeling techniques. This advancement is because of the evolution in bridge modeling methods which has led to the use of Finite Element Modeling (FEM) for analyzing bridge health conditions and detecting damage.

3D modeling techniques majorly involve the use of Building Information Management (BIM) technology that has transformed analytical modeling techniques by integrating 3D models with FEM methods, enhancing full-scale structural damage mapping. This research proposes a BIM-based automated FEM modeling technique, utilizing a Visual Programming Language (VPL) interface to generate curves and points for efficient analysis. The BIM-FEM integrated approach emphasizes the parallel development of 3D modeling and BIM processes, ensuring seamless model exchange and comprehensive structural evaluation.

Three case studies are discussed in this research to elaborate the use of Analytical and 3D modeling techniques for bridge health monitoring. In one case study, the FEM analysis helps identify bridge damages and reduced load-bearing capacity, indicating structural degradation. It helps to develop a bridge SHM system to extend the bridge life cycle with minimal repair costs and reduced failure risks. In the second case study, static and dynamic load testing validate the existing SHM system's accuracy and effectiveness, confirming the need for sensors and identifying additional devices for reliable monitoring. This comprehensive overview ensures safer bridge operations for existing and newly constructed bridges.

Further in this research, the integration of SHM and BIM technologies is discussed using the applications of the Internet of Things (IoT). This integration has proven transformative in bridge health monitoring, enabling real-time monitoring and remote management of bridges. BIM technology, when combined with IoT, ensures an accurate virtual representation of the physical structure, enabling predictive maintenance and safety enhancement. The integrated system provides real-time data visualization, virtual representation of bridge conditions, and predictive maintenance solutions. The research also developed a proprietary IoT system using low-cost wireless sensors and a web platform for real-time data monitoring and management. The system enables early detection of bridge damage and real-time predictive maintenance.

As a major objective of this research, the third case study discusses the basic concepts of using Virtual and Mixed Reality (VR/MR) for the visualization of bridge health monitoring data. This approach pioneered the use of such technologies for the assessment of health. In fact, it revolutionized bridge health monitoring systems by developing an immersive Bridge Digital Twin Platform (IBDTP). It is developed using Unity 3D game engines, where the BIM tools are used for bridge monitoring in an MR environment, enhancing the traditional SHM systems' capabilities. The IBDTP uses Digital Twin technology for automatic data collection and proactive maintenance, thus improving infrastructure management. This smart system overcomes limitations in data management and visualization and facilitates the fusion of virtual and physical assets, which can perform real-time automated SHM of the bridge in the immersive MR environment.