HISTORIC BRIDGES MONITORING THROUGH SENSOR DATA MANAGEMENT WITH BIM METHODOLOGIES

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KEY WORDS: Scan-to-BIM, InfraBIM, Digital Twin, IoT, Sensor Monitoring, Facility Management.

ABSTRACT:

The implementation of geometric, alphanumerical and documentary data within BIM models is opening up interesting scenarios in the integrated management of existing infrastructure works. In particular, data from the application of sensors for structural monitoring of historic bridges can originate a flow of information exchange between real artifacts and Digital Twin capable of activating effective reactive or planned responses in the operation and maintenance phase of the asset by the facility manager. This 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 models aimed at the management of data from incoming and outgoing sensors towards analysis, supervision and control systems of the facilities organization. The case study of the Toppoli Bridge over the Arno River along the S.P. 64 road in the Province of Arezzo (IT), an artifact dating back to the early decades of the 1900s and built using traditional construction techniques and recently subject to renovation, is addressed. The experience conducted has highlighted how the BIM methodology for information management of existing assets, effectively responds to the current needs of monitoring and control of historical infrastructure assets, being able to integrate with multiple information management systems of the facilities organization, as well as the latest AI and AR technologies.

1. INTRODUCTION

The contemporary scenario, also following serious events reported in the news, has brought to the attention of the public the complexity and delicacy of managing existing heritage. The study of methodologies capable of classifying, managing, and storing the large amount of historical and real-time data on artifacts is becoming central to the prevention and scheduled maintenance of works. For an infrastructure management company, bridges, like any other facilities, are assets subject to an inevitable deterioration, linked both to external factors and to the aging of the material. Many studies have focused on how this inexorable process of degradation can be monitored in order to intervene promptly, if necessary, in order to prevent the occurrence of catastrophic events. The use of an *Asset Management System* (AMS), as a system that collects and organizes information and makes it available through rapid queries, allows for better risk management through faster and more effective decision-making processes, also conducted in real-time. Furthermore, recent developments in the field of IoT (Internet of Things) and digital technologies for geospatial detection of artifacts have provided facility managers with increasingly powerful tools for data collection and asset monitoring, improving their ability to analyze ongoing phenomena and make assessments on the most suitable operational procedures to activate in response to maintenance and operational requests at every stage of the artifact life cycle.

The topic has recently become so relevant as to give rise to a new discipline, *Structural Health Monitoring* (SHM), which specifically deals with bridges. A study by the European Commission, *"Research and innovation in bridge maintenance, inspection and monitoring"* (EU Commission, 2019), has shown the growing interest of the international scientific community in issues related to risk management of bridges. The current inspection systems are mainly based on visual assessments carried out by experts combined with some simplified survey techniques. In case of not exhaustive or doubtful results, further in-depth analyses are conducted, which may lead to ordinary or extraordinary maintenance interventions carried out by the infrastructure owner. The information obtained from inspections must be processed and used as input for the AMS system, and therefore reworked with a considerable computational effort. These procedures can now be optimized and made more efficient with the introduction of *Building Information Modeling* (BIM) tools and methodologies, which allow for the management of structured geometric and alphanumeric information within a dedicated *Common Data Environment* (CDE) for the asset. Traditional inspection techniques can be integrated with advanced data acquisition systems through specifically installed sensors in the bridge, along with also indirect collection from other sensors variously located in different devices that populate the wide world of big data.

Data is therefore the main player in infrastructure asset monitoring activities and the ability to manage its various stages of acquisition, storage, processing, and validation is essential in order to develop truly predictive decision-making processes and enable any corrective actions in the management of the structure. In 2018, following the collapse of the Morandi Bridge, a wide technical-scientific debate opened up on the efficiency and maintenance status of bridges currently in operation across all transportation networks in the Italian territory, and on which strategies to define to overcome that cultural, even before technological, delay in many infrastructure owners, methods and tools for risk management and bridge safety assessment. In 2020, the Ministry of Infrastructure issued the *"Guidelines on risk classification and management, safety assessment and monitoring of existing bridges"* (Ministerial Decree n. 578/2020), which outline a precise framework for all bridge inspection and monitoring activities, also considering the use of digital

The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-M-2-2023
29th CIPA Symposium "Documenting, Understanding, Preserving Cultural Heritage:
Humanities and Digital Technologies for Shaping the Future", 25–30 June 2023, Florence, Italy

technologies for their *"smart"* management through sensors implemented in SHM systems and the creation of informational models of the structures developed with a view to future establishment of the *National Digital Archive of Public Works* (AINOP).

The proposed study started during the experimentation of the multilevel methodology for the efficient analysis of bridges, which took place in 2019 as part of a Collaboration Agreement between the Tuscany Region Administration and the Regional Federation of the Orders of Engineers of Tuscany entitled: *"Expeditious analysis and visual examination of priority bridges"* and forewent the later adoption of the Guidelines. The pilot case was the Toppoli Bridge over the Arno River along the S.P. 64 road in the Province of Arezzo (IT) (Fig. 1). In the first stage, a visual inspection of the bridge was carried out according to the procedures established by the study program, which involved filling out a survey form for the defects found in each constituent element (abutments, piles, deck, etc.).

Figure 1. Views of Toppoli Bridge

The next step involved implementing an information model of the bridge, following a Scan-to-BIM modeling process based on a geometric survey carried out using laser-scanning equipment. The model was then used as a reference database for the setting of an instrumental monitoring system, which involved the use of the cloud-based platform *Autodesk Platform Services* (formerly *Forge*), which offers numerous services and APIs for managing engineering data via cloud.

2. OVERVIEW ON BRIDGE MANAGEMENT SYSTEM

Infrastructural works are generally perceived as safe by their users, and it is rare for drivers of a common vehicles to question whether the bridge they are crossing is safe: this condition is generally taken for granted. (Santarsiero et al., 2021).

Aggressive environmental phenomena, usage mechanical loads greater than those hypothesized during the design phase, operation time longer than initially planned, poor maintenance, and other similar factors can strongly influence and compromise the stability of bridges. (Santarsiero et al., 2021; Saback et al., 2022; Zinno et al., 2022)

For these reasons, many infrastructure management companies have equipped themselves with software known as *Bridge Management Systems* (BMS). BMSs are information modular systems, whose modules typically perform the following functions (Woodward et al., 2001; Saback et al., 2022b):

- production of an inventory of managed bridges,
- understanding of the preservation conditions of the bridge and its components,
- assessment of risks borne by users (including load capacity assessment),
- management of operational constraints and routing of exceptional convoys,
- evaluation of costs for different maintenance strategies,
- prediction of deterioration conditions and estimation of costs for various maintenance strategies;
- assessment of the socio-economic importance of the bridge (indirect costs) and optimization under budget constraints,
- definition of maintenance priorities,
- budget monitoring for various time horizons.

Employing a BMS, to investigate the structural condition of those bridges that have been placed under surveillance following a visual inspection by a specialized technician, SHM techniques are often used.

As reported in "*Bridge Health Monitoring and Inspection - A Survey of Methods*" (Gastineau, Johnson and Schultz, 2009), it is possible to define different types of monitoring organized according to a *time-frame* of activity or in relation to the *scale* of investigation intended to be carried out. Their combination allows to identify the most suitable monitoring system for each specific structure. A classification that follows a *time-frame* organization must refer to these issues:

a) short-term: monitoring aimed at obtaining an immediate response;

b) long-term: monitoring aimed at obtaining a response over a longer period of time;

c) inspection: monitoring intended as an evaluation of the bridge's conditions within a planned schedule;

d) early warning: monitoring that produces an alarm when certain predefined parameters are exceeded;

e) collapse warning: monitoring that leads to taking action to prevent access to the bridge in case a limit value is reached.

If the classification takes into account the *scale* of the components under examination, we obtain monitoring types:

-local, if they focus only on a specific portion of an element;

-per element, if they focus on a single element;

-global, if they concentrate on the entire set of elements comprising the bridge under examination.

Another important aspect is the *monitoring metric*, which refers to a set of parameters aimed at measuring the conditions and performance of the bridge. The metric varies from case to case based on factors such as the type of bridge, its location, and year of construction, but it can still be evaluated through general

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parameters such as the acceleration due to bridge vibrations, weather conditions, curvature, displacement, load, slope, and erosion of the soil around the piles.

Other more specific measures, including corrosion, cracking, and stresses, pertain to individual construction materials such as reinforced concrete and steel.

Based on these factors, one can then proceed to choose the most suitable type of monitoring, which may involve the use of various types of sensors such as accelerometers, fatigue sensors, electrochemical sensors, fiber optic sensors, as well as GPS and laser stations, depending on the case.

For further investigations, finite element method (FEM) analyses can be made more reliable if accompanied by continuous analysis of output data from installed sensors to evaluate the intensity of degradation phenomena present.

A disruptive technology such as Artificial Intelligence (AI), and more specifically Machine Learning (ML) techniques, can introduce significant improvements in the field of SHM. Machine Learning can be used for the automatic recognition of patterns in the data provided by the installed sensors and related to bridge defect phenomena. In this case, the intelligent algorithm recognizes the pattern and alerts the manager about the presence of defects, indicating their intensity and potential danger. The most commonly used approaches in SHM applications are: Fuzzy Clustering (FCM), K-means clustering (Lloyd's algorithm), Artificial Neural Networks (ANNS), K-Nearest Neighbor (KNN), Support Vector Machine (SVM), Decision Tree, Random Forest e Deep Learning. (Zinno et al., 2022; Malekloo et al., 2022).

A digital information model that includes geometric data and information on the physical and performance characteristics of bridges has been proven useful in the field of SHM, and for this reason is increasingly associated with the concept of "*Digital Twin*", which is typical of *Smart Manufacturing* and has been proposed in recent research in the field of infrastructure. (Osello 2019). In the AECO sector, the concept of Digital Twin is inherently linked to the information management methodology known as Building Information Modelling (BIM). In the field of bridges, the BIM acronym is often replaced by the following:

- InfraBIM (Osello, 2019), referring to BIM related to the entire infrastructure field;

- BrIM (Saback et al., 2022; Barazzetti et al., 2016), Bridge Information Modelling, specifically related to bridges;

- HBIM, Heritage Building Information Modelling, used for very old bridges that have acquired historical value over time (Barazzetti et al. 2016; León-Robles, Reinoso-Gordo e González-Quiñones 2019; Borin e Cavazzini 2019; Murphy et al. 2012; Stavroulaki et al. 2016);

- HBrIM, Heritage Bridge Information Modelling, proposed as a synthesis of the two previous ones (León-Robles, Reinoso-Gordo and González-Quiñones, 2019).

Being a built infrastructure heritage, the survey phase of the structure plays a fundamental role, which nowadays is largely carried out through laser scanning techniques (León-Robles, Reinoso-Gordo, and González-Quiñones, 2019; Boardman et al., 2018; Pritchard et al., 2017) and/or image 3D (digital photogrammetry) (Ioli, Pinto and Pinto, 2022; Jáuregui, Tian and Jiang, 2006; Mohammadi et al., 2021) now commonly used both with ground-based equipment and UAV-borne systems.

The various surveying methods produce point clouds (PC) as a result, on which a series of processing operations must be carried out, more or less automated, to achieve the BIM modeling of the various parts of the studied object; these procedures are generally referred to as Scan-to-BIM. (Croce et al., 2023; Wang et al., 2019; Sing et al., 2022; Roggeri et al., 2022).

In delivering a BIM model ready for further applications in specific BIM Uses related to the infrastructure sector, the development of the latest version of the open data format Industry Foundation Classes (IFC) by buildingSMART International is of particular interest, as it will allow for a coherent description of infrastructure. With the IFC 5 data schema, the AECO sector will have the opportunity to "*coexist, within a coherent knowledge base, the management of buildings in terms of environmental sustainability and safety, hydraulic networks by connecting sensors for efficiency control, transport systems - roads, railways, airports, seaports - and specific structures such as bridges and viaducts*" (Borin and Zanchetta, 2020).

In Italy, through Ministerial Decree n. 578 of 17.12.2020, the "*Guidelines on risk classification and management, safety assessment and monitoring of existing bridges*" were introduced on a trial basis, and their scope of application will be gradually extended to all infrastructure management bodies that have bridges among their assets, excluding the railway sector. The topics related to SHM are addressed in various chapters of the guide.

In the recent Italian National Research Plan 2021-2027 (PNR), the topic is particularly prominent in the areas of "Safety for social systems" and "Digital, industry and aerospace", corresponding to Cluster 3 of the Horizon Europe 2021-2027 program and in line with the goals of Goals 9 and 11 of the United Nations' Agenda 2030: "Build resilient infrastructure, promote innovation and sustainable and equitable industrialization" and "Make cities and human settlements inclusive, safe, resilient, and sustainable".

3. BIM AND BRIDGE MONITORING

The proposed methodology (Fig. 2) provides an operational and replicable process workflow for creating infrastructural digital information models that can interact with data coming from the real world via IoT devices. The resulting *Digital Twin* can be used to manage assets throughout their lifecycle. The main goals of the modeling were to create a digital model of the manufact under consideration, to assign coding for individual elements, to validate both geometric and informational data, and finally to integrate the digital model with data coming from devices placed in the real environment. Together a process for storing data from the BIM authoring environment within specific software for managing information databases is also proposed.

3.1 HBrIM data management

The first phase in the development of this process workflow focuses on data collection and search of information concerning the asset under examination and has the objective of providing a knowledge base for the implementation of an information model in its fundamental geometric, alphanumeric and documental components suited to the requirements for monitoring activities. In general, this is a task that could be particularly complex in the case in which data and information on the asset, if available, are still fixed on paper, or in formats that cannot be digitally re-elaborated as they come from the rasterization of old graphic or textual documents. Reference is made in particular to direct historical sources, constituted by drawings and archive documents relating to the original designs of the artifacts, or to indirect sources represented by the treatises on the *Art of Building* produced between the 19th and 20th centuries with their repertoires of typological and constructive solutions, which can provide us a precious knowledge base on the technical culture coeval with the period in which the bridges were built. In order for these information contents to be effectively reused to support BIM-based information management processes, it is necessary to proceed to their complete digitisation, organising the data on the basis of the asset's semantic and functional decomposition

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structure into parametric objects and as far as possible in open and non-proprietary formats.

The implementation of the geometric component of a BIM model of a bridge is influenced by many factors, including significantly the morphological structure of the manufact and the construction technique used: a massive geometry, such as that of a masonry arch bridge, lends itself well to an ordinary Scan-to-BIM workflow; on the contrary, a very articulated structure, such as a reticular metal truss that is considerably deformable under the action of static and dynamic loads, composed of numerous slender elements and rich in sharp edges, can be more usefully modelled using specific software for the automatic recognition of geometric profiles with a predefined section (e.g. Faro As-Built). The privileged starting basis for beginning information modelling processes remains in any case the massive acquisition of geospatial data through a survey carried out with laser scanning or 3D Image techniques, even though in many cases the information requirements foreseen for the use of the BIM model in monitoring activities can be guaranteed through simpler CAD-to-BIM processes, when supported by a reliable set of 2D graphic survey data.
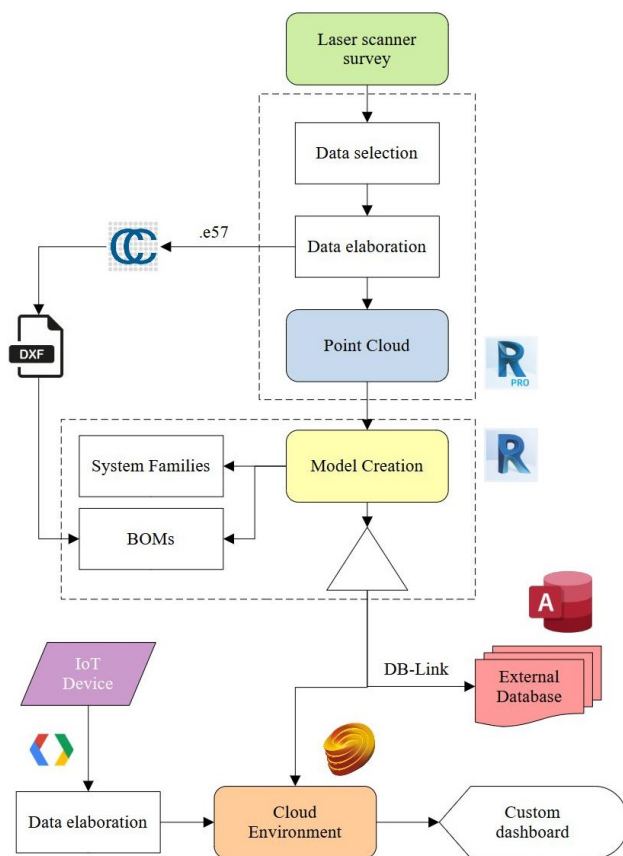

Figure 2. Process workflow

The modelling phase involves the creation of parametric objects, which fit with the highest possible level of accuracy the *"real"* geometries of the artefact captured by the point cloud. The *Levels of Accuracy* (LOA) (USBID, 2019) define a metric for assessing the compliance of the geometric model and its parts with the information requirements of the management plan. They are characterised in particular by an *"instrumental"* component linked to the accuracy of the measured data and a *"graphical"* component dependent on the accuracy of the 3D representation of the model. Increasing levels of accuracy correspond to increasingly smaller uncertainty ranges (*standard deviation*), but

the level of reliability of the geometric information is also assessed in relation to the importance of the individual element and in relation to the specific BIM Use.

At the end of the BIM model creation process, the model must be validated in both the geometric and information components. The geometric validation procedures make use of software (e.g. Cloud Compare), that compares the point clouds acquired in the survey phase with the surfaces of the 3D model, elaborating geometric deviation maps, from which it is possible to deduce the error range obtained in the modelling phase (Biagini et al., 2022). The information content is validated through the verification of the completeness of data in the cells provided by the matrix of object attributes, the checking of the correctness of data entry and the attribution of the coding established for the naming of objects and models. Other model validation procedures concern the geometric verification of interferences between objects belonging to the same model or aggregated models (clash detection) and the control of compliance with regulatory prescriptions, which can be carried out through the implementation of specific rule sets (code checking).

The information content of the model is fed by an extensive on-site photographic campaign and the observations made during the bridge inspections. Furthermore, in the absence of the technical documentation of the original project, indirect sources from old bridges with the same construction techniques are used to understand the structural equipment.

For the classification of the model's parametric objects, the naming convention defined in the CNR's "*Instructions for the Structural Safety Assessment of Road Bridges in Masonry*" (CNR-DT 213, 2015) was used, which provides for a subdivision of this type of manufact into recurring structural elements and their classification.

The availability of a shared scheme of subdivision of the bridge into elements, also at the normative level, has been critically important in the modelling phase of the parametric objects, since it was possible to orientate the logic of semantic decomposition of the information model, creating ad hoc families of macro-elements, which were then used for the assignment of the relative parameters.

In particular, the database has been organised based on rules provided by the Ministerial Guidelines for the classification and monitoring of existing bridges, which in chapter 7 give the criteria for choosing a coding system: "*The purpose of the identification system is to associate data and information from the surveillance and monitoring system to the various construction elements of the bridge, auxiliary equipment, deck support apparatuses and in general to "objects" whose state of condition can be observed (or determined through surveys and instrumental measurements) independently of each other and which constitute a separate entity from the point of view of the degradation and damage phenomena suffered and the possible maintenance, replacement and/or restoration interventions. ... In order to be able to identify the elements in their position it is necessary that each of them be associated with an identification code, univocal within the work, even if the logic of the formation of the codes may be common to the different structural types and different materials*" (Ministerial Decree n. 578/2020).

The modelling rules of the parametric objects are therefore derived from the previous setting of a structured database, which guided their encoding, geometric conformation and information content.

The BIM model makes the collected information easily accessible to the various operators, making the processes of data storage and sharing more efficient. This constitutes a key element in information management with BIM methodologies by public administrations that require the use of open and non-proprietary formats for information exchange. This need, which is also

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mandatory, entails the transition of models from a proprietary format related to the BIM authoring software used in modelling, to an open format, such as that represented by the IFC schema, for example. The processes of exporting models created with proprietary software into the IFC format still present some limitations both on the software side, since the IFC format itself is a continuously evolving schema to meet the ever-changing needs of the AECO sector, and on the user side, which often faces such information exchanges without the necessary knowledge of the IFC schema, easily incurring in errors in setting up the procedure.

3.2 Sensor data management

Once the modelling phase was completed, experimentation was conducted on the management of data and information collected in the BIM model through two different data management approaches: in the first case, the information content of the model was exported within a specific database management software; in the second case, a specific cloud-based platform was used for the management of BIM models to be interconnected and fed with heterogeneous data coming in real time from different types of sensors located in the physical environment.

3.2.1 RDBMS for data management - In this approach, the management of data and information collected in the BIM model is proposed through the creation of a specific external RDBMS (Relational Database Management System). The information contents of the model are exported to the Microsoft Access software via the Autodesk Revit DB-Link application. This plug-in allows a direct link between the *.rvt* model and the database management software Access. The procedure made it possible to export both the default parameters within the database and the shared parameters previously created. For better management of the collected data, consultation masks were created to query the database. By creating specific queries, it is in fact possible to cross-reference the data contained in the various tables in order to obtain all the information associated with a given element. Thanks to this methodology, we obtain a bi-directional link, where changes made in one software are also reflected in the other. The process, illustrated for a database allocated in a local server, can also be extended in a cloud environment. The HBrIM model generated in a process of acquiring geospatial data and alphanumeric information, and subsequent information modelling, is exported together with its database to a cloud environment where operators, depending on their tasks and access permissions, can interact and modify the valorisation of parameters within the database.

3.2.2 Autodesk Platform Service (formerly Forge) - This application is more clearly oriented towards the management of data from sensors installed in the building. The implementation process of the data management system involves the creation of sensor objects within the BIM model and the use of a simple and easily controlled hardware platform, such as Arduino microprocessors. The device used in the case study was an accelerometer of the ADXL3xx type. In the sensor field, there are a lot of low-cost accelerometer sensors, which also allow data to be connected via Bluetooth technology. For the implementation of the data from the device within the BIM model, a cloud-based platform was chosen that could be easily integrated with the BIM authoring software used, such as Autodesk Forge (name at the time of this experiment) now renamed Autodesk Platform Services. The procedure is rather complex, but can be summarised in two main steps:
a) uploading the model for visualisation on a browser;
b) implementing data visualisation.

The first step consists of creating an Autodesk Forge account. Once the account has been created, the personal page is accessed, where it is possible to create a customisable *reference app* within which BIM models are linked with data from heterogeneous sources (e.g. sensors). In this case, a reference app is essentially a code, which refers to the Autodesk Forge API. When the reference app is created within the platform, the following credentials are generated: *Client ID*, equivalent to a unique identification code; *Client secret*, equivalent to a password; *App name*, the name of the app created; *Description*, a brief description of the reference app itself; *CallBack URL*, the redirection path that is turned over to Autodesk to re-enter the reference app. Once the procedure for creating the reference app is complete, it is possible to request an OAuth2 access token. In the case study, Postman was used, downloading a special pre-configured package and filling in the necessary fields: in this case Consumer Key, Consumer Secrete and BuketKey. At the end of the procedure, an AccessToken is requested and loaded, which is used later on. To work with Forge (and thus modify the code), the Visual Studio Code editor was used, and then the reference app packages were downloaded from Github and uploaded to Visual Studio Code together with node.js.
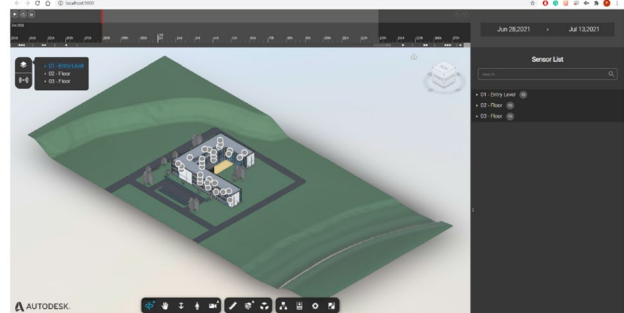

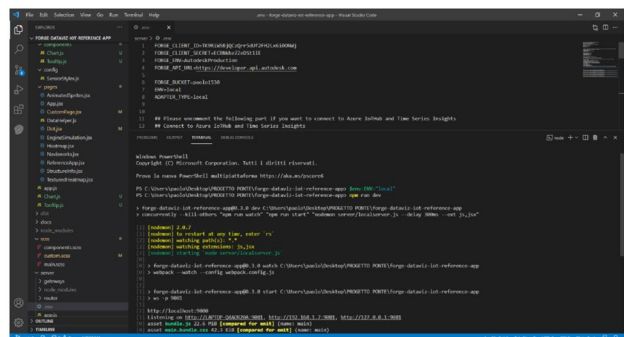**Figure 3.** Reference app with the default BIM model in Forge

Figure 4. Coding for changing the reference app in Forge

To run the reference app instance on a local port, the command "*npm run dev*" must be entered from the terminal. Once the command is finished, one is redirected to the page http://localhost:9000, which can be opened from any browser. Here we can be found the reference app, corresponding to the case study on which the reference sensors have been placed (fig. 3). Proceeding in this way, it is possible to view any model coming from Revit, directly from the browser without the need to have installed any software on own computer.

Now it is possible to replace the reference template by creating a new *.env* file to be compiled with the access key obtained via *Postman*. The following points are then compiled:
- FORGE_CLIENT_ID
- FORGE_CLIENT_SECRET
- FORGE_BUCKET

Once the compilation within the *.env* file is completed, the variable ENV is set locally (fig. 4). This is done from the terminal

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by entering the commands:
- $env:ENV="local"
- npm run dev

Having completed the procedure and started the command, it is possible to upload the model within the browser from the reference page http://localhost:9000/upload. We proceed to check the "Enable SVF2 Upload" command to select a BIM model saved within the hardware and upload it in a format optimised for online viewing. Once the upload procedure is complete, we are redirected back to the http://localhost:9000 page, from which we can view the uploaded model.

At this point, reference "*sprites*" are created within the model, i.e. icons that simulate the position of the sensor in the artefact. To do this, it is necessary to interact with the *dot.jsx* page supplied with the reference app. The react and viewer components already present within the reference app must then be called up using the command:
- import React from "react"
- import {Viewer} from …

"forge – dataviz – iot - react-components".

The sensor basically consists of a unique identifier and a position in space. The sprite at this stage is still just an icon within the model with no event associated with it. An event is therefore created as soon as the mouse passes or clicks over the icon. This is done by creating the tooltip component from the *Tooltip.js* page. For the creation of the chart component, used for the visualisation table, it was decided to use a free solution such as Google Charts.

Once the events have been created, it is possible to go and compile the data from the sensor within the *dot.jsx* page, as we do not have a Web Service for the management of live data. This latter service can however be implemented.

At the end of the process, it is possible to display the live data from the sensor directly on the screen.

4. THE CASE STUDY OF TOPPOLE BRIDGE

The proposed case study is related to the Toppoli Bridge over the Arno River near Bibbiena in the Province of Arezzo (IT), along the S.P. 64 road at km 3,700. It is an artifact dating back to the early decades of the 1900s and built using traditional construction techniques, of which no archival documentation of the original design could be traced. It consists of a massive masonry structure with a double arched span, each having a length of 19.60 m, a mount of 3.00 m and a width of 5.00 m. The central pile is 3.00 m thick, while the abutments connect with the bank profile of the riverbed. The pile and abutments are made of a square stone masonry while the arches are made of a brick masonry.

Around the 1960s, the widening of the road deck is probably to be reported, which is made of a reinforced concrete slab about 7.50 m wide and 0.25 m thick and cantilevers out from the masonry arches below. The bridge presents some situations of degradation of constituent materials mainly related to infiltration of rainwater, as well as some cracks in structural elements.

This bridge was part of the experimentation of the multilevel methodology, which took place in 2019 as part of a Collaboration Agreement between the Tuscany Region Administration and the Regional Federation of the Orders of Engineers of Tuscany entitled: *"Expeditious analysis and visual examination of priority bridges".* (Fig. 5, 6, 7). It was from that experience that the need arose for the authors to develop a more innovative BIM-oriented approach to bridge risk management and monitoring, some partial outcomes of which are presented in this paper.

The operational workflow illustrated above provided for the case study the preliminary drafting of an information management plan (pGI) capable of supporting the modeling and cataloging phases of the data acquired in the survey phases. In particular

since we are dealing with infrastructural works, extensive reference was made to the operational procedures set out in the Guidelines (Ministerial Decree n. 578/2020), which provide for increasing levels of depth in bridge analyses to be performed with different approaches and tools.
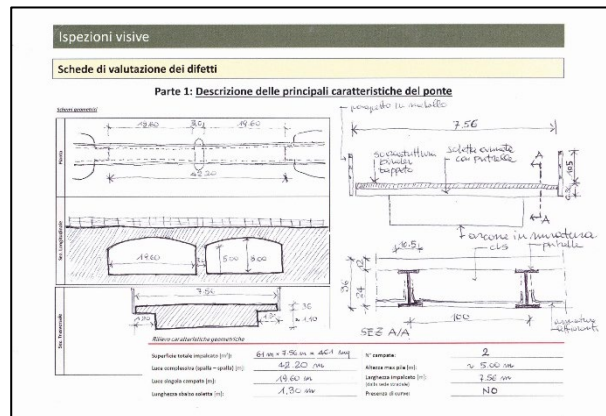

Figure 5. Defect sheet for masonry bridges

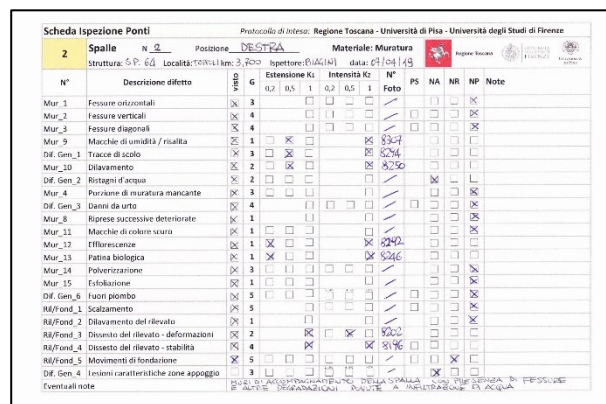**Figure 6.** Expeditious survey sheet

Figure 7. Compiled visual examination sheet

The acquisition of geospatial data was then carried out by means of a laser scanner survey, which enabled the generation of point clouds readable by the chosen BIM authoring software Autodesk Revit. Before importing, the point clouds were appropriately processed within Autodesk ReCap software (Fig. 8), proceeding to align the scans into a single model and subsequent decimation of the points to eliminate redundancies and disturbing elements. From the ReCap software, a unified version of the point cloud was then stored in .rcp format to allow import within Autodesk

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Revit software (Fig. 9).

The initial model was created using system families and then moved on to the generation of custom objects in the form of loadable families, always trying to maintain the classification logic reported in the CNR classification of masonry bridges.

For the modeling of the custom parametric objects (BOMs), the workflow was followed, already proposed by the authors in other studies (Biagini et al. 2022), which involves the use of the open-source software CloudCompare for importing portions of the point cloud in .*dxf* format within the family editor.
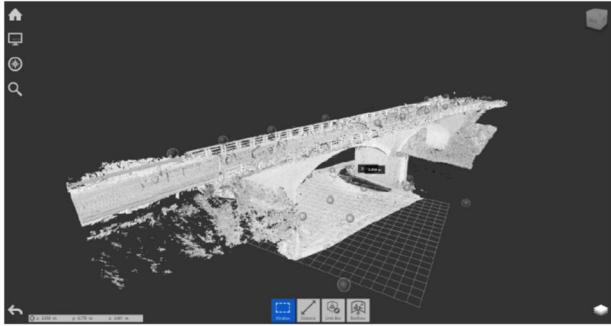
Figure 8. Point cloud of Ponte Toppoli in ReCap software

A number of shared parameters associated with individual families were then added within the information model, corresponding to those in the defect sheets used for monitoring the "priority bridges" of the Tuscany Region Administration. The geometric component of the obtained model was then validated against the geospatial data acquired in the laser-scanner survey using CloudCompare software. This allowed us to validate the geometric model by declaring the level of accuracy (LOA) achieved for each subdivision object, which composes the bridge.
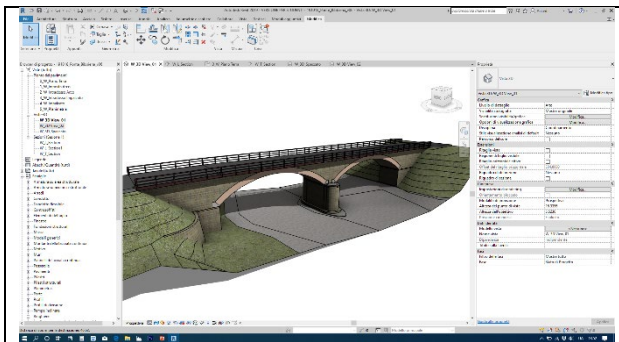

Figure 9. BrIM model of Toppoli Bridge in Revit

Through the DB-Link plug-in the information content of the model was then exported and linked within the Microsoft Access software where it was possible both to set queries for interrogating the database and to keep the same database information updated in real time as a result of possible changes that occurred in the model.

For example, in the case of the central bridge pile within the Revit software the parametric object was associated with the shared parameters "YEAR" and "IDENTIFICATION." In the corresponding Access sheet, it is possible to find these parameters associated with the same element, to which they are linked in the model by a unique ID (Fig. 10). The database modification is bidirectional in that if a parameter or element is modified in either software the change is carried over accordingly into the other. In particular, the modification of a data item in the database can also be updated in the BIM model in Revit via appropriate window. With the saving of changes in the database a log file is created with a legend of the changes made.

A BIM-oriented system was then set up to manage data from sensors. In particular, the most frequently installed sensors in bridge monitoring are accelerometers. In the case study, a WIT-type accelerometer sensor capable of reading: angle, acceleration, angular velocity, and magnetic field on the 3 XYZ axes was used. For acceleration, the error is about 1% and accelerations up to 16g are measured. Software for connecting and setting up the device can be downloaded from the manufacturer's website, to which it can be connected via Bluetooth. As can be seen from the following image, the panel shows the first input data read from the sensor. The data obtained can be exported in .txt format and imported into a spreadsheet, from which graphs of the accelerations along the 3 axes can be derived (Fig. 11).
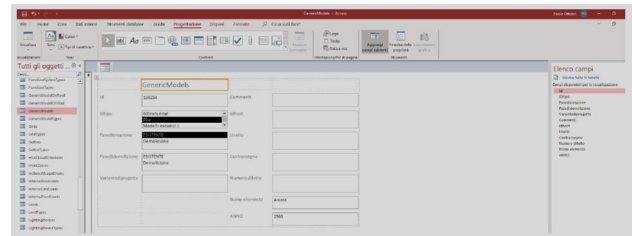

Figure 10. Custom panel in Microsoft Access

Following the implementation process outlined in the previous section, the default information model within Autodesk Forge software (working locally) was replaced with the Toppoli Bridge HBrIM model. Along with the model, all the tools necessary for querying and editing the model itself are also loaded. There is also the ability to view all the features of both the overall model and the individual loaded elements. The setting then of a *"sprite"* within the model allowed the visualization of data obtained in real time from the sensor directly on the screen (Fig. 12). This allows the elements being monitored to be kept under control in real time and with user-friendly graphics.
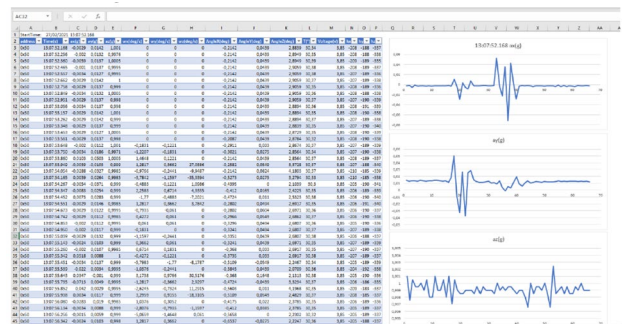

Figure 11. Representation of data by device in a data sheet

It should be pointed out that the process workflow based on BIM methodologies developed for the management and integration of data from bridge monitoring both periodically collected by expert personnel and continuously from sensors, has some breakdowns in terms of interoperability of data exchange between software applications to which partial answers have been given from time to time. Furthermore, the technical and operational management of the sensors to be placed in situ on the bridge has not been addressed, having limited the interest of this study to the implementation and optimization of the process workflow.

5. CONCLUSION

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

The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-M-2-2023
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line with the recent orientations of the technical-scientific community, both at the national and European level, on risk management and assessment, which had their legislative translation in 2020 in Italy in the Guidelines of DM 578/2020. It was also developed in parallel with an experimentation promoted by the Tuscany Region Administration, concerning the first phase of a multilevel analysis for the safety assessment of bridges on a significant sample by construction type, which provided useful insights for the definition of processes for the digitization of structural control and monitoring activities of these artifacts.

The application of Building Information Modelling tools and methodologies was the first step in the information management of bridge knowledge. In particular, the availability of masonry bridge classification protocols (CNR-DT) made it possible to organize the information model database and object decomposition structure in coherence with that of the real work, also with reference to the descriptive parameters related to the detected defects to be attributed to each element. 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. The set of procedures for creating "ready" BIM models (e.g., scan-to-BIM), already defined in many studies in the literature and also presented in this study, already provide a reliable basis for subsequent applications of sensor-sourced data management systems.
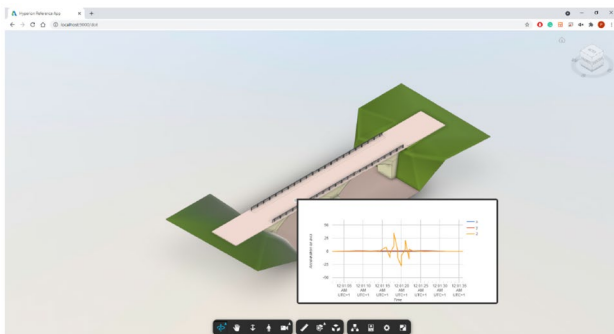

Figure 12. Custom dashboard inside Forge local page

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.

The research conducted a double test of systems for managing data from bridge monitoring. In one case it was done with a view to digitizing planned processes for inspection activities, which are strongly centered on the skills and competencies of maintenance personnel. In the other case, a process of continuous data acquisition from sensors deployed on the actual manufact was outlined as a first approach for "smart" management of bridge risk assessment, using the cloud-based Autodesk Forge platform easily integrated with BIM authoring software for information models.

Information management methods for bridge monitoring data from multilevel analysis already appear adequate to support the survey criteria required by the Guidelines. Information collected by operators when inspecting artifacts can be effectively integrated within a sharing environment (CDE) as part of BIM-based management. On the other hand, the integration of continuous data from sensors appears to be more complex due to the need to deal with highly articulated process workflows, where issues related to the interoperability of information exchanges between models, sharing environments and data management

platforms, even in cloud, result in frequent process breakdown; in this aspect, the study was able to identify only partial solutions. Further research developments may concern, in addition to the aspects highlighted above, the technical management of the sensors to be deployed and implemented on-site on the bridge (procedures for calibration, control, maintenance, etc.) to make this risk management system effectively operational.

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