A BIM-BASED APPROACH TO THE MANAGEMENT OF HISTORIC BRIDGES

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ABSTRACT: *Building Information Modelling applied to civil infrastructure has opened up interesting scenarios for integrated management of existing infrastructural works. In the last few years Bridge Management System (BMS) have been increasingly used by infrastructure owners, based on different control systems: from stochastic methods, which make it possible to define a condition ratio (CR) starting from periodic inspections of bridges, to sensors for structural monitoring, which can originate a flow of information exchange between real artifacts and the digital model capable of activating effective reactive or planned responses in the operation and maintenance phase of the asset.*

The paper intends to outline a BIM-oriented process workflow, which from the creation of parametric objects for infrastructural works using Scan-to-BIM acquisition techniques and procedures, arrives at the implementation of information bridge models to manage both static data from scheduled inspections of technicians of defects and their severity according to specific guidelines, and dynamic data from incoming and outgoing sensors placed in the physical asset for real time monitoring towards analysis, supervision and control systems of the facilities owner. The defined process workflow will be applied to some case studies, related to bridges of different characteristics, outlining some directions for future developments. In detail the research showcases the tasks undertaken and the outcomes achieved on four selected bridge case studies, which are real and situated within the geographical area of the Tuscany region, Italy. The studied bridges are all still in use and hold historical significance, as they were constructed between two hundred and one hundred years ago.

KEYWORDS: *Bridge Management System; InfraBIM; HBrIM; Digital Twin, Scan-to-BIM, SHM, IFC.*

1. INTRODUCTION

Generally, users perceive infrastructure projects as safe, and it's uncommon for drivers of regular vehicles to doubt the safety of the bridge they're crossing (Santarsiero et al., 2021). However, factors like extreme environmental conditions, mechanical loads surpassing the design assumptions, extended operational durations, inadequate maintenance, and similar elements can significantly impact and jeopardize the structural integrity of bridges (Saback de Freitas Bello et al., 2022; Santarsiero et al., 2021; Zinno et al., 2022).

After a series of incidents, including the Morandi Bridge collapse (Santarsiero et al., 2021), the Italian Government in 2020 enacted the "Guidelines on risk classification and management, safety assessment, and monitoring of existing bridges" through legislation (Ministerial Decree number 578/2020). The ministerial decree number 204/2022 essentially reaffirmed the aforementioned guidelines, extending their temporal validity to forty-eight months, or until the end of the year 2024. Further complementing the Italian regulatory framework are the "Operational Instructions for the Application of the Guidelines for Risk Classification and Management, Safety Assessment, and Monitoring of Existing Bridges" proposed by ANSFISA and annexed to the ministerial decree number 204/2022.

For the risks that older bridges run and for regulatory issues similar to those described above for the Italian case, in recent years, Bridge Management Systems (BMS) have gained much importance and numerous infrastructure management companies have adopted it. Particularly, those systems based on stochastic methods have gained prominence, allowing the determination of a Condition Ratio (CR) based on regular bridge inspections and on the detection of the defects of the bridges themselves. Bridge Management Systems (BMSs) are modular information systems with designated functions (de Freitas Bello et al., 2021; Woodward et al., 2001), including inventory compilation, preservation assessment, risk evaluation (including load capacity), operational management, cost estimation for maintenance strategies, deterioration prediction and associated costs, socio-economic importance analysis with budget constraints, maintenance priority setting, and multi-temporal budget tracking. BMSs, along with Structural Health Monitoring (SHM) techniques, are employed to assess bridges post-visual inspections by

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specialized technicians.

The majority of current BMSs employ a two-dimensional (2D) approach to record and store information without visual representation and dynamic integration (Li et al., 2023). Building Information Modeling (BIM), which involves creating and managing a comprehensive 3D model embedded with informative data for the entire lifecycle management of a specific asset (Kaewunruen et al., 2022), emerges as the most natural source of information and data storage for next-generation BMSs.

In the field of the SHM it is now common practice to place sensors on the bridges that it is believed to have to check or monitor for what has emerged from inspections on the same. The type of sensors that can be installed varies according to the phenomenon to be monitored but also with respect to its purpose: it is possible to install different sensors for short, medium or long-term monitoring or to install sensors capable of sending an alarm when a certain threshold value is reached. Enhancing finite element method (FEM) analyses with continuous sensor data can bolster the reliability of studying degradation. Artificial Intelligence (AI), especially Machine Learning (ML), offers transformative potential for Structural Health Monitoring (SHM). ML techniques automate pattern recognition in sensor data, aiding defect detection and risk assessment (Malekloo et al., 2022; Zinno et al., 2022).

Considering AI as a predictive technology that utilizes data and "experience" to formulate forecasts, which in turn serve as inputs for the decision-making process, it can be asserted that the initial solutions conceived and applied to date across various fields, including Structural Health Monitoring (SHM), have been “Point Solution” where AI has replaced previous predictive tools (Agrawal et al., 2018, 2022). However, it is reasonable to anticipate a substantial paradigm shift in the medium term within this sector, as well as others. Stemming from the concept of reducing the cost associated with forecasting, a principal economic facet introduced by contemporary Machine Learning (ML) algorithms, a complete reorganization of SHM is foreseeable. Referring to this form of AI-based solution as a “System Solution” is appropriate.

The Italian Guidelines also envision the utilization of digital technologies for their "intelligent" administration, achieved by integrating sensors into SHM systems and constructing informative models of structures. This is regarded as a step towards the realization of the National Digital Archive of Public Works (AINOP).

A digital model integrating geometric and performance data aids SHM and aligns with the "Digital Twin" concept of Smart Manufacturing and infrastructure research. In the AECO sector, the Digital Twin concept is tied to Building Information Modelling (BIM). In the realm of bridges, the term "BIM" is often replaced with: InfraBIM (Osello, 2019), BrIM (Barazzetti et al., 2016; Saback et al., 2022), HBIM (Barazzetti et al., 2016; Borin & Cavazzini, 2019; León-Robles et al., 2019; Murphy et al., 2011; Stavroulaki et al., 2016), HBrIM (León-Robles et al., 2019).

In the field of built heritage, surveying plays a crucial role in comprehending structures. Contemporary techniques such as laser scanning(Boardman et al., 2018; León-Robles et al., 2019; Pritchard et al., 2017) and photogrammetry (Ioli et al., 2022; Jáuregui et al., 2006; Mohammadi et al., 2021) are widely employed, utilizing both ground-based tools and UAV systems. These methods generate datasets in the form of point clouds (PC), which then require further processing to create Building Information Models (BIM). Known as Scan-to-BIM, this process is well-documented in the literature(Croce et al., 2023; Roggeri et al., 2022; Sing et al., 2022; Wang et al., 2019).

The surveys and consequently the point clouds can serve at different stages in the useful life of a bridge:

- They can form the database foundation to create a BIM model if it doesn't already exist.
- They can be work an AS IS representation of the structure.
- In the capacity of AS IS, they can be used for comparisons with a BIM model representing a situation prior to the survey.

When a Building Information Model (BIM) of an existing bridge is being developed, several factors come into play that strongly affect the modeling process. These factors include the bridge's characteristics, how easy it is to access the bridge for data collection, and the availability of detailed design plans or information about the bridge's original construction and its current state. All of these elements have a significant impact on how the BIM model of the bridge is created and how accurate and comprehensive it can be. The process of creating a Building Information Model (BIM) from scanned data is easier for bridges with massive components like masonry structures. On the other hand, this process is more complex for bridges made of metal trusses. The complexity arises because metal truss bridges consist of many intricate elements with edges and corners that are difficult to accurately capture using laser scanning and photogrammetry techniques. It's easier to model massive bridges using scan-to-BIM methods compared to complex metal truss bridges due to the challenges of capturing detailed data.

With the widespread adoption of BIM as a methodology for building modeling, the IFC data schema, Industry Foundation Classes, has gained importance. Leveraging the principles inherent in Object-Oriented Programming (OOP), IFC presents a novel shared language across the entire Architecture, Engineering, Construction, and Operations (AECO) sector. IFC is not a replacement for the language of technician draw nor an evolution thereof; rather, it serves as a schema enabling the transmission of comprehensive information about a construction. This logically structured data extends far beyond mere geometric representation. As described above, IFC has become an essential component of knowledge incorporated into all leading university programs within the sector. With the upcoming version of IFC, the schema will expand into the domain of infrastructure, which until now has been only partially representable or represented using non-conventional methods.

The topics addressed by this research are relevant to Cluster 3 of the Horizon Europe 2021-2027 program and also dealt with in the 2021-2027 National Research Plan (PNR), in line with the objectives of Goals 9 and 11 of the 2030 Agenda of United Nations Organization.

2. MATERIALS AND METHODS

In recent years, the intersection of engineering, digital technology, and heritage preservation has paved the way for innovative approaches in the study of historic structures. This research article presents a comprehensive examination of the digital documentation and structural monitoring of four distinct historic bridges. By employing Building Information Modeling (BIM) techniques, each bridge was meticulously captured in a virtual environment, enabling a detailed analysis of its architectural and structural features. Furthermore, this study explores diverse strategies for the digital representation of these historic constructions and the implementation of structural monitoring solutions.

The preservation of historic bridges holds significant cultural, historical, and engineering value. Through the integration of BIM methodologies, these bridges can be accurately documented and analyzed, facilitating the development of effective strategies for their maintenance and conservation. The four selected case studies serve as tangible examples of this interdisciplinary approach, shedding light on the challenges and opportunities that arise when dealing with the intricate balance between preserving heritage and ensuring structural integrity. By examining the challenges and successes encountered in the digital documentation and structural monitoring of historic bridges, this study aims to inform best practices and inspire further advancements in the field.

Fig. 1, 2: Masonry bridge over Masera Ditch | Laser scanner survey.

2.1 Case Study 1: Masonry Bridge over the Masera Ditch

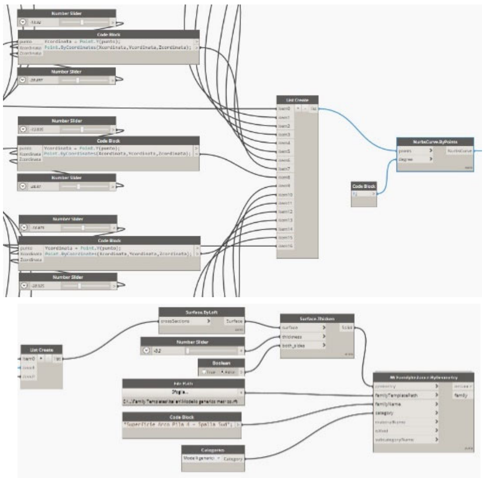
The masonry bridge over the Masera Ditch is situated in the Crespino over Lamone-Biforco section of the railway line connecting Borgo San Lorenzo to Faenza. The “Faentina” Railway is a state-owned railway line that connects Florence to Faenza via Borgo San Lorenzo (fig. 1). Its construction took place between 1880 and 1893, with the idea originating as far back as the 1840s. This railway was closed for an extended period due to significant damage sustained during World War II. Traffic resumed partially in the 1950s, but the line experienced another closure in 1971. The gradual reopening began in the 1990s and was completed in the early 2000s. Essentially, it’s a sparsely utilized line, hence its lack of electrification and the presence of a single track.

The bridge over the Masera Ditch is a masonry structure with five arches, situated on a curved path. At its highest point, the structure stands 40 meters above the ground. Adjacent to the bridge, both upstream and downstream, are two galleries manually excavated from the rock.

2.1.1 Documentary research and survey campaign

No original bridge designs have been found, nor have any other technical drawings of any kind been located. Near the bridge, there is an access point to regular road traffic, and it's also possible to ascend the mountain to reach little clearings at the bridge's height, away from the rail track. Given the scenario described in the preceding paragraph, a significant portion of the survey was conducted without the presence of surveillance personnel. However, this did involve a temporary suspension of railway traffic.

The survey campaign was conducted using a Z+F IMAGER 5016 Laser Scanner, which also captured RGB data (fig. 2). Additionally, photographic documentation was captured using a Sony H300 Camera with 35x optical zoom. The point cloud datasets were captured in .fls format and subsequently imported into Autodesk Recap® software.



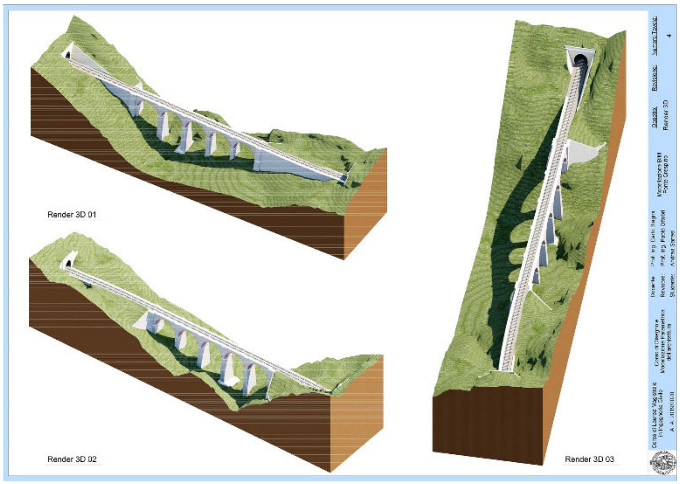


Fig. 3, 4: VPL script for arches modelling | Views of the BrIM model

2.1.2 BIM Modeling and Implementations

Given the absence of technical drawings for the bridge, in the case study of the Masonry Bridge over the Masera Ditch, a BIM modeling was carried out using a conventional Scan-to-BIM workflow.

The initial step taken towards modeling the viaduct involved refining the provided point cloud data. This was achieved by removing portions of the surrounding vegetation and segmenting the point cloud into three parts, aimed at reducing the file size to expedite the modeling process. Subsequently, these three segments of the point cloud were integrated into Revit to initiate the modeling process. The bridge has been decomposed into its constituent elements based on the methodologies employed by the management company of the Italian railway line, similarly to what was done for the case study of the metal girder on the Osa river. The three segments of the point cloud were successively integrated into the Revit environment, and reference grids were generated from them. These grids were then utilized to position individual components in subsequent stages.

Chronologically, the first elements that were modeled are the viaduct piers. For the BIM component describing the piers, the parameters that have been made parametric include the height, dimensions of the upper rectangular base, and the various inclinations characterizing the short and long sides of the pyramid. Based on these dimensions, the dimensions of the lower rectangular base were then defined. Furthermore, the material with which the piers were constructed has been made parametric and based on observations of images and the point cloud, masonry was chosen as the material. The arch surface was generated using the Dynamo platform, as the represented form exhibits a complex double curvature that is challenging to model otherwise (fig. 3). Initially, commands were implemented in Revit to select the edges on which the arch relies. Subsequently, median points of the segments were placed to create a central line. Alongside two other lines positioned at the ends of the selected segments, these components facilitated the creation of the arch surface.

The subsequent step involved establishing control points on the previously generated lines. Each control point was defined with its respective height relative to the arch springing level and the setback. Following this, a curve was constructed. Finally, after executing these procedures for the three segments that define the curve, the surface was generated and assigned a thickness. Ultimately, the thus-formed geometry was incorporated into the Revit project. The abutment and backfill were modeled using the "Generic Models" category. Both components were initially modeled as solid forms, and subsequently, the shape of the arch was subtracted using an empty arch model. For these elements, in addition to the parameters defining their shapes, a material attribution parameter was introduced. For the abutment, the material is masonry, while for the backfill, it is railway crushed stone (fig. 4).

2.2 Case Study 2: Giorgini Bridge over the Bruna River

The presented case study revolves around the "Giorgini Bridge" in Castiglione della Pescaia (Grosseto, Tuscany Italy), build from 1827 to 1828 as part of the Maremma reclamation works (fig. 5). Designed by mathematician and civil engineer Gaetano Giorgini, the bridge was constructed across the Bruna River. The bridge featured three floodgates, aimed at preventing the intermingling of Bruna River's freshwater with the saline seawater. The construction, initiated in 1827, aimed to address the belief that this mingling caused malaria, belief of the time which later proved to be scientifically unfounded. The bridge, 26 meters wide and 12 meters high, is composed of lateral shoulders, lowered round arches, and pylons. Positioned between these pylons were three floodgates enclosed in oak and framed with metal. These floodgates rotated on iron pins, closing manually or automatically via high-tide currents, preventing seawater intrusion into the marsh. During low tide, the force of the lake water facilitated the opening of the floodgates, discharging water into the sea.

Fig. 5, 6, 7: View of Giorgini Bridge | Digital photogrammetry from drone | Views of the BrIM model

2.2.1 Documentary research and survey campaign

The investigation involved multiple methodologies: a laser scanner was utilized for acquiring geometric data, and a drone facilitated a photogrammetric survey. This was further supplemented by a topography network (polygon) for survey phases. The approach encompassed a sequence of steps, starting with a total station and GPS survey, followed by drone-based photosets creation, and concluding with the generation of a point cloud through a laser scanner.

The instruments employed in the survey campaign are: a SOKKIA SET3 130-R3 total station, a TOPCON GR-3 GPS receiver, optical prisms, a DJI 3 Phantom UAV, and a FARO FOCUS CAM2 laser scanner. The drone flight was organized using the Altizure® application, enabling the definition of the GPS-coordinated flight path. Subsequently, the photographic dataset was post-processed with Agisoft PhotoScan® software to generate a point cloud. Meanwhile, the laser scanning dataset underwent processing using Autodesk Recap® software (fig. 6).

The comparison in terms of “deviation of the cloud of points”, to evaluate the difference between the two clouds generated using different data acquisition technologies, was performed with Cloud Compare open-source software. The original design drawings were retrieved, and their accuracy was subsequently verified during the BIM modeling process. This validation was achieved by comparing them with the point clouds obtained from the previously described survey campaign.

2.2.2 BIM Modeling and Implementations

To develop the H-BIM model representing this unique historical infrastructure, a semantic deconstruction was required. This involved defining individual BIM components ranging from primary structural elements to intricate detailing components (fig. 7).

Both point clouds were imported into the chosen BIM modeling software, Autodesk Revit®. By concurrently utilizing the point clouds and the original design drawings, each component of the structure was meticulously modeled one by one. The metal components of the bridge were primarily modeled using the original design plans, whereas the masonry components were predominantly elaborated based on the point clouds.

2.3 Case Study 3: Metal Truss Bridge over the Osa River

The subsequent case study pertains to a dual-track metal truss railroad bridge that dates back to the early 1900s. This bridge remains operational, spanning the Osa River in Italy as part of the Albinia-Talamone railway section on the Rome-Grosseto line, which is managed by RFI (Rete Ferroviaria Italiana), an Italian railway company (fig. 8). The metal bridge boasts a 42-meter span and features abutments constructed using a composite material of masonry and concrete. Notably, a diverse array of components deviating from standard commercial metal profiles can be observed. These elements consist of a combination of "plate" profiles, each implemented with distinct configurations, and they incorporate supplementary reinforcement plates in the areas subjected to the highest stress levels. The connections between disparate components were forged using plates and secured with hot-riveted nails.

Fig. 8, 9: View of metal bridge over OSA River | Perspective view of the BriIM model

2.3.1 Documentary research and survey campaign

The original design documentation for the metal bridge has been retrieved, comprising seven technical drawings. Additionally, there are documents pertaining to the materials used in the bridge, the conducted load tests, and other activities related to the construction phases. The survey campaign was executed utilizing the Faro® Focus 3D x 330 Laser Scanner. The survey operations were meticulously scheduled to coincide with intervals when train traffic was absent. At the time of the survey, the riverbed exhibited cleanliness and optimal condition. The point cloud datasets were captured in .fls format and subsequently imported into Autodesk Recap® software. This software facilitated the alignment procedures for the distinct scans acquired during the campaign.

2.3.2 BIM Modeling and Implementations

The bridge has been conceptually broken down into constituent elements following the procedures utilized by the management company of the Italian railway line. Given the presence of detailed original designs, the BIM modeling of the various bridge components was based on these drawings. The point cloud obtained as a result of the survey campaign was used as an "AS IS" comparison for the modeled components. The comparison was possible with the Cloud Compare open-source software (fig. 9).

The chosen modeling workflow was partly influenced by the availability of the original technical drawings and partly dictated by the complexity of the metal truss. This truss comprises a high number of components that include edges, vertices, perforated elements, and other geometric intricacies, making its survey using a Laser Scanner challenging and difficult, along with the subsequent generation of a point cloud representation. The software used for BIM modeling was Autodesk Revit®. Given the uniqueness of the bridge components, a family was created for each type of element, and a report was produced for each of them.

The concept underlying the breakdown into "elements" logic, as provided by the Italian railway company, aligns with the D.O.M.U.S. Software. This software aids maintenance engineers in the railway infrastructure sector in evaluating the condition and preservation status of bridges. A dedicated master dataset is employed for cataloging both the structures and their identifiable defects. These defects are linked to corresponding indices, facilitating the algorithm in forming assessments.

During the inspection visit, engineers identify and photograph each defect present on the bridge, utilizing official catalogs and documenting the specific bridge component affected by each defect. Based on the previously mentioned data encompassing the geometric configuration of the bridges and inspection outcomes, the algorithm computes some indices. These indices are associated with a particular level of defectiveness, aligning with the established protocol for inspecting railway structures. Through assigning level of defectiveness, the bridges, infrastructure management gains the ability to ascertain priority interventions and make well-informed choices concerning measures for mitigating risks.

The operationalization of the management software functionalities was achieved through a synthesis of Python code scripts utilized within the visual programming environment (VPL) Dynamo. These scripts were integrated with Excel spreadsheets and an Access database, encompassing various tables and numerous queries, the latter of which were scripted directly in SQL language. The Dynamo-developed algorithm is composed by several interconnected node clusters in groups, each of them serving distinct functions. These functions include querying the BIM model for crucial input, exporting datasets to Excel, enabling automated interactions between Excel and Access, reading and importing externally processed data, and ultimately recording achieved results – or macro-outputs – within pertinent fields in BIM environment (fig. 10).

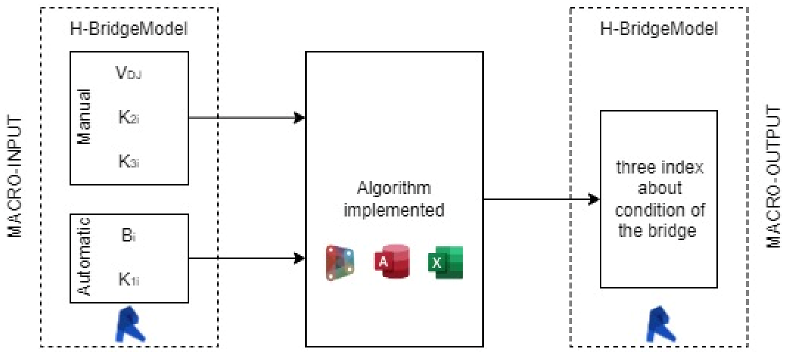


Fig. 10: Data flow. From macro-inputs to macro-outputs

The implemented management functionalities within the BIM environment enable railway engineers to record bridge defects directly in the BIM environment, execute the Dynamo algorithm, and access the calculated indices in the same software. Finally, an IFC model of the metal truss over the Osa River was generated in accordance with the IFC4 standard. In this model, bridge components were categorized as follows:

- all beam-like components have been converted into IfcBeam instances;
- flat metal profiles have been translated into IfcPlate instances;
- bolts have been categorized as IfcMechanicalFastener instances;

- masonry abutments are classified as IfcBuildingElementProxy instances;
- supports have been transformed into IfcBuildingElementProxy iinstances.

With the upcoming release of IFC 5 and its corresponding implementation by commercial software, it will be possible to more accurately map the elements of an infrastructure.

2.4 Case Study 4: Toppoli Bridge over the Arno River

The presented case study pertains to the Toppoli Bridge located over the Arno River near Bibbiena in the Province of Arezzo (Tuscany, Italy) (fig. 11, 12). This bridge, originating from the early 1900s, was constructed using traditional building techniques. The structure comprises a substantial masonry construction featuring a dual arched span. Each arch possesses dimensions of 19.60 meters in length, 3.00 meters in height, and 5.00 meters in width. The piers and abutments are constructed using square stone masonry, while the arches are composed of brick masonry. In the approximate timeframe of the 1960s, a noteworthy event involves the expansion of the road deck. This expansion entails a reinforced concrete slab measuring around 7.50 meters in width and 0.25 meters in thickness. This slab extends out as a cantilever from beneath the masonry arches.

Fig. 11, 12: Views of Toppoli Bridge over the Arno River

The bridge was part of a 2019 experiment in multilevel methodology, conducted through a collaboration between the Tuscany Region Administration and the Regional Federation of the Orders of Engineers of Tuscany. This initiative aimed to analyze and inspect priority bridges efficiently. The experience prompted the authors to develop an innovative BIM-centered approach for bridge risk management and monitoring.

2.4.1 Documentary research and survey campaign

No archival records of Toppoli Bridge original design have been discovered. The acquisition of geospatial data was achieved through a laser scanner survey, facilitating the creation of point clouds compatible with the chosen BIM authoring software, Autodesk Revit®. Prior to importing, the point clouds underwent necessary adjustments within Autodesk ReCap® software. This included aligning the scans into a unified model and reducing the point count to eliminate redundancies and the noise. The point cloud was then stored in .rcp format for seamless integration into Autodesk Revit® software.

2.4.2 BIM Modeling and Implementations

The preliminary BIM model was established utilizing system families, followed by the development of customized loadable families to represent specific components. Throughout this process, the aim was to adhere to the classification structure outlined in the CNR classification of masonry bridges. To model individual components, the point cloud was segmented, component by component, using the open-source software Cloud Compare. Each point cloud segment was then employed for BIM-based modeling of the corresponding component, either directly or by extracting sections in .dxf format (fig. 13).

Utilizing the DB-Link plug-in, model information from the Toppoli Bridge BIModel was exported and integrated into Microsoft Access software. This facilitated real-time updates reflecting any alterations made to the model. Any changes made in either Revit or Access were synchronized seamlessly between the two. Moreover, modifications to the database could be propagated back to the BIM model in Revit.

A BIM-centric system was established to manage sensor data, with a focus on accelerometers. In the case study, a WIT-type accelerometer sensor capable of capturing angle, acceleration, angular velocity, and magnetic field along the 3 XYZ axes was employed. The acceleration measurements exhibit an error rate of approximately 1%, with a capacity to record accelerations up to 16g. Extracted data can be exported in .txt format and imported into spreadsheets for generating graphs that depict accelerations along the three axes (fig. 14).

Building on the earlier described implementation process, the default information model in Autodesk Forge® software was substituted with the Toppoli Bridge HBrIM model, functioning locally. This model integration includes all essential tools for querying and editing the model. Additionally, it offers a comprehensive view of both the overall model and individual elements. Reference “sprites” are created within the model, i.e. icons that simulate the position of the sensor in the artefact. The setting then of a “sprite” within the model allowed the visualization of data obtained from the sensor directly on the screen. Notably, the study's scope primarily concentrated on optimizing the workflow process and did not delve into the technical and operational management of sensors installed on the bridge.

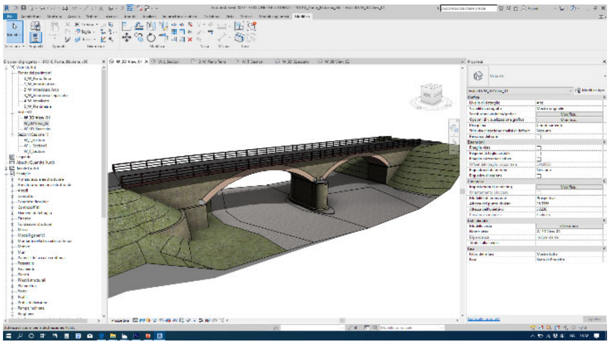
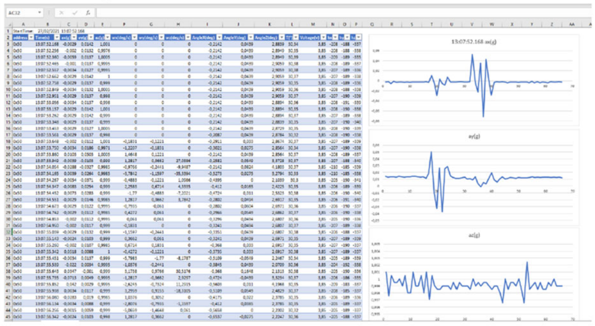



Fig. 13, 14: View of BrIM model | Representation of data by sensor device in a data sheet.

3. RESULTS AND DISCUSSION

3.1 Results

The results of the topographic survey campaigns and experiments conducted for each distinct case study are presented below.

1) Masonry Bridge over the Masera Ditch - The laser scanner survey campaign yielded excellent results, partly owing to the bridge's composition of easily distinguishable massive elements. RGB data was acquired. The workflow in this case was forced given the absence of technical documents. Using the Dynamo platform, a dedicated tool was developed to model elements characterized by double curvature, in this specific case the arches of the bridge. The tool described above produced the desired results and can be reused in similar situations, which are often encountered in the study of the heritage of Italian historic bridges.

2) Giorgini Bridge over Bruna River - The point cloud generated by the laser scanner comprise a total of 19 million points, while the one generated by UAV photogrammetry reached the size of 14 million points. The comparison in terms of standard deviation between the two point clouds, conducted using Cloud Compare, yielded optimal results.

3) Metal Truss Bridge over the Osa River - The survey campaign on the metal truss proved to be challenging due to its complexity. Given its numerous components and the sharp angles that define them, acquiring the bridge's geometry using laser scanners is hindered by the inevitable presence of “shadowed areas” in the acquired dataset. The chosen modeling workflow was partly influenced by the availability of the original technical drawings and partly dictated by the complexity of the metal truss described above.
The implemented management functionalities within the BIM environment enable railway engineers to record bridge defects directly in the BIM environment, execute the Dynamo algorithm, and access the calculated indices in the same software. In the generated IFC model, bridge components were categorized as follows:
- all beam-like components have been converted into IfcBeam instances;
- flat metal profiles have been translated into IfcPlate instances;
- bolts have been categorized as IfcMechanicalFastener instances;
- masonry abutments are classified as IfcBuildingElementProxy instances;
- supports have been transformed into IfcBuildingElementProxy instances.

With the upcoming release of IFC 5 and its corresponding implementation by commercial software, it will be possible to more accurately map the elements of an infrastructure.

4) Toppoli Bridge over the Arno River - The laser scanner survey campaign produced outstanding results, in part due to the bridge's makeup of clearly distinguishable large components, similar to what was previously noted for case study 1). A two-way connection between the BIM model in Revit, viewed as a collection of elements, and a dedicated database created in Microsoft Access has been developed and tested, yielding satisfactory results. A workflow was tested and optimized to connect a sensor, specifically an accelerometer, with the BIM model of the Toppoli Bridge. The objective was to visualize the sensor's output on the Autodesk Forge platform. Historical sensor data was used in the test; nevertheless, it is possible to achieve the same result with real-time data using a more powerful software version and a connected sensor.

3.2 Discussion

The present study aimed to offer a contribution to the development of Structural Health Monitoring systems in the context of transport infrastructures and bridges in particular, in line with the recent orientations of the technical-scientific community, both at the national and European level, on risk management and assessment.

The application of Building Information Modelling tools and methodologies was the first step in the information management of bridge knowledge. The obtained BIM models for the various studied bridges demonstrate the reliability of the scan-to-BIM methodology for modeling both infrastructure and bridges, just as it is for buildings. The conducted survey campaigns vary in terms of the instruments used and the surrounding conditions. Consequently, these experiences are valuable for identifying common factors that have influenced them: the intrinsic nature of the bridge and the materials of which it is made, the ability to suspend bridge usage, the size of the river or obstacle crossed by the bridges, the overall accessibility of the structure, and the economic and time costs associated with potentially repeating the survey campaign.

The most significant factor influencing the choice of BIM modeling workflow is the presence or absence of reliable design documentation. In the case of historical bridges, a survey campaign is essential. However, for some cases, the survey results become the primary or sole dataset for modeling, while in others, they serve only as a comparison. The processes of implementing bridge information models from the geospatial data acquisition phases conducted with laser scanning or 3D image surveying techniques show an adequate level of maturity for the intended and foreseeable uses in bridge control and monitoring activities. In particular, the use of scripts created in Visual Programming Language (such as Dynamo) into the BIM authoring software allows for the effective handling of complex shapes, which are derived from the geometric-constructive rules used in the design of railroad tracks and artwork in the late 1800s.

At the interoperability level, it has been demonstrated that translating a BIM model of a bridge into the IFC schema is already feasible, although currently, there are occasional challenges in classifying certain elements. Geometric data, however, is readily translatable into the IFC data schema. On the contrary methods of managing data from bridge monitoring can vary widely depending on the criteria set by the owner, which based on its strategic goals and internal organizational structure may define different approaches in terms of Asset Management System and related supporting technological infrastructure.

An initial strategy for enabling a "smart" approach to bridge risk assessment has been developed in the fourth study case, involving the implementation of a continuous data acquisition process through sensors installed on the physical structure. This approach leveraged the cloud-based Autodesk Forge platform, seamlessly integrated with BIM authoring software for information models. The functionalities of the corporate software assisting engineers in evaluating the safety and maintenance condition of railway bridges have been replicated within the BIM environment in the third case study. It was possible to provide information necessary to support decision-making regarding prevention and mitigation of natural and anthropogenic hazards, that pose a threat to the stability of the examined bridge and the integrity of the infrastructure network.

4. CONCLUSION

The conducted studies demonstrate the benefits achievable through the approach 'BIM - first of all', which prioritizes the use of BIM models at the core of bridge management processes for these infrastructures.

The approach used in the proposed experiments, can be attributed to the economic concept of a "Point Solution", whereas the more desirable approach for Bridge Management Systems (BMS) is certainly a "System Solution". This implies a comprehensive rethinking of BMS within the context of BIM and AI integration, aiming for a comprehensive and holistic solution.

The topics covered occupy a prominent place in the National Research Plan 2021-2027, particularly in the areas related to security and digital innovation. This is in line with Cluster 3 of Horizon Europe 2021-2027 and supports goals 9 and 11 of the United Nations Agenda 2030, which focus on resilient infrastructure, innovation and sustainable urban development.

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