STRUCTURAL HEALTH MONITORING OF BRIDGES: INTEGRATING OPENBIM, GIS, AND IOT IN THE BREGANZE BRIDGE CASE STUDY

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Abstract

Current bridge Structural Health Monitoring (SHM) workflows suffer from semantic disconnection, missing metadata validation, and inefficient model-updating. Addressing these deficiencies, this paper introduces a cloud-based platform. The developed workflow uses Information Delivery Specifications (IDS) for metadata integrity, nests sensors and hosts via IfcElementAssembly and IFC model updates using IfcOpenShell. Validated through the Breganze Bridge case study, the platform enables 3D model visualization, sensors measurements plots and threshold-based alerting. The lasting contribution is an OpenBIM SHM framework that integrates metadata validation, sensor-host linking, and threshold evaluation, bypassing proprietary lock-in and the dual-database integration step from model updating workflows.

Introduction

Bridges increasingly require structural health monitoring (SHM) to ensure their safety, operational performance, and long term reliability, particularly as they age and are exposed to growing load demands(Sun et al., 2025). The Architecture, Engineering, and Construction (AEC) industry has seen the widespread adoption of Building Information Modeling(Panah & Kioumarsi, 2021), with recent studies successfully demonstrating the integration of BIM and SHM by using 3D models for sensor placement and data visualization(Biagini et al., 2023; Huang et al., 2024; Li et al., 2022).

However, these BIM-SHM studies prioritize 3D geometric representation without verifying that the model and sensors contain the necessary metadata (properties, materials). Furthermore, although sensors are installed in close physical proximity to structural elements, they remain semantically disconnected entities within the BIM model, lacking formal relationships. Existing workflows typically plot database values without updating the sensor elements in the BIM model itself. Few studies have addressed model updating. Huang et al. (2024) demonstrated updates within Revit using Dynamo, while Marcellino et al. (2025) proposed IFC-based workflow with dual-database integration and file regeneration that may constrain performance for high-frequency updates

(e.g., intervals shorter than one hour), requiring appropriate optimization strategies.

This work investigates the development of a cloud-based platform for Structural Health Monitoring of bridges, validated through a real-world case study of the Breganze bridge. The core contribution is a methodology with four integrated components. First, the integration of Information Delivery Specification (IDS) to validate BIM model metadata integrity before integration. Second, semantically nests sensor instances within their host structural elements using IfcElementAssembly, establishing explicit machine-readable relationships that transform sensors from isolated objects into integral components of the monitored structure thereby enabling automated queries and contextual interpretation of monitored elements. Third, updating the IFC model by directly querying the sensor database and modifying the IFC file using IfcOpenShell, thereby overcoming the proprietary lock-in of Revit-dependent workflows and bypassing the dual-database integration and IFC model regeneration step required by prior work. Finaly, visualizes the enriched model and sensor data in a cloud-based platform with BIM-GIS-IoT integration, where users can access the spatial context of the bridge model within the GIS MapLibre open-source interface and switch to other interfaces to interact with the 3D BIM model and visualize sensor measurements enabling to understand and evaluate localized structural element behavior such as displacement and tilt angles as well as environmental conditions including water level, relative humidity, and temperature.

The structure of this paper is as follows: a literature review on SHM, BIM-SHM integration, and BIM-GIS integration for SHM; followed by a description of the adopted methodology; then the presentation of the applied project case study; and finally, the conclusion.

Literature Review

Structural Health Monitoring (SHM)

Structural health monitoring (SHM) is defined as the process of implementing an autonomous damage detection strategy for aerospace, civil, and mechanical engineering infrastructure. It involves the installation of sensors, at key locations along the structure. These sensors monitor a range of variables, including loads, strains, displacements, accelerations, temperatures, and chemical composition of concrete and steel (Figueiredo et al., 2013). SHM has been extensively applied in several engineering fields to track, identify and measure the responses of structures (Gharehbaghi et al., 2022).

Evolution from Traditional BMS to BIM-Based Monitoring

Despite the availability of monitoring technologies, traditional Bridge Management Systems (BMS) often lack 3D geometric representation and rely on manual data entry (Buuveibaatar et al., 2025). Recent studies suggest that the integration of BIM and SHM provide more sophisticated capabilities for bridge health monitoring addressing the limitations of conventional SHM approaches(Angelosanti et al., 2023; Huang et al., 2024).

Panah and Kioumarsi (2021) highlighted how BIM facilitates SHM by making sensor data accessible, practical, and comprehensible, offering improved means of visualization, interpretation, and documentation. Furthermore, having a 3D model is recognized as essential for BIM-SHM integration. For existing infrastructure, many studies rely on the Scan-to-BIM approach to recreate accurate digital representation for integration with SHM(Biagini et al., 2023; Fawad et al., 2025). As Huang et al. (2024) demonstrated, a 3D virtual model aligned with physical sensors enables precise sensor integration and allows for the colored visualization of strain distribution and residual fatigue life directly within the BIM environment, facilitating a deeper understanding of local bridge component behavior.

However, early implementations of BIM-SHM integration often relied on proprietary formats to build either desktop or web-based platforms. For instance, Li et al.(2022) proposed a BIM-SHM workflow centered on the 3D Revit model as a visual reference, where sensor data from the bridge is managed through a SQL Server database. A Revit plugin developed in C# allow users to view real-time measurement plots in conjunction with the 3D model, rather than updating the model geometry itself. Similarly, Fawad et al. (2023) developed a cloud-based IoT platform for bridge SHM that used a 3D Revit model, where clicking on the represented sensor objects enables access to real-time visualization dashboards for strain, temperature, and acceleration data. Expanding upon previous approaches toward model updating, Huang et al. (2024) employed a methodology utilizing a 3D Revit model, a MySQL database, and MATLAB for processing sensor data. In this framework, Dynamo was used not only to display measurement plots but also to update the instance parameters of sensor elements in Revit with real-time strain and residual fatigue values, ensuring the 3D model remained synchronized with the physical structure. While these studies demonstrate BIM-SHM integration with some plotting measurements and one going beyond to update the model they all share the limitation of relying on proprietary data formats. This dependency creates software lock-in and presents challenges for interoperability.

Among the open standards that support vendor-neutral interoperability across the Architecture, Engineering and Construction (AEC) industry, the sector relies primarily on the Industry Foundation Classes (IFC) standard used to represent both geometry and semantic data. Originally developed with a focus on buildings, the schema has evolved to integrate infrastructure domains as well. This evolution is reflected in the IFC 4.3.2 release published in 2023 by buildingSMART International, which introduces several bridge types and their associated structural elements (Teixeira et al., 2024). In 2024, IFC 4.3 became officially ISO 16739-1:2024. Despite the international recognition and widespread adoption, recent research highlights limitations of IFC bridge applications. Teixeira et al. (2024) point out that many commercial structural analysis software tools still lack full support for importing IFC bridge models; to prevent data loss, they propose a dedicated tool for interpreting bridge element semantics, geometry, and material properties. Additionally, Nakamura et al. (2025)observe that IFC does not currently provide schemas for maintenance and inspection information essential for bridge management. Lee et al.(2025) further notes that the IFC schema lacks definitions for the entities and property sets needed to integrate national design standards, as in the case of elements such as joints and approach slabs particularly common in Korean bridges, leading to the definition of custom extensions to meet local infrastructure requirements. Alongside these limitations in IFC bridge applications, the IFC schema also fails to represent the overall sensor network of an SHM system. Smarsly & Tauscher (2015) noted that while basic sensor types can be mapped, monitoring-related information such as the configuration, interaction protocols, and network topologies of sensors cannot be formally described using standard IFC entities. To address this gap, they proposed a conceptual approach for extending the IFC object model for semantic modeling of monitoring-related information. Building on this work, Theiler & Smarsly(2018) proposed the IFC Monitor schema extension, which defines dedicated entities for sensor nodes, sensor networks, and SHM systems, along with an enumeration for network topology. Their extension demonstrates that IFC can be expanded to represent not only individual sensors but also the topological structure of sensor networks. However, despite this advancement, the validation of the IFC Monitor remains limited on a laboratory-scale prototype of a shear frame structure, rather than a real building or infrastructure asset.

BIM-GIS Integration for SHM

While BIM-based SHM approaches have demonstrated advantages in visualizing and managing sensor data, their limitation lies in the lack of geographical context. As Bjelotomić Oršulić et al. (2024) argue, the integration of GIS and BIM is becoming increasingly important for the digitalization of the built environment. In the context of infrastructure monitoring, Gao et al. (2024) highlight that GIS integration into a digital platform allows operators to examine a structural element in the BIM model while simultaneously assessing its spatial context through the GIS interface. This spatial awareness is important for effective SHM.

Malekloo et al. (2020) conducted a comparative analysis of standalone GIS, standalone SHM, and integrated SHM-GIS approaches across multiple criteria, including structural damage assessment, spatial analysis, database management, decision-making, risk assessment, scalability, and cost. They demonstrated that while GIS alone lacks structural damage assessment capabilities and SHM alone lacks spatial analysis, their integration unifies all evaluated functionalities into a single, comprehensive framework for bridge management.

Methodology

The proposed methodology integrates IFC model, GIS, and sensors into a unified web-based platform for bridge SHM. While lightweight formats such as JSON offer advantages for web-based data integration over IFC files and have been used successfully used for BIM-IoT integration(Chatsuwan et al., 2025), few research work rely on IFC.JSON. Moreover, converting the original IFC-STP to IFC.JSON adds an additional step to the workflow and potential semantic loss. Therefore, IFC is adopted as the data backbone throughout the entire workflow.

The workflow comprises four sequential main stages as illustrated through the IDEF0 process map in Figure 1. The First stage consists of the definition of information requirements and model production, where both human-readable and machine-readable information requirements are defined using the Information Delivery Specification (IDS) standard. These specifications formally declare which properties and attributes must be present in the BIM model to support SHM integration. With the human readable specification, a digital representation of the bridge, including its sensor instances, is developed in Revit and exported to IFC4.3 the most recent open standard for infrastructure data exchange.

Following the model production, the second stage involves the model validation and semantic enrichment. The exported IFC model is validated against the machine-readable specification using the IFCTester tool within BonsaiBIM. If validation fails, the tool displays the non-compliant elements and properties. Corrections are made either by directly editing the properties in BonsaiBIM and saving the IFC model, or by returning to Revit to adjust the model, re-exporting it to IFC, and re-running the validation. This iterative process continues until the model successfully passes the compliance check. After model validation, semantic enrichment is performed to establish explicit, relationships between sensors and their host structural elements. Addressing the lack of explicit sensor-host relationships in the current IFC 4.3 schema, this methodology adopts IfcElementAssembly as a pragmatic modeling pattern to nest sensors within their structural hosts, enabling meaningful machine-readable relationships and automated queries. To achieve the semantic nesting, a custom metadata property is attached to each host element, declaring which sensor instances belong to it. A script then parses this metadata, matches sensors to their respective hosts. The resulting assembly preserves the spatial context of the host element while linking sensors as integral components of the monitored element.

Moving to third stage of the methodology, the database system adopted to store the sensors is a relational database implemented on MySQL. Having the static IFC model and sensor values stored in the database, the model is updated with significant sensor readings using a MySQL python connector in conjunction with IfcOpenShell. Embedding important sensor readings into the IFC model within each IfcSensor instance generates a temporally consistent view of the element status over a specific period of time. This allows users to select a sensor in the 3D model, inspect its properties, and assess localized element behavior or environmental conditions without reviewing the measurement plots.

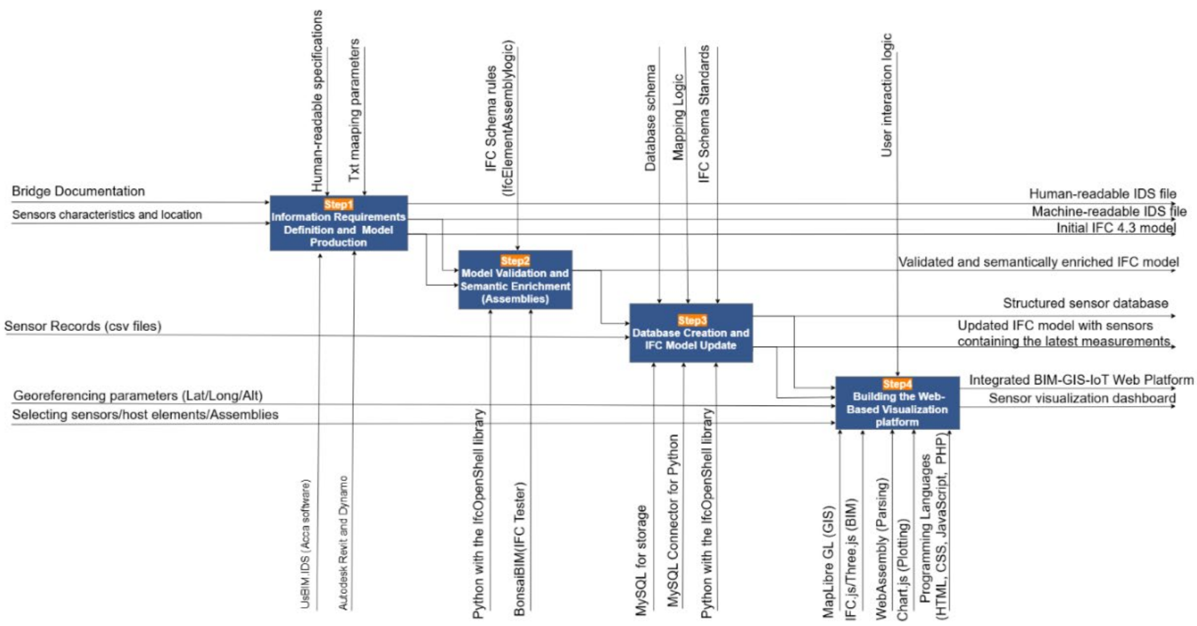


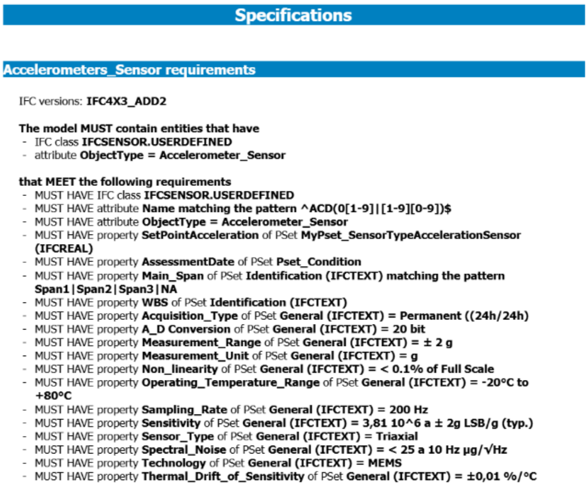
Figure 1:Process map of the methodology adopted

Finally, a web platform is developed to enable the integration of GIS, IFC model, and sensors following a three-tier client-server architecture. The architecture is structured into three distinct layers, the frontend layer serves as the client-side interface for user interaction and visualization; the backend layer manages server-side processing and the logic required for data retrieval; and the database layer provides the environment for data storage and management.

Result and Discussion

Case Study Context and Model Validation

The project case study is a reinforced concrete arched bridge. Various sensor types are installed at different locations on the bridge, including accelerometers, potentiometers, inclinometers, temperature sensors, water level sensor, and thermohydrometer. Prior to bridge model production, the human and machine-readable specifications was defined using the Information Delivery Specification (IDS) standard through the usBIM.IDS tool. Figure 2 illustrates the human-readable requirements defined for the accelerometers sensor metadata.


Specifications

Accelerometers_Sensor requirements

IFC versions: **IFC4X3_ADD2**

The model MUST contain entities that have
- IFC class **IFCSENSOR.USERDEFINED**
- attribute **ObjectType = Accelerometer_Sensor**

that MEET the following requirements
- MUST HAVE IFC class **IFCSENSOR.USERDEFINED**
- MUST HAVE attribute **Name matching the pattern ^ACD(0[1-9]|[1-9][0-9])$**
- MUST HAVE attribute **ObjectType = Accelerometer_Sensor**
- MUST HAVE property **SetPointAcceleration** of PSet **MyPset_SensorTypeAccelerationSensor (IFCREAL)**
- MUST HAVE property **AssessmentDate** of PSet **Pset_Condition**
- MUST HAVE property **Main_Span** of PSet **Identification (IFCTEXT) matching the pattern Span1|Span2|Span3|NA**
- MUST HAVE property **WBS** of PSet **Identification (IFCTEXT)**
- MUST HAVE property **Acquisition_Type** of PSet **General (IFCTEXT) = Permanent ((24h/24h)**
- MUST HAVE property **A_D Conversion** of PSet **General (IFCTEXT) = 20 bit**
- MUST HAVE property **Measurement_Range** of PSet **General (IFCTEXT) = ± 2 g**
- MUST HAVE property **Measurement_Unit** of PSet **General (IFCTEXT) = g**
- MUST HAVE property **Non_linearity** of PSet **General (IFCTEXT) = < 0.1% of Full Scale**
- MUST HAVE property **Operating_Temperature_Range** of PSet **General (IFCTEXT) = -20°C to +80°C**
- MUST HAVE property **Sampling_Rate** of PSet **General (IFCTEXT) = 200 Hz**
- MUST HAVE property **Sensitivity** of PSet **General (IFCTEXT) = 3,81 10^6 a ± 2g LSB/g (typ.)**
- MUST HAVE property **Sensor_Type** of PSet **General (IFCTEXT) = Triaxial**
- MUST HAVE property **Spectral_Noise** of PSet **General (IFCTEXT) = < 25 a 10 Hz µg/√Hz**
- MUST HAVE property **Technology** of PSet **General (IFCTEXT) = MEMS**
- MUST HAVE property **Thermal_Drift_of_Sensitivity** of PSet **General (IFCTEXT) = ±0,01 %/°C**

Figure 2: Human-readable requirements defined for the accelerometer sensor metadata

Following the information requirements definition, the 3D bridge model including sensors and metadata from the human-readable specification was created in Revit then exported to IFC4.3, and audited against the machine-readable requirements using IFCTester in BonsaiBIM. Figure 3 presents the validation outcome for the accelerometer sensors. The results demonstrate that the model successfully passed all compliance checks, thereby verifying that the sensors correctly adhere to the defined information requirements.

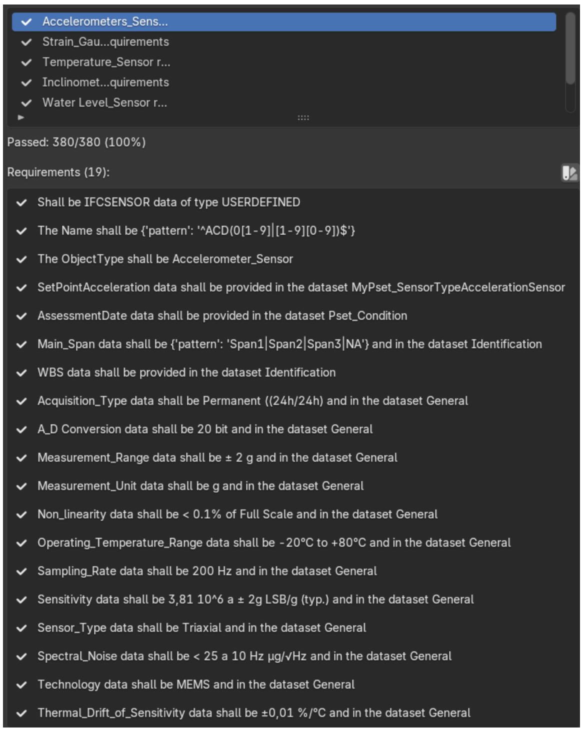


Figure 3: Human-readable requirements defined for the accelerometer sensor metadata

Semantic Linking

Following the successful validation of the model, the next step is to aggregate sensor elements with their hosts under IfcElementAssembly. An initial inspection of the IFC model within widely used BIM viewers, such as BIM Vision and BIMcollab Zoom, confirms that the physical and hierarchical relationships between the host elements and their associated sensors are not natively reflected.

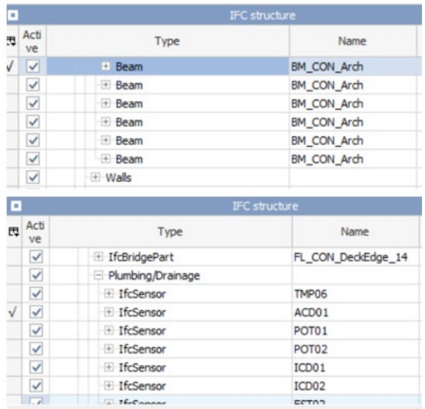


Figure 4:Beams and sensors elements hierarchical representation

Figure 4 displays the default spatial-tree representation, where beams and sensors appear as separate groups without any explicit semantic linkage. To address this, the adopted approach relies on metadata added to each host element to identify which sensors must be grouped with that specific element. This information is provided through the property "Sensors_Instances_Hosted" within the "Data" propertyset of the host element, as illustrated in Figure 5.

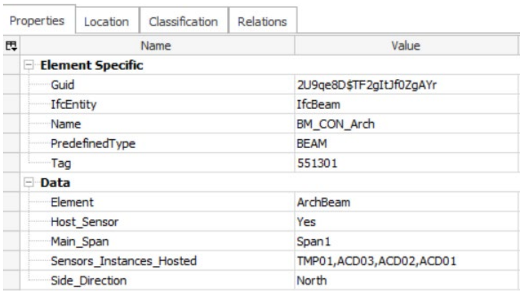


Figure 5:Identification of "Sensors_Instance_Hosted" property to establish linkage between sensors and their host

The overall workflow adopted to aggregate sensors to their host using IfcOpenShell library is illustrated in Figure 6.

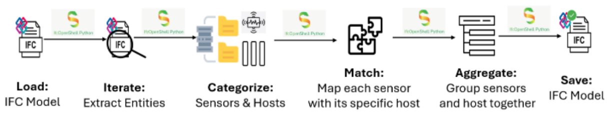


Figure 6:Workflow to semantically link sensors and host element

The entities of the IFC model are iterated, and sensors and potential hosts are categorized into two groups. All IfcSensor entities are indexed by their Name attribute and Globally Unique Identifier (GUID) and stored in a dictionary. Then, during the matching phase, a list of candidate host entities is iterated, and retrieve the value of the custom property "Sensors_Instances_Hosted". This value is parsed into a list of unique identifiers, each cross-referenced against the sensor index to map each sensor directly to its specific host element. Finally, the matched elements (host element and its corresponding sensors) are aggregated into an IfcElementAssembly.The developed script successfully establishes a semantic link between sensors and their host. The result demonstrates interoperability compatibility across different BIM viewers, as shown in Figure 7 (BIM Vision) and Figure 8 (BIMcollab Zoom), where sensors (ACD01, ACD02, ACD03, TMP01) and their host element (BM_CON_Arch) are now grouped together under the assembly (BM_CON_Arch_ASB_12).

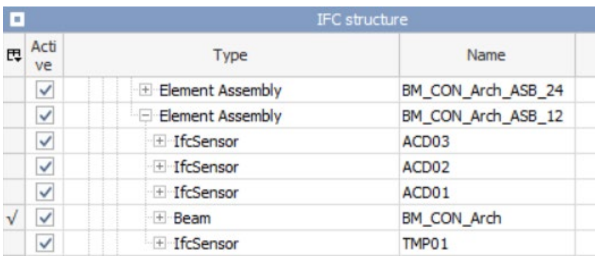


Figure 7:Resulting IfcElementAssembly of a beam element with sensors within BIM vision

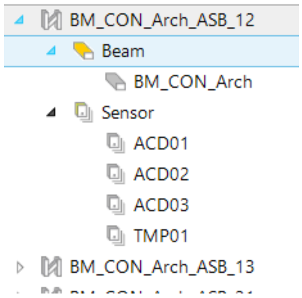


Figure 8:Resulting IfcElementAssembly of a beam element with sensors within BIMcollab Zoom

Database and Model Updating

The relational database designed on MySQL for storing sensor data is illustrated by the entity-relationship model represented in Figure 9.

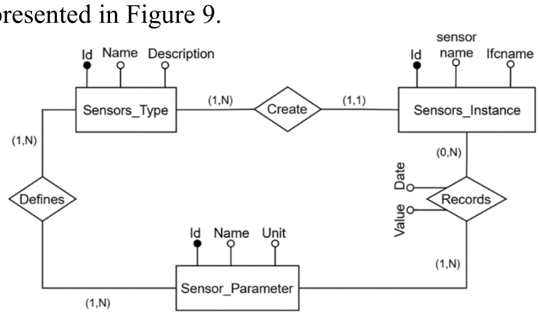


Figure 9:Entity relation model for the sensors database

The data model is organized around three core entities: Sensor_Type, representing the device category; Sensor_Instance, representing the specific physical devices installed on the structure; and Sensor_Parameter, which defines the measured physical quantities. Additionally, the "Records" relationship functions as a transactional entity, storing time-series measurements for each sensor instance

Regarding the IFC model update of IfcSensor instances with significant readings, they are updated with the latest, minimum, and maximum values over the synchronization interval, along with their respective timestamps. The workflow adopted to perform the operation is illustrated in Figure 10.

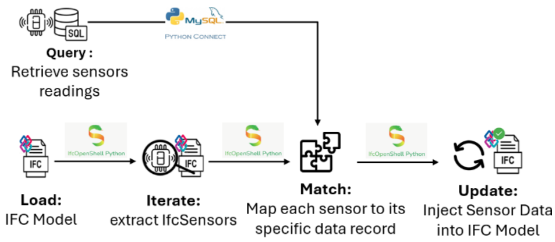


Figure 10:Workflow to update the IFC model with sensor reading

The script developed using IfcOpenShell performs the update as follows. First, the script queries the database to retrieve the values from the appropriate tables. Next, loads the IFC model and iterates through its entities to extract all IfcSensor elements.

During the matching and update phase, the script maps each sensor name from the database to the corresponding IfcName of the sensor within the model. Finally, the model update is performed by injecting the new measurement values and timestamps into the specific IfcProperty fields. The synchronization interval is one hour. Values are overwritten with each update and historical data is not retained within the IFC file. Instead, the complete time-series history is stored in the relational database. Identical IFC sensors that do not receive new sensor data are bypassed and remain untouched. The implementation of this approach is highlighted at Figure 11 and Figure 12, where Figure 11 presents the initial state of a potentiometer sensor (POT01) with default displacement value.

MyPset_Date	
AssessmentDate_Latest	21/05/2022
AssessmentDate_Max	21/05/2022
AssessmentDate_Min	21/05/2022
MyPset_SensorTypeDisplacementSensor	
SetPointDisplacement_Latest	0.01
SetPointDisplacement_Max	0.01
SetPointDisplacement_Min	0.01
Pset_ConstructionOccurence	
AssetIdentifier	POT01

Figure 11:Initial state of the POT01 sensor property before update

Figure 12 presents the successfully updated properties, with the new value and timestamp queried from the database.

MyPset_Date	
AssessmentDate_Latest	2024-12-09 01:59:59
AssessmentDate_Max	2024-12-09 01:59:58
AssessmentDate_Min	2024-12-09 01:12:29
MyPset_SensorTypeDisplacementSensor	
SetPointDisplacement_Latest	0.385801
SetPointDisplacement_Max	0.385806
SetPointDisplacement_Min	0.385636
Pset_ConstructionOccurence	
AssetIdentifier	POT01

Figure 12:Updated property of the POT01 sensor

Web Platform

To make the enriched model accessible, a three-tier web platform was developed as illustrated in Figure 13.

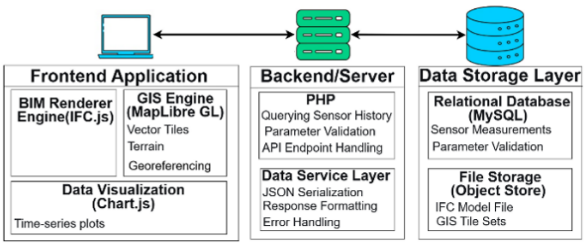


Figure 13:Updated property of the POT01 sensor

The architecture utilizes a MySQL database for data storage, a PHP backend for data processing, and a JavaScript-based frontend. To achieve BIM-GIS-IoT integration, the user interface leverages MapLibre for geospatial rendering, IFC.js for native 3D BIM interaction, and Chart.js for plotting sensor measurements

Figure 14 illustrate the bridge model within the GIS context.

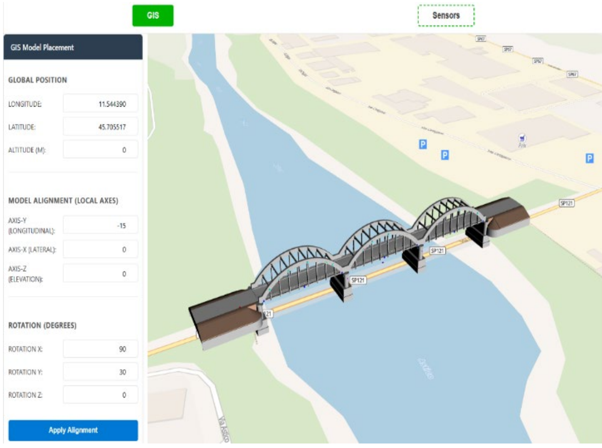


Figure 14:Bridge model into the GIS context

The sensor management interface provides 3D visualization, visibility filtering and element property inspection. Additionally, by interacting with the bridge geometry, users can retrieve measurement data; double-clicking a specific sensor or host element automatically generates the corresponding measurement plots for detailed analysis, as illustrated in Figure 15 for the case of an inclinometer being double-clicked.

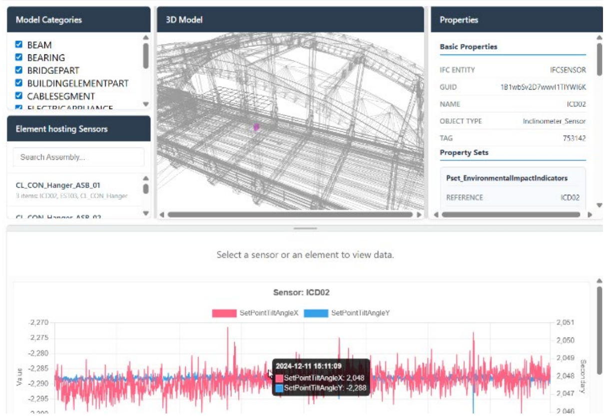


Figure 15:Data plot of an inclinometer measurements by double clicking on the sensor in the 3D model

Similarly, the list of host elements and their semantically nested sensors under IfcElementAssembly is provided in a dedicated window. Selecting an assembly automatically highlights the host element and displays plots for all associated sensors.

Furthermore, a threshold evaluation system was developed for static measurements to visually identify structural host elements exceeding predefined limits within a specified timeframe. Figure 16 shows the 3D model where host elements below the limit appear in green, while those above the threshold are highlighted in red

Figure 16:Threshold-based highlighting of bridge elements in the 3D model

The threshold manager dashboard illustrated in Figure 17 allows users to input threshold values and timeframes, displaying which inclinometer sensors that exceed or remain below the five-degrees limit.

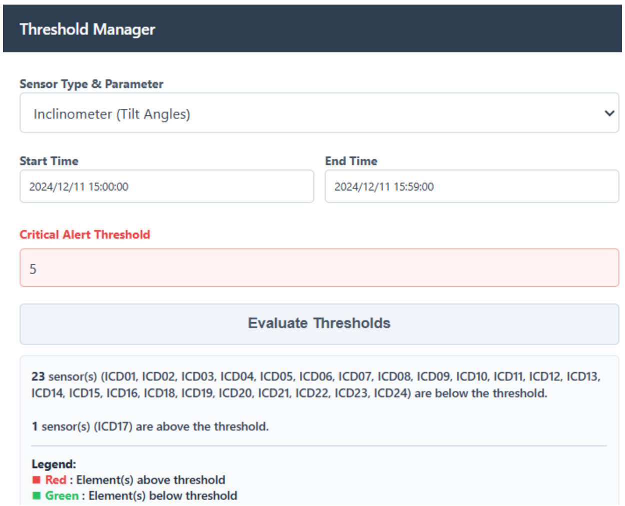


Figure 17:Threshold Manager showing inclinometer sensors above and below the critical limit

Conclusion

This study addressed critical needs identified in both literature and practice by implementing a web-based platform that integrates BIM, GIS, and IoT sensors for bridge monitoring. The platform integrates model checking using Information Delivery Specifications (IDS) to ensure data quality prior to integration. Furthermore, the use of the existing IfcElementAssembly entity links sensors with their host elements, enabling meaningful, machine-readable relationships that support automated querying. The proposed workflow also eliminates the reliance on proprietary data formats and dual-database synchronization for the model updating of IfcSensor instances. By injecting significant measurement values directly into the sensors, generates a temporally consistent view of the host element or environment status over a specific period. This allows users to select a sensor in the 3D model, inspect its properties directly without needing to review a separate measurement plots window. In addition, visualizing the bridge model within the GIS environment provides essential spatial context, while the sensor management interface allows users to interact with the 3D model and plot sensor measurements for detailed analysis. The platform enables the evaluation of both localized element behavior such as displacement tracked via potentiometers and tilt angle measured by inclinometers on specific structural elements and contextual environmental conditions, including relative humidity, temperature, and water levels. Additionally, a threshold-based alert system automatically highlights host elements in the 3D model when sensor readings exceed predefined limits, providing intuitive visual warnings. Nevertheless, some limitations must be noted. Because the semantic linking relies on exact metadata matching, the process can fail if sensor names are missing or incorrect. Future studies could therefore incorporate spatial collision detection algorithms to link sensors to elements based purely on their physical 3D location. Furthermore, while direct static sensor measurements provide a good understanding of localized element behavior, the global structural assessment remains incomplete, future research could integrate experimental data from Operational Modal Analysis (e.g., natural frequencies and mode shapes) with numerical FEM data to evaluate global structural behavior. Despite these current limitations, the proposed workflow provides a highly reliable, open-standard foundation for bridge SHM leveraging openBIM.

Acknowledgments

This work was conducted as part of the Indice Project, Task 2.3, Deliverable 2.3.1, focused on defining Digital Twin solution based on openBIM and IoT protocols. Gratitude is expressed to the BIM team of ITS Engineering Company for their support.

AI Declaration

The authors used generative AI tools to improve the readability and linguistic quality of the manuscript, as well as to assist with code development.

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