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BIM4CE

BIM-based digital twin platform based on a demonstrator

Work package 2

Version 1

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Table of content

1. Introduction

The critical need for reliable infrastructure monitoring has brought advanced digital modeling techniques, such as Building Information Modeling (BIM) and Digital Twins (DT), to the forefront of bridge maintenance and safety. Central Europe, with its aging bridge infrastructure and diverse environmental conditions, faces unique challenges that demand innovative approaches to ensure structural health and longevity. In this project, we aim to demonstrate a BIM-based Digital Twin approach specifically tailored for one of the pilot bridges identified in WP1, providing a real-world example of how real-time data integration can enhance bridge monitoring capabilities.

This report presents the BIM approach utilized to create a dynamic and interactive Digital Twin of a pilot bridge, integrating real-time sensor data to support structural health monitoring. By combining a precise BIM model created from 3D scanning data with a sensor-based measurement system, and using Infohub and DESITE BIM md as the central digital twin platform, it is aimed to establish a scalable, adaptable framework for bridge monitoring. This approach allows for real-time visualization and data-driven insights that can inform stakeholders, foster preventive maintenance, and improve public safety.

The demonstrator will not only validate the BIM and DT methods chosen in previous project phases but will also showcase their real-world application. Furthermore, it will serve as a communication tool to demonstrate the value and capabilities of Digital Twin technology to regional stakeholders and the general public, accessible through an interactive model. This report details the processes, tools, and requirements involved in creating and implementing this Digital Twin, as well as the practical and technical insights gained from the demonstrator project.

2. Demonstrator Project Overview

2.1. Project Goals and Objectives for the Demonstrator

The goal of the BIM4CE project is to create an affordable and scalable structural health monitoring system for bridges with the integration of the data into a digital twin of the structure. While the hardware parts of the system have individually been tested on real bridges, the purpose of the demonstrator is to showcase the integration of all the different sensors into a digital twin model.

The digital twin will enable live monitoring of various parameters important for the structural monitoring of the bridge:

- Gross vehicle weight (GVW) of heavy goods vehicles passing over the bridge
- Air temperature
- Acceleration of the bridge
- Natural frequencies of the bridge
- Leakage

2.2. Selection of the Pilot Bridge

Selection of bridges was part of WP1, Deliverables 1.3.1 and 1.3.2. Three main criteria were used to select pilot sites:

- Analysis of existing bridges in Germany, Italy, and Slovenia: pilot sites had to correspond to the types of bridges that are common in all three countries.
- Logistical aspects: parameters, such as the ease of access to the bridge, access to the electrical grid, internet coverage, etc., were also taken into consideration.
- General requirements for bridge WIM: Since bridge weigh-in-motion (WIM) is part of the system, the selection also followed general guidelines in the selection of bridges appropriate for bridge WIM measurements.

One of the selected pilot sites is Tomačevo bridge, which is located at the outskirts of Ljubljana, Slovenia, and will also serve as a demonstrator. There are two separate parallel bridges at the location, but only the bridge, which carries a 2-lane expressway in the direction of Ljubljana, will be used in the project.

The bridge measures 204 m in length and is 11 m wide. It is a prestressed concrete girder bridge with seven spans, comprising six pairs of reinforced concrete piers, a continuous cast-in-place deck with a double-T concrete section, and abutments located at both ends of the bridge. The structure itself is in good condition, although some problems with leakage have been observed in the area of the bridge joint.

Figure 1: Tomačevo bridge

With scalability of the SHM system in mind, it is not necessary to visualize or monitor all of the aforementioned parameters; the bridge owner/structural engineer can decide on which exact variables to include in the structural health monitoring system. This is especially important since infrastructure owners use different SHM methodologies to monitor their bridges; some emphasize vibration-based monitoring, others strain data, traffic data, etc.

2.2.1. Monitored parameters

For the purposes of Activity 2.3, the following parameters will be monitored at Tomačevo bridge and integrated into the digital twin:

- Gross vehicle weight of heavy vehicles (vehicles over 3.5 t)
- Air temperature
- Acceleration of the bridge in the z direction (perpendicular to the road surface)
- Natural frequencies of the bridge
- Leakage

Heavy vehicles can be an important component in the assessment of existing bridges, which must remain inside the safety margins under actual and future traffic (Zhou, 2013). At the same time, law enforcement agencies are interested in the data on GVW of heavy vehicles, as the national legislations govern the maximum allowed mass and axle loads of HGVs due to their impact on roads, bridges and traffic safety.

The measurement of acceleration forms the basis for the vibration-based monitoring of bridges. Acceleration is the basic data, from which one can derive additional information, such as deflection, natural frequencies, damping, etc.: “Analysis of acceleration measurements can derive natural frequencies that depend on weight, material, stress and strain as well as the geometry of the object. Hence this data can be used to derive additional information about the capacity and condition of a structure (Neitzel et al., 2011).” Changes in the natural frequency of the structure are used to identify changes in the structural behaviour due to damage and structural deterioration. Since the natural frequency also varies with temperatures, it is important to also monitor atmospheric parameters when analysing these parameters (Laory et al, 2014).

Water leakage can be problematic for bridges, especially for expansion joint - a survey in the USA conducted by the Federal Highway Administration showed that 60 % of joint were leaking water. This is problematic due to the intrusion of salt into the structure, which propagates corrosion, spalling of the back wall, and the substructure (Chang and Lee, 2012).

Integration of the aforementioned data through BIM-DT approach will enable different stakeholders to access and use the data they need. First and foremost, the purpose of the system is long-term structural health monitoring of bridges. This facilitates the decision-making process when it comes to predictive maintenance, bridge engineers will be able to use the data in bridge analysis, law enforcement agencies will be able to monitor heavy vehicles, etc.

2.3. Stakeholder Involvement and Communication

The Tomačevo bridge is managed by the Slovenian infrastructure agency, a state-owned agency, which manages approximately 6.000 km of state and regional roads in Slovenia. They are responsible for the maintenance of the bridge and the road at the Tomačevo road section.

The demonstrator will be shown to the representatives from the agency’s department for bridges. They will be taken on a tour of the bridge, where the installed equipment and software will be presented to them. Additionally, a presentation of the developed digital twin and the collected data will be prepared.

2.4. From Vision to Implementation: Transitioning to Technical Requirements

The demonstrator outlined in the previous sections establishes the strategic framework for integrating real-time monitoring into a digital representation of bridge infrastructure. To realize this vision, a robust and semantically structured Building Information Model (BIM) is essential. The following chapter defines the technical requirements and specifications for developing such a model, ensuring that it supports the integration of sensor data, enables seamless interoperability, and aligns with international standards. This forms the foundation for implementing a functional and scalable Digital Twin of the Tomačevo Bridge.

3. Defining Requirements for the BIM Model

The creation of a Building Information Model (BIM) is a foundational step in the development of the Digital Twin (DT) demonstrator for the Tomačevo Bridge. This chapter defines the key requirements for the BIM model, ensuring alignment with the project's objective of integrating real-time monitoring data within an intelligent, interactive platform. Building on the methodologies and outcomes of Deliverable 2.1.1, this section defines the scope of the model, technical requirements, data standards, and the semantic and structural organization needed to support integration into the digital twin platform.

3.1. Scope and Objectives of the BIM Model

The BIM model functions as the central digital representation of the bridge within the DT system, enabling the integration of spatial geometry, semantic data, and sensor inputs for real-time monitoring. The core objectives are as follows:

- Geometric Representation for Monitoring: The model will provide simplified yet spatially accurate geometry for essential bridge elements (e.g., beams, columns, abutments) suitable for sensor positioning.
- Semantic Enrichment and Sensor Integration: The model is structured to enable linking of real-time data streams with sensor elements for condition tracking and performance analysis.
- Open and Interoperable Framework: The use of openBIM standards such as IFC ensures compatibility with tools and software like DESITE BIM md, DEWESoftX, and Infohub.
- Support for Data Exchange and Visualization: The BIM model serves as the reference for visualization within the DT interface, supporting enriched interaction through metadata and monitoring data.

These objectives provide a practical foundation for realizing a bridge-specific Digital Twin aligned with cost-effective and scalable asset monitoring goals.

3.2. Technical Specifications and Standards

The BIM model requirements in this project are guided by the principles of Level of Information Need (LOIN) as defined in BS EN ISO 7817-1:2024 and aligned with ISO 19650. LOIN provides a unified framework for defining and delivering information that includes geometric, alphanumerical, and documentary components — all contextualized to the purpose and timing of use. As such, LOIN has been adopted as the overarching methodology for specifying information in this project, fully replacing the traditional concept of Level of Development (LOD).

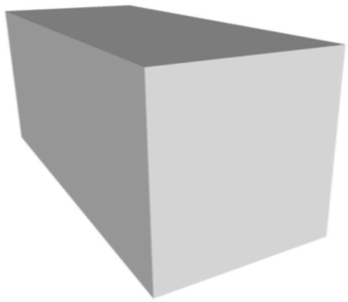
3.2.1. Level of Information Need (LOIN)

LOIN specifies the amount, format, and precision of data required to support key project uses such as sensor placement, condition monitoring, and digital twin integration. In this context, LOIN includes:

- Geometrical Information: 3D model elements such as beams, abutments, and columns with approximate location, shape, and orientation, sufficient for contextual sensor placement and visualization.
- Alphanumerical Information: Metadata about the objects, including structural material, unique identifiers, and linked sensor types.

- Documentation: Accompanying files such as attribute libraries, file naming conventions, and monitoring protocols stored in structured formats.

This project uses LOIN to establish what information is necessary for sensor placement, bridge condition monitoring, and data exchange with Infohub. The scope of geometric detail aligns with what was previously considered LOD 200, where model elements are graphically represented as approximate placeholders sufficient for recognition and general layout (BIMForum 2023), as illustrated in Figure 2.



LOD 200:
Elements modeling to include:

- Type of structural concrete system
- Approximate geometry (e.g. depth) of structural elements

Figure 2: Highway Bridges Precast Structural I Girder (Concrete) (BIMForum, 2016).

To ensure that the BIM model fulfills its role as a functional Digital Twin for bridge monitoring, it will adhere to specific technical specifications and standards that align with project requirements for simplicity, accuracy, and compatibility.

3.2.2. File Formats and Interoperability

To ensure seamless data exchange and interoperability between different software platforms, the following industry-standard file formats are used:

- Point Cloud Data: E57 – Compatible with CloudCompare for pre-processing
- BIM Model Data: IFC (Industry Foundation Classes) – openBIM-compliant, ensures compatibility with DESITE BIM md and Infohub
- Sensor Data: CSV – Compatible with DEWESoft X for integration with Infohub
- Metadata and Naming Conventions: CSV and JSON.

Using standardized formats allows for smooth data transfer between scanning devices, sensor data collection devices, and the digital twin platform.

3.2.3. Data Management and Structuring

Consistent naming conventions and attribute definitions and classifications are used to organize data within the model. This ensures clear identification and management of key structural elements.

Naming Convention: To ensure uniform and systematic naming throughout the project lifecycle, a structured naming convention is developed for naming models, documents, and other project-related materials. This convention significantly improves both organization and collaboration.

The naming conventions are divided into multiple levels, with each level encoding specific information such as project phase, discipline, or version to ensure a clear and consistent file name structure. This structured approach enables the efficient use of common data environments (CDE), in this project Infohub, systems for storing, filtering, and managing project information.

The naming convention is structured into ten hierarchical levels to ensure clarity, traceability, and consistency across all project files. The first three levels pertain to geographic identification:

- **Level 01** contains a four-character code representing the bridge name.
- **Level 02** uses a two-character code for the country of the bridge.
- **Level 03** includes a three-character code denoting the city where the bridge is located.

The following levels define the document's content and origin:

- **Level 04** identifies the file creator.
- **Level 05** specifies the responsible project partner.
- **Level 06** indicates the trade or discipline model (e.g., structural, sensor data).
- **Levels 07 and 08** define the general and specific document types, respectively.
- **Level 09** provides space for additional metadata, such as the date of data collection.
- **Level 10** assigns a unique sequential number for version control.

The exact character length and format requirements for each level are summarized in Table 1.

Table 1: Naming convention for the files

LEVEL	DESCRIPTION	CODE LENGTH	EXAMPLE
Level 01	Project Name	4 characters	Sant Ambrogio Bridge (SAMB) IDA-KI Bridge (IDAK) Tomačevo Bridge (TOMA)
Level 02	Location 1 (Country)	2 characters	Austria (AU) Croatia (CR) Czech Republic (CZ) Germany (GE) Hungary (HU) Italy (IT) Poland (PO) Slovakia (SK) Slovenia (SN)
Level 03	Location 2 (City)	3 characters	Dresden (DRE) Ljubljana (LJU) Turin (TUR)
Level 04	Creator	2-3 characters	Joint (JO) Lead partner (LP) Owner (LP) Project partner (PP) Third parties (TP)

LEVEL	DESCRIPTION	CODE LENGTH	EXAMPLE
Level 05	Responsible partner	2-4 characters	Joint (JO) TUD (LP) FOS (PP2) CSP (PP3) SPD (PP4) Cestel (PP6) ZAG (PP8) SINA (PP9) … (PP10)
Level 06	Discipline model	2-3 characters	Interdisciplinary (INT) Civil engineering (CE) Monitoring data (MD) Surveying and/or scanning (SU)
Level 07	Document type (General)	2-3 characters	2D plan (2D) Coordination model (CM) Discipline model (DM) Documentation (DOC) Internal standards (IS) Report (REP) Sensor data (SD) Templates (TEM)
Level 08	Document type (Detailed)	2-3 character	General (GEN) BIM attributes (BA) Bridge data frequency (BDF) Bridge data leakage (BDL) Bridge data temperature (BDT) Name convention file level (NCF) Name convention object level (NCO) Vehicle data acceleration (VDA) Vehicle data gross vehicle weight (VDG)
Level 09	Free Text Field	1-25 characters	Data gathering date (YYMMDD)
Level 10	Versioning	3 characters	0 (000) 1 (001) . . . 999 (999)

For example, the file name TOMA_SN_LJU_PP_PP6_MD_SD_VDA_250423_000.csv can be interpreted as follows:

- **TOMA**: The project name, referring to the Tomačevo Bridge.
- **SN**: The country code, indicating Slovenia.
- **LJU**: The city code, representing Ljubljana.
- **PP**: The file was created by a project partner.
- **PP6**: The specific partner responsible for the file, in this case, Cestel.

- **MD**: The document type, indicating bridge monitoring data.
- **SD**: A detailed classification, specifying that the file contains sensor data.
- **VDA**: The type of sensor data—Vehicle Data Acceleration.
- **250423**: The date the data was collected, in DDMMYY format (23 April 2025).
- **000**: A sequential number identifying this as the first version of the file.

Attribute definition and classification: To enable efficient monitoring and seamless data integration, each bridge element and sensor must be assigned a set of clearly defined attributes aligned with the project's monitoring objectives.

The elements are organized into two main groups: Bridge and BridgeSens. Within these, subgroups are specified to refine classification:

- For the Bridge group, the subgroups include Substructure and Superstructure.
- For the BridgeSens group, the Sensor subgroup is defined, which includes the following key elements:
  - 3AxialAccelerometer
  - WeighInMotion
  - Leakage

Each of these elements is further described using specific PropertySets, categorized as:

- **General** – for metadata and identification
- **Structure** – for physical and geometric properties
- **Measurement** – for monitoring and sensor data

Additionally, each property is classified as either mandatory or optional, establishing a clear hierarchy and scope for data processing. This structured approach ensures precise, consistent model development and guarantees that all critical information is captured and utilized effectively throughout the monitoring and analysis process. This attribute structure and classification hierarchy is illustrated in Figure 3.

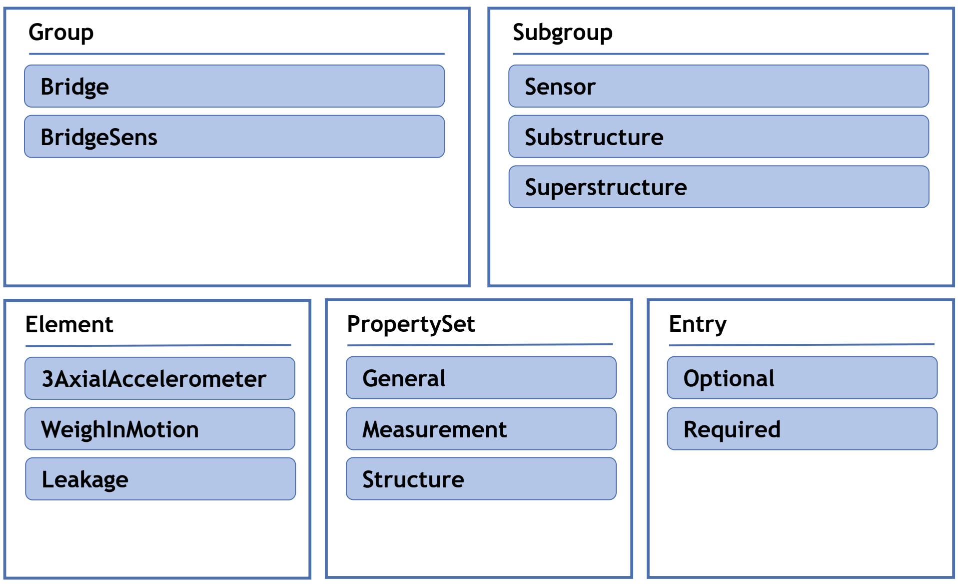


Figure 3: Classification of the attributes.

By fully applying the Level of Information Need framework, this BIM model delivers the necessary semantic and geometric information to support Digital Twin functionality, while remaining aligned with international BIM standards and optimized for integration with real-time monitoring data.

4. Creating the BIM Model

The development of the BIM model for the Tomačevo Bridge forms a fundamental component of the Digital Twin demonstrator. It establishes the spatial and semantic foundation upon which real-time monitoring, data integration, and visualization processes are built. This chapter outlines the structured workflow adopted to transform available data, including existing CAD drawings and 3D scans, into a semantically enriched, interoperable BIM model aligned with the project's monitoring requirements and international BIM standards.

4.1. Processing Available Data and Creating Geometric Model

The process begins with the acquisition and structuring of geometric data from two primary sources: existing CAD documentation and newly collected point cloud data. The aim is to generate a simplified geometric model representing essential bridge components, particularly those relevant for sensor integration, while maintaining alignment with the LOIN requirements.

4.1.1. Existing CAD Documentation

Where available, existing 2D CAD drawings or 3D models are used as foundational references. These documents provide valuable geometric and spatial data about structural elements. Although often outdated or incomplete, they help accelerate the modeling process and reduce redundant data acquisition efforts. In this project, certain CAD drawings have also been used to determine appropriate sensor positioning, particularly in areas where detailed geometric information from point cloud data was not sufficient or accessible. These drawings provide baseline spatial references for aligning sensors with structural components in the model.

4.1.2. Point Cloud Data Collection and Processing

In parallel, high-resolution 3D point cloud data is collected through LiDAR scanning devices. The point cloud captures the actual, as-is condition of the bridge, serving as the basis for geometric modeling.

Data Pre-Processing: CloudCompare, an open-source tool, is used to clean, align, and segment the point cloud. This includes noise reduction, coordinate transformation, and extraction of key structural elements.

Segmentation and Mesh Generation: Structural features such as beams, columns, and abutments are isolated and converted into mesh geometries. Care is taken to retain sufficient accuracy for sensor placement while simplifying the model for usability.

Model Structuring and Export: Using Python scripts, the processed geometry is organized into a hierarchically structured model compliant with openBIM standards. The final geometric model is exported as a geo-referenced IFC file and stored on Infohub for use in the DT platform.

4.2. Semantic Enrichment of the Geometric Model

Once the geometric model of the bridge has been generated, it is semantically enriched with structured data to enable its use within the Digital Twin platform. This semantic layer ensures that each bridge component and associated sensor can be uniquely identified, classified, and linked with corresponding monitoring data.

The enrichment process begins with the classification of model elements into two main groups, following the attribute schema defined in Chapter 3:

- Bridge: encompassing physical structural elements, such as the substructure (e.g., abutments, columns) and superstructure (e.g., beams).
- BridgeSens: representing sensor systems, which include subgroups and elements such as 3AxialAccelerometer, WeighInMotion, and Leakage detection.

Each element within these groups is enriched using a standardized set of PropertySets, which fall into three primary categories:

- General – Includes metadata such as bridge name, object ID, and element classification.
- Structure – Describes the physical characteristics of each element, including approximate geometry, material type, and spatial orientation.
- Measurement – Defines the data fields relevant to monitoring processes, such as sensor ID, measurement type, and threshold indicators.

Attributes are further tagged as mandatory or optional, based on their role in data processing and visualization within the DT platform. This helps prioritize data integration and ensures completeness during model development.

In addition to semantic tagging, sensor locations are instantiated in the model according to the actual installation layout defined in the monitoring plan. These sensor objects are georeferenced and hierarchically structured according to the LOIN framework, using data from standardized .csv and .json files stored on Infohub.

The enriched model is saved in the IFC (Industry Foundation Classes) format to maintain interoperability and long-term usability. The open IFC structure allows seamless integration with Infohub and DESITE BIM md, ensuring that real-time sensor data can be linked directly to the model elements for visualization, monitoring, and analysis.

Through this structured semantic enrichment process, the BIM model becomes more than a geometric representation, it evolves into an intelligent, data-driven foundation for real-time digital twin monitoring and predictive maintenance.

5. Measurement System and Sensor Data Collection

5.1. Overview of Sensor Data Requirements

The system installed at Tomačevo bridge is composed of the following types of sensors:

- Strain transducer sensors and temperature sensors (together forming the bridge weigh-in-motion system)
- Accelerometers
- Leakage sensors

Bridge weigh-in-motion sensors will gather data on the gross vehicle weight (GVW) of the passing vehicles. One of the design parameters of bridges is traffic loading, which will pass over the structure during its lifetime. In this regard, an especially important group of vehicles is exceptional transport vehicles, which are defined as vehicles whose weight or dimensions are outside of the parameters allowed in normal traffic. When looking at the GVW, in Slovenia, the maximum allowed limit for normal traffic operation is 40 t, so any vehicles weighing over this limit need to have a special transport permit. The road section, where the Tomačevo bridge is located, is in the vicinity of a factory, which produces electrical generators; these can weigh over 300 t and are often transported over the bridge. Recording the frequency of the passage of this kind of vehicle is thus valuable for bridge engineers. Bridge weigh-in-motion system also includes two temperature sensors, which measure air temperature and concrete temperature – temperature input is needed for the compensation algorithm of the bridge WIM system, while it is also a valuable information in and of itself for the engineers, as the air temperature can be correlated with the changes in the natural frequencies of the structure.

Accelerometers measure various parameters: from the peak acceleration, which is correlated to the passage of heavy vehicles, to the natural frequencies of the structure. Any changes in the natural frequency, which cannot be explained by the differences in temperature or traffic composition, may indicate an alteration in the bridge's structural response, potentially signalling damage or degradation. This can serve as an alarm to the bridge owner for a bridge inspection.

Leakage sensors detect the presence of water at the area of installation. During a bridge inspection of the Tomačevo bridge, significant amounts of water have been observed at an area below the bridge joints. Monitoring this area with the leakage sensors would give bridge engineers an information on how often the leakage occurs and how extensive the affected area is. Since the principal inspection of the bridge is done every 6 years, leakage sensors would enable the detection of leakage much earlier.

5.2. Sensor Selection and Installation

5.2.1. Bridge Weigh-in-Motion Sensors

ST-504 bridge weigh-in-motion sensors (Figure 4), which are part of the SiWIM MkIV bridge weigh-in-motion system (produced by PP6), will be used in the bridge weigh-in-motion role. These are made of four strain gauges connected in a full Wheatstone bridge configuration. They are installed across the width of the bridge at the mid-point of the span, where the bending moment caused by the passage of a heavy vehicle is the largest. These sensors were chosen as they are the only commercially available bridge weigh-in-motion sensors on the market.

Figure 4: ST-504 sensor (Source: Cestel).

Figure 5 shows the installation of the bridge weigh-in-motion system at a slab bridge.

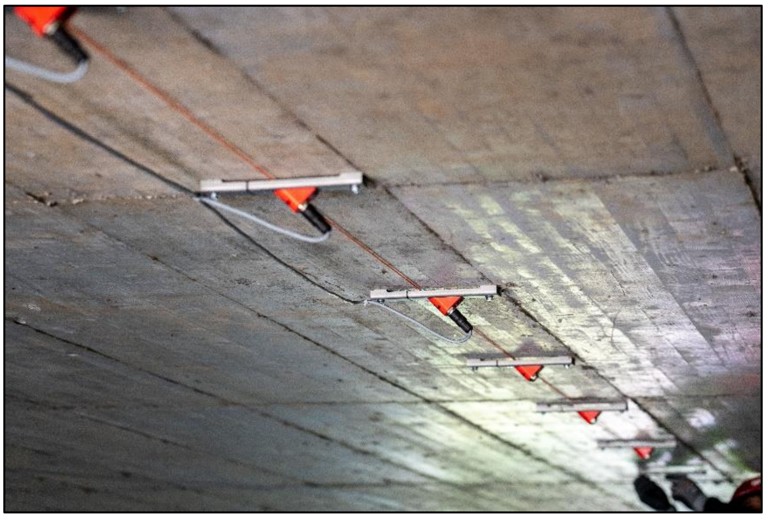


Figure 5: Bridge WIM sensors installed under the bridge(Source: Cestel).

On concrete bridges, such as the Tomačevo bridge, ST-504 sensors are fastened to the soffit of the bridge with two bolts (M6x25) and are connected to the systems cabinet with cables (Figure 6). ST-504 sensors are strain transducer sensors, whose raw output is measured in millivolts. The measuring algorithm is used to convert these raw signals to usable data, such as gross vehicle weight of a passing vehicle.

Figure 6: Installation procedure, ST-504 sensors (Source: Cestel).

ST-504 sensors do not need any special maintenance procedures. Since the bridge weigh-in-motion system is modular, sensors are only replaced if they malfunction, as the failure of a sensor only affects the lane, where it is installed.

5.2.2. Temperature Sensors

Temperature sensors (Figure 7) are an integral part of the bridge weigh-in-motion system. The type of sensors used is platinum resistance sensor with 100 Ω resistance. These sensors can be used to measure air temperature, while the probe of the sensor can also be used to measure the temperature of asphalt or concrete.

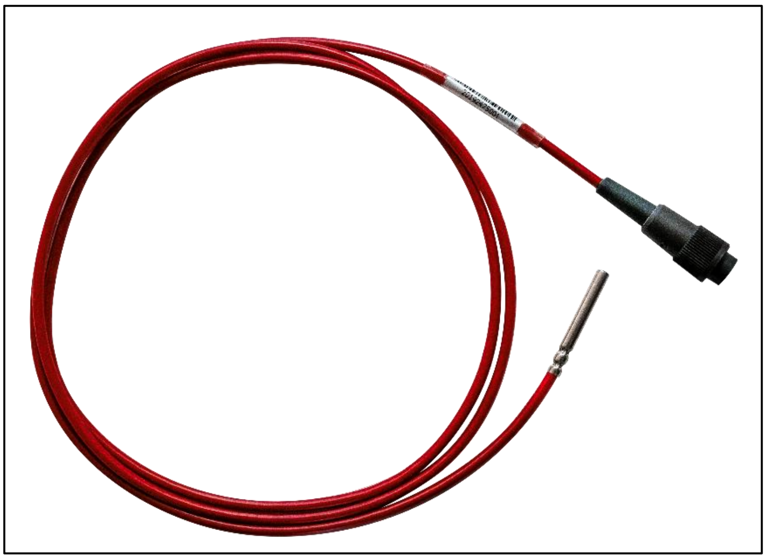


Figure 7: PT100 temperature sensor (Source: Cestel).

5.2.3. Accelerometers

Triaxial accelerometers made by Dewesoft (Figure 8) will be used in the structural health monitoring role. The sensors can measure various physical quantities; at Tomačevo bridge, the accelerometers will be used to measure the vertical acceleration of passing heavy goods vehicles, which will be correlated to the output of the bridge weigh-in-motion system, and the natural frequency of the bridge (measured in Hz). These sensors were chosen because they support the PoE connection, making the integration with the bridge WIM system data easier.

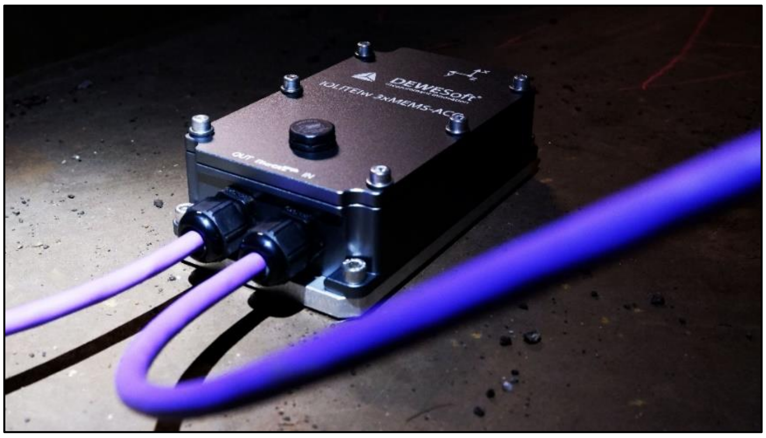


Figure 8: Triaxial accelrometer, Dewesoft IOLITE 3xMEMS (Source: Cestel).

Accelerometers are installed on a bridge with the help of steel mounting plates, which are bolted to the structure with M6x20 bolts. Sensors have been designed for long-term monitoring, so no special maintenance tasks are needed during their operation.

5.2.4. Leakage Sensors

Flexible sensor foils (Figure 9) will be used to detect leakage at the critical parts of the bridge. These types of sensors are printed on a foil, its dimension can be customized for the specific affected area.

The installation of sensor foils depends on the duration of the measurement and the area of installation.

Figure 9: Sensor foil (Source: Cestel).

5.3. Data Collection and Storage with DewesoftX

Figure 11 shows the integration pipeline. The system consists of three parts: bridge WIM sensors, accelerometers, and leakage sensors. DewesoftX data acquisition software is used whenever time synchronization of data between different parts of the system is needed. It is a free software with free lifetime updates, which is running on a computer installed in a cabinet at the measuring location (see Figure 10).

Figure 10: Cabinets of the system - one cabinet contains the electronic components of the bridge WIM system, another one contains the components of the SHM system, the last one is an electrical cabinet (Source: Cestel).

A separate .csv file will be created for each parameter – acceleration will be contained in one file, leakage data in another, etc. Timestamps, which are an essential part of each .csv file, will then be used to match the data in the Digital Twin. Two sets of timestamps will be used:

- vehicle-related timestamps
- bridge-related timestamps

Vehicle-related timestamps are created by the bridge WIM system based on the passage of a heavy vehicle. In order to assign a value from accelerometers to a vehicle (for example: what was the maximum acceleration of the bridge during the passage of a 40 t vehicle), DewesoftX correlates the output of bridge WIM sensors and accelerometers via the Network Time Protocol. This setup does have some limitations in case of multilane bridges (more than 4 lanes) and dense traffic conditions, where it is difficult to accurately assign structural parameters to a passage of a single vehicle. In such cases, the solution is to use the data which was gathered during the time of day, when the traffic was less dense (for example, at night). At Tomačevo bridge, the traffic flow is in normal parameters, so this limitation does not come into effect.

Bridge-related timestamps are correlated with parameters, which are important for monitoring the structure of the bridge and are determined arbitrarily. Currently, bridge-related data is stored every 10 minutes, but this can be changed depending on the requirements of the users. At Tomačevo bridge, the bridge-related data is the ambient temperature and leakage information.

In case of any malfunctions of the system's hardware, the .csv file will contain a "NoData" value under the Sensors Value column.

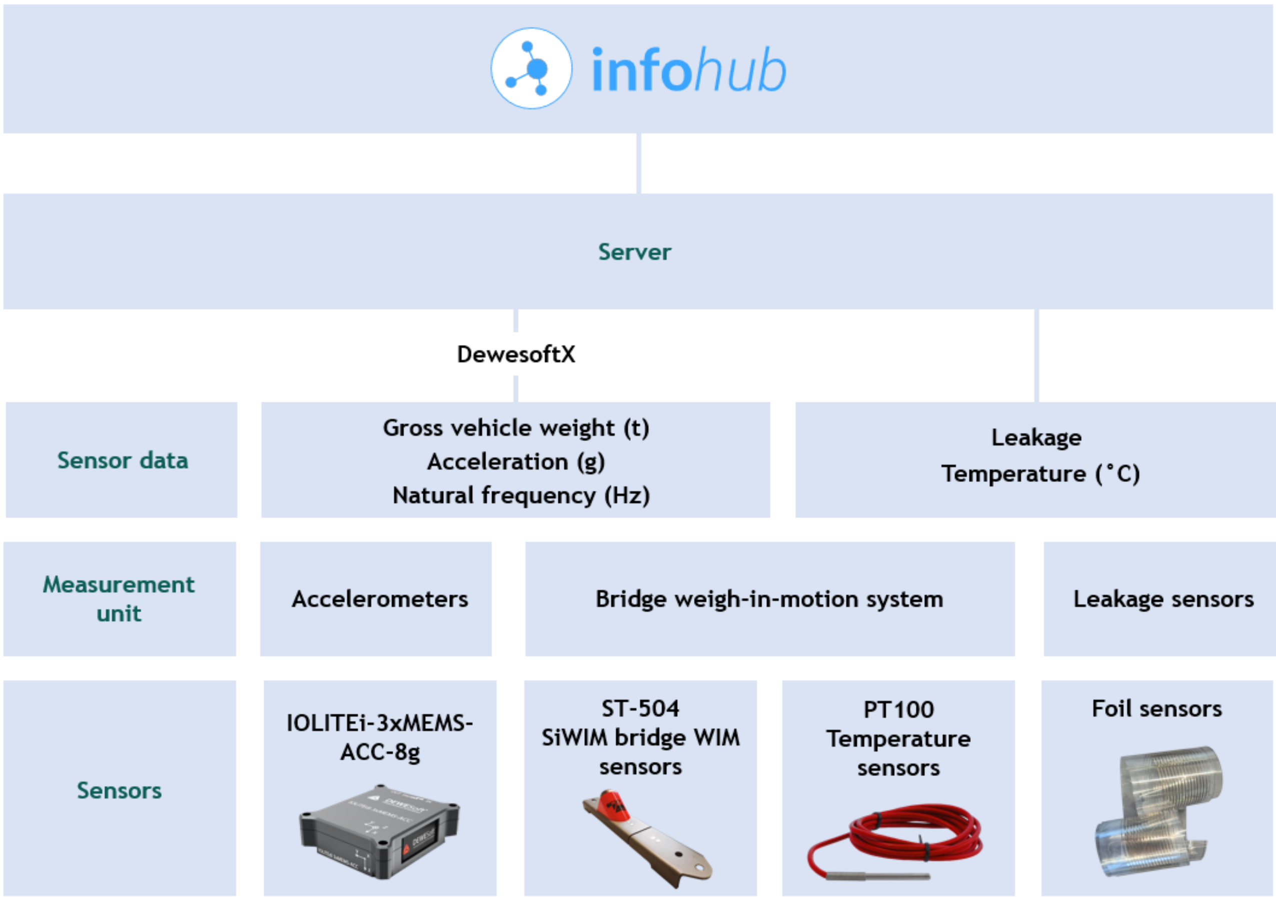


Figure 11: An overview of the integration of the system components into Infohub.

5.3.1. Integrated data

A separate .csv file will be prepared for each measured parameter. All the .csv files will be sent to Infohub after midnight with the data from the previous day. Based on the tests done at Tomačevo bridge, the size of each .csv file is in the range of 10 KB. The variables, which have the biggest effect on the size of the files, are the following:

- Traffic density
- Sample rate of accelerometers and the frequency at which the accelerometer data is gathered (for example: accelerometers can have a sample rate of more than 500 Hz: writing this much data into a .csv file would inflate its size)
- Data type

Table 2 shows all the possible outputs of the sensors, which are installed at the pilot site Tomačevo bridge.

Table 2: Sensor output overview.

SENSOR TYPE	DATA	INTEGRATED AT TOMAČEVO DIGITAL TWIN
Bridge WIM	Gross vehicle weight of heavy vehicles (t)	Yes
Bridge WIM	Axle loads of heavy vehicles (t)	No
Bridge WIM	Speed of heavy vehicles (m/s)	No
Bridge WIM	Vehicle classification based on axle configuration	No
Bridge WIM	Axle distances (m)	No
Bridge WIM	Temperature (°C)	Yes
Accelerometer	Acceleration in three axes (m/s^2)	Yes, only in vertical axis
Accelerometer	Deflection in three axes (mm)	No
Accelerometer	Vibrations (Hz)	No
Accelerometer	Natural frequency (Hz)	Yes
Leakage sensor	Presence of water	Yes

Bridge WIM sensors detect each individual heavy vehicle (vehicle over 3,5 t) and determine its gross vehicle weight, axle loads, speed and axle characteristics, based upon which the vehicle can also be classified.

3-axial accelerometers primarily measure acceleration in x, y and z axes. With the method of double integration, approximation of the deflection of the bridge can also be derived from acceleration measurement, as well as natural frequencies of the bridge. A complete estimation of bridge dynamic characteristics, such as natural frequencies, modes shape and damping, is obtained from acceleration data through the method of Operational Modal Analysis (OMA).

Leakage sensors detect the presence and quantity of water, which indicates leakage.

All the data from Table 2 can be integrated into the .csv files and sent to the Digital Twin platform, Infohub.

5.4. Real-Time Data Processing and Preliminary Analysis

At the bridge, there is a special cabinet containing a computer (see Figure 10), which will be used to join the data from different parts of the system. Accelerometers are connected to the computer via the EtherCAT protocol, while the data from the bridge WIM system is sent to the computer via Transmission Control Protocol. The Network Time Protocol method is utilized to synchronize the data from accelerometers and bridge WIM sensors. Leakage sensor data will be uploaded to the computer via WiFi connection.

DewesoftX data acquisition software, which is running on the computer, is used to join and, if necessary, match the output from bridge WIM and accelerometers. The following procedure is used: bridge weigh-in-motion system detects a vehicle and its timestamp. This timestamp is then sent to the DewesoftX software, which searches for the data from accelerometers in the timestamp of the event and half a second before and after the event. The maximum value of the acceleration in this time window is then written into the .csv file next to the vehicle’s timestamp.

A Python script running on the computer converts the files into a .csv file and does additional processing of data. At the Demonstrator, the data processing via the Python script will be done with the calculation of the natural frequencies of the bridge and the conversion of GVW from kN to t, but the process can be used later for various other calculations needed by the users.

The output from the leakage sensors will be uploaded to the system’s computer and inserted into a separate .csv file.

The documentation regarding the DewesoftX software (API, code automation process, etc.) is available via the link below.

Alert thresholds can be set for certain parameters. At the Demonstrator, the threshold, which will be set, can be found in Table 3. In the next phase of the project, further analysis will be conducted, and appropriate threshold values for changes in natural frequencies will also be established.

Table 3: Thresholds of the measured parameters.

PARAMETER	THRESHOLD
Gross vehicle weight	40 t (vehicles over 40 t can be considered overloaded except for exceptional transports)
Acceleration	One standard deviation from the maximum value
Leakage	Frequency of 8000 Hz for dry state, and approx. 4000 Hz for leaking state. The sensor is still in development; exact thresholds will be determined at a later stage

5.4.1. Data visualization

Two main graphs will be initially visualized online for the digital twin of the Demonstrator:

- GVW (y axis) vs. timestamps of vehicles (x axis) –Figure 12

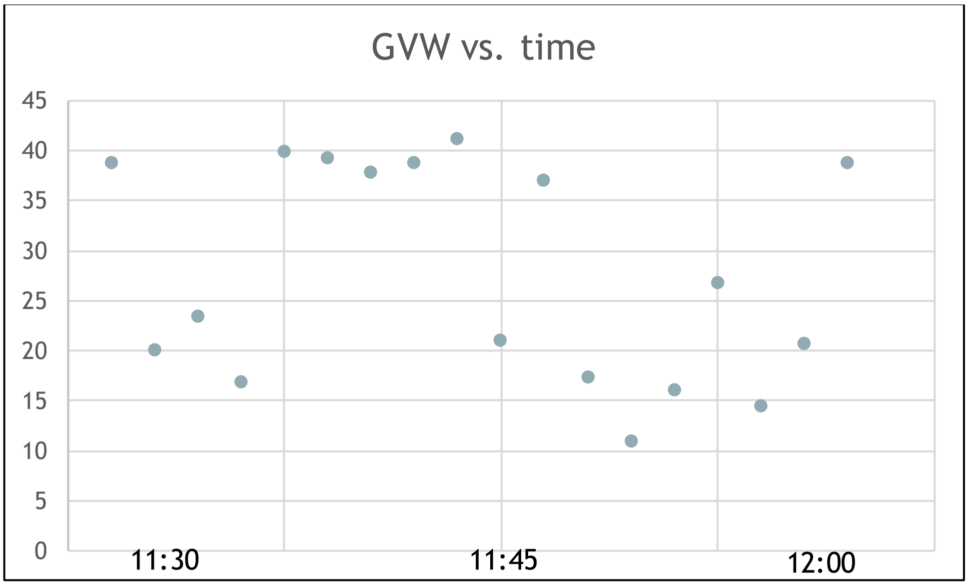


Figure 12: An example of a graph depicting GVW of vehicles.

- Maximum acceleration of accelerometer A12 (y axis) vs. timestamps of vehicles (x axis) – Figure 13

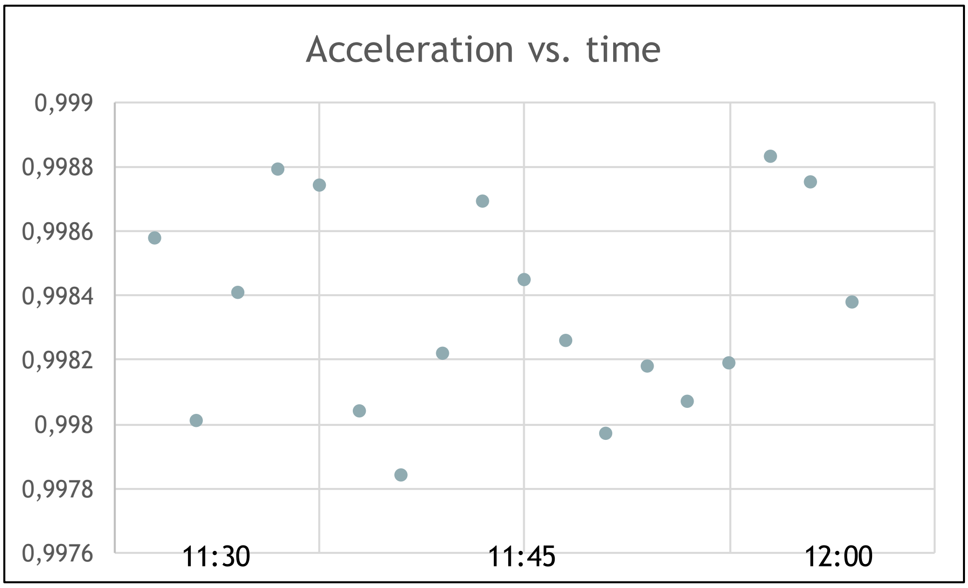
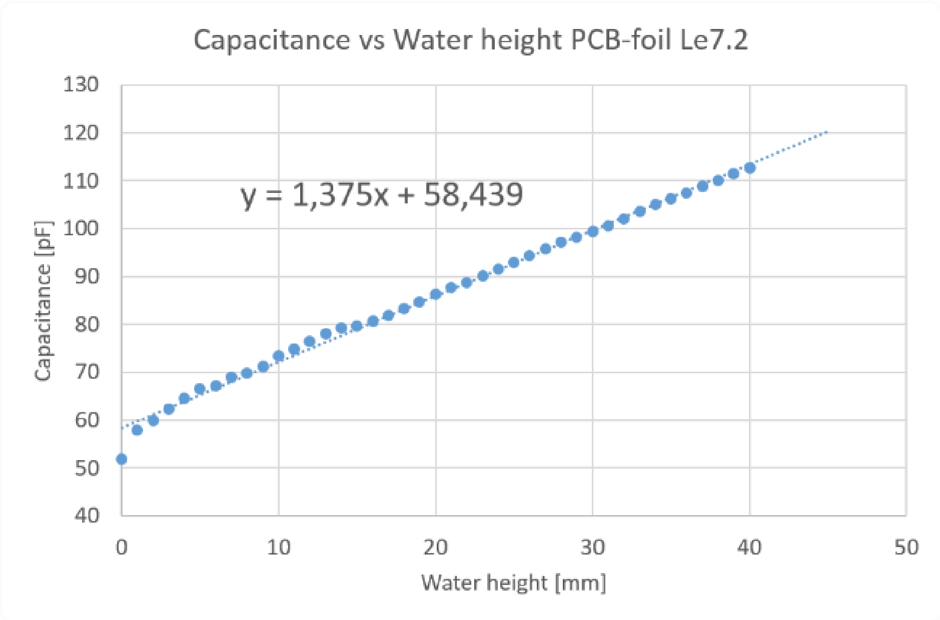


Figure 13: An example graph, acceleration vs. Time.

- Leakage data – capacitance of the sensor in relation to the water height - Figure 14



Foil was measured again with repared electrodes. Sensitivity is way higher: 1.375 pF/mm water.

Figure 14: A screenshot of the leakage sensor output visualization from Python.

6. Digital Twin Development Pipeline

The development of the Digital Twin (DT) platform for the Tomačevo Bridge follows a structured, multi-phase data processing pipeline. This workflow transforms raw sensor and 3D spatial data into an interactive, semantically enriched DT environment capable of real-time infrastructure monitoring.

Figure 15 illustrates the end-to-end architecture of this pipeline, detailing each step from data acquisition to the deployment of the fully functional DT interface.

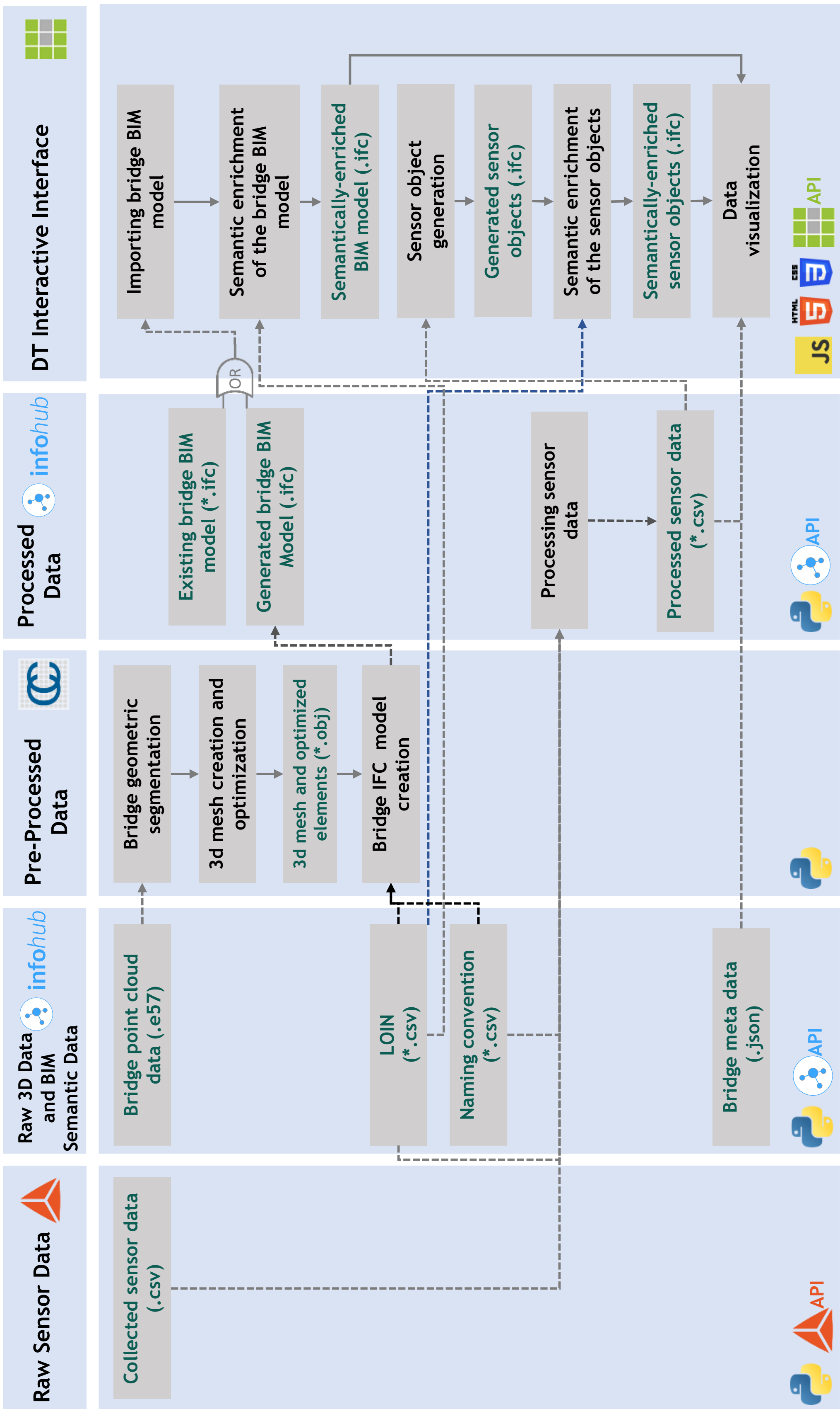


Figure 15: Data processing pipeline for the development of the interactive Digital Twin platform.

The pipeline is divided into five key phases:

1. Acquisition of raw sensor data
2. Collection and organization of raw 3D data and BIM semantic data
3. Pre-processing of spatial and sensor data
4. Generation of processed BIM and sensor data models
5. Development of the interactive Digital Twin platform

6.1. Raw sensor data

The process begins with the continuous acquisition of sensor data from the monitoring system installed on the Tomačevo Bridge, as detailed in Chapter 5. Each night at approximately 01:00, sensor data is automatically exported from the local system and uploaded to Infohub. A custom Python script processes this data in approximately 20 minutes, converting it into structured .csv files organized according to the predefined folder and naming conventions.

6.2. Raw 3D Data and BIM Semantic Data

Simultaneously, 3D point cloud data of the bridge—collected using handheld LiDAR scanners—is stored on Infohub in the .e57 format. Infohub acts as the central BIM-based data repository, organizing and storing spatial data critical for DT development.

In addition to geometric data, project-specific BIM semantic files, such as naming conventions and the LOIN, are saved as .csv files. These standards ensure consistency, interoperability, and traceability throughout the project, as discussed in Chapter 3. Furthermore, general bridge metadata is stored in a .json file to support later visualization and interaction on the DT platform.

6.3. Pre-Processed Data

Following the acquisition and organization of raw data, the pre-processing phase transforms this unstructured input into structured, interoperable content suitable for BIM and Digital Twin (DT) integration. As detailed in Chapter 4, the pre-processing of 3D data is carried out using CloudCompare, an open-source software tool widely adopted for point cloud management.

The process begins with the cleaning of the raw point cloud to remove noise and redundant data points. Next, the cloud is aligned and registered using reference markers or known coordinates to ensure spatial accuracy across multiple scans. The aligned dataset is then segmented into meaningful structural components, such as beams, columns, abutments, reflecting the physical divisions of the bridge. These components are used to generate 3D mesh models, which are further optimized by simplifying their geometry while preserving topological integrity and dimensional relevance. Special attention is paid to maintaining compatibility with BIM standards, particularly in terms of scale, proportion, and geometric fidelity.

Once segmentation is complete, Python scripts are employed to structure the data into a hierarchical format that mirrors the logical arrangement of bridge components. This structured model is converted into an IFC (Industry Foundation Classes) file, conforming to openBIM principles for maximum interoperability. The file is also geo-referenced, ensuring its spatial alignment with real-world coordinates, a crucial step for integrating sensor data and supporting visualization in the DT platform.

Finally, the pre-processed and structured IFC model is uploaded to Infohub, the central digital environment used for this project. It serves as the foundational geometric model upon which further semantic enrichment and sensor integration are performed, ultimately enabling the development of a live, interactive Digital Twin of the Tomačevo Bridge.

6.4. Processed Data

In the processed data phase, the core datasets required for the creation of the Digital Twin (DT) platform are finalized, structured, and centrally stored on Infohub. This includes both the structured BIM model and standardized sensor data.

The BIM model, whether developed from point cloud data through the workflow described in Section 6.3 or derived from available files is saved in IFC format and uploaded to Infohub, forming the geometric and spatial foundation for the DT environment.

In parallel, sensor data collected via the DEWESoft X application is pre-processed and standardized according to the defined Level of Information Need (LOIN) and the project's naming conventions. This ensures consistency in how sensor information is structured, accessed, and visualized within the DT interface.

Each .csv file representing a time series of sensor readings follows a strict content schema. The files include:

- A unique identifier (sensorName) that corresponds to the object's tag in the BIM model. This identifier ensures the correct mapping of data to its associated location in the 3D model.
- Local coordinates (x, y, z) that define the sensor's relative position on the bridge. These coordinates are later translated into global georeferenced positions based on the bridge's spatial data stored in Infohub.
- Timestamps for each measurement entry, supporting accurate temporal analysis.
- Values and units, specific to the sensor type (e.g., °C for temperature, mm/s^2 for acceleration, tonnes for weight).

Notably, the function or measurement type (e.g., temperature, acceleration, weight) is encoded in the filename itself rather than as a column within the file. This approach supports simplified categorization, filtering, and mapping when loading data into the platform and reduces redundancy across large datasets.

By the end of this phase, all critical components, geometric BIM data, processed and standardized sensor data, and bridge metadata, are fully prepared and stored in Infohub. Together, these form a unified, interoperable dataset, enabling seamless integration into the interactive DT platform and supporting real-time visualization, analysis, and monitoring.

6.5. DT Interactive Interface

The final phase focuses on developing the interactive Digital Twin (DT) interface. Built using JavaScript, HTML, and CSS, the interface is integrated into the coordination platform DESITE BIM md, offering a user-friendly environment.

The interface allows seamless import of the bridge's IFC model, whether newly generated or pre-existing, directly from Infohub into DESITE BIM md. Once imported, the model is semantically enriched using the LOIN (Level of Information Need) structure stored on Infohub. This enrichment involves assigning relevant attributes to model elements (e.g., columns, beams) and populating them with appropriate values, enabling clear differentiation between various structural components.

Sensor instances are automatically created and accurately positioned using standardized .csv files containing sensor data and local coordinates. Each sensor is linked to semantic attributes based on LOIN definitions, resulting in a fully enriched and context-aware BIM environment.

After the bridge and sensor models are prepared, real-time sensor data is visualized within the platform. Various sensor types, such as temperature, weigh-in-motion, and acceleration, are displayed using customized visual styles. If sensor readings exceed predefined thresholds, they are highlighted in red, allowing for immediate identification and triggering of maintenance actions.

6.6. Demonstrator project's DT platform

In this chapter, the developed DT platform based on the demonstrator project is illustrated.

To access the DT platform, the user first logs in to the Infohub account created for BIM4CE project (Figure 16).

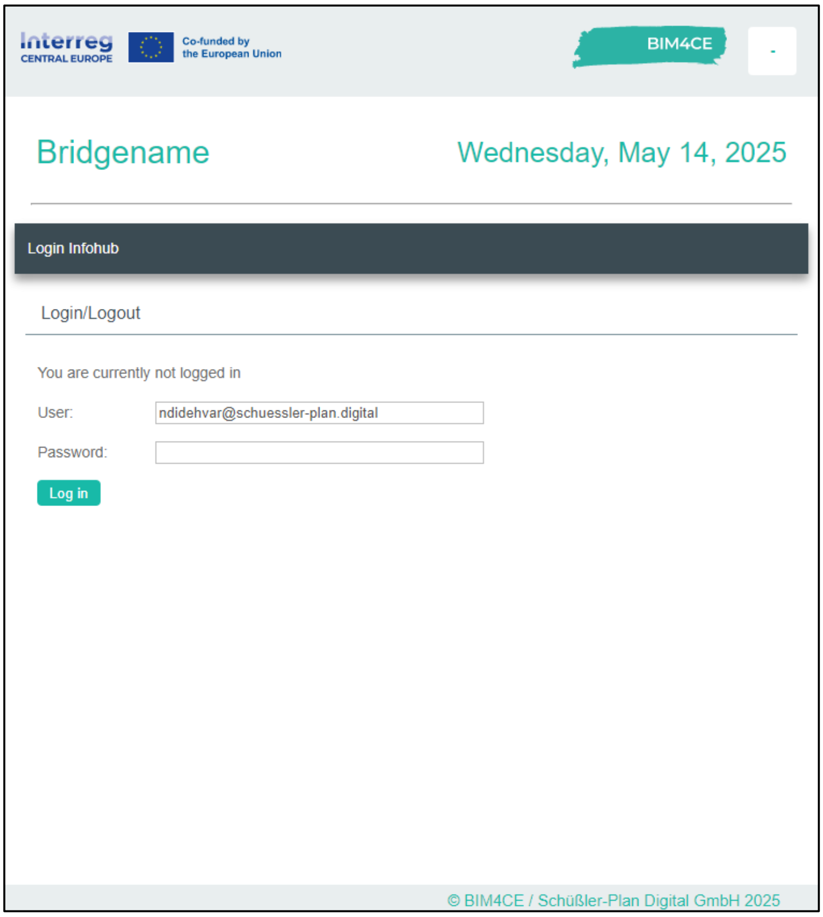


Figure 16: Login interface of the Digital Twin platform.

The next steps include selecting the scope (cn_sp02), project name (BIM4CE), and bridge name (Tomačevo Bridge), as shown in Figure 17.

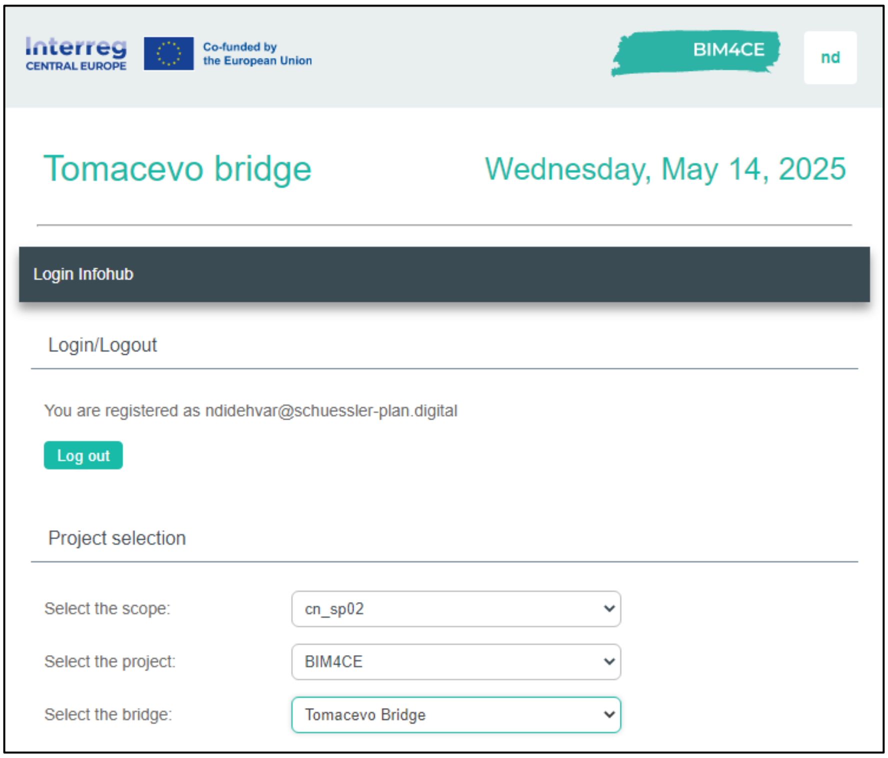


Figure 17: Selection of scope, project, and bridge within the DT platform.

The bridge's IFC file, stored on Infohub, is initially imported into the Digital Twin platform using the "Import" function. During this process, a temporary copy of the model is saved in the tempDownloads folder, which is automatically created within the main directory of the DESITE BIM project. Following import, semantic enrichment is performed using the "Semantic Enrichment" function. This step links the IFC model to the attribute definitions provided in the Level of Information Need (LOIN) dataset, also hosted on Infohub (Figure 18). Once imported and enriched, the fully integrated IFC model of the bridge is available on the platform, as illustrated in Figure 19. A detailed view of the assigned PropertySets and attributes to a representative bridge component is shown in Figure 20.

Figure 18: Interface buttons for importing the IFC bridge model into the DT platform and initiating semantic enrichment.

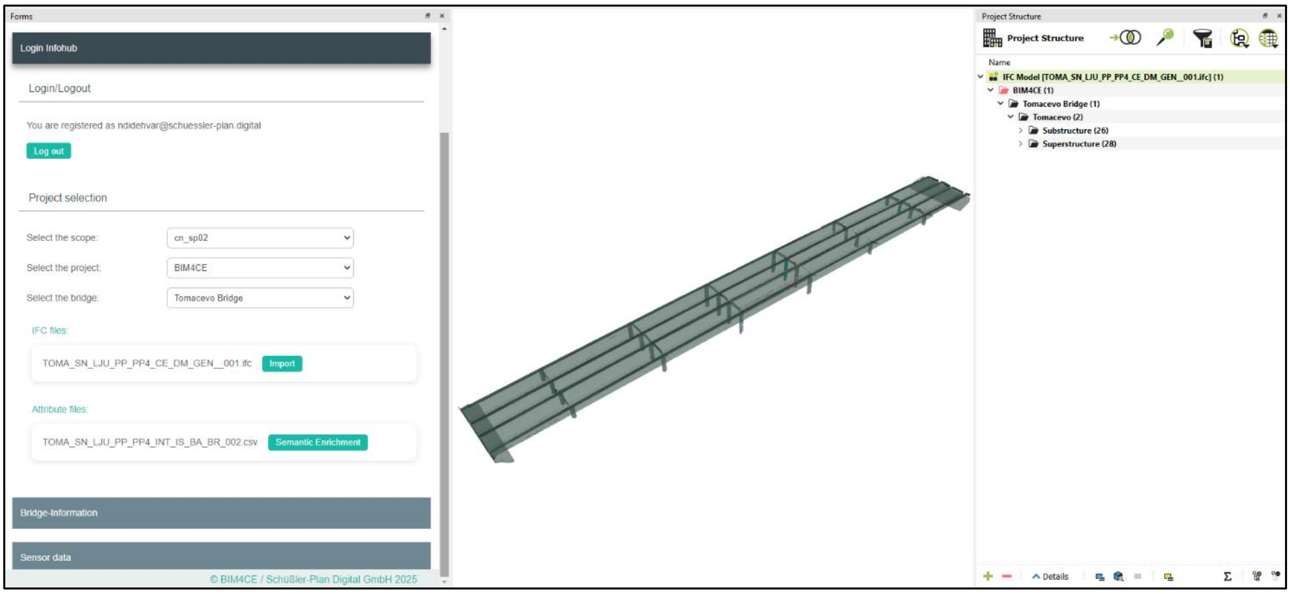


Figure 19: Imported and semantically enriched IFC model of the bridge displayed in the platform.

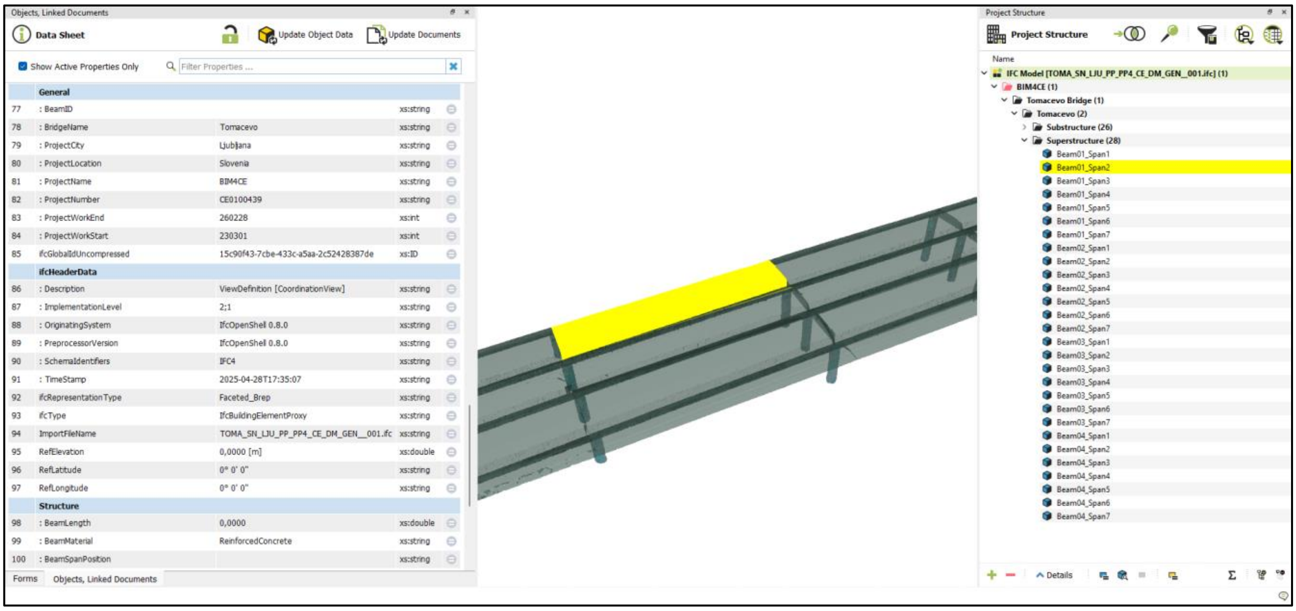


Figure 20: Example of a semantically enriched structural element with assigned attributes.

The platform interface presents general bridge information, including structural and location data, which is read from a .csv file stored on Infohub (Figure 21).

Bridge-Information

Information about the bridge

Bridge ID/name:	Tomacevo bridge
Date:	Friday, May 16, 2025
Country:	Slovenia
City:	Ljubljana
Construction year:	1982
Road section:	104
Total length:	204.5 m
Construction type:	Cast-in-place prestressed concrete girder bridge with cantilever RC circular piers
Material:	Reinforced concrete
Height:	From 5.1 m to 8.6 m
Number of spans:	7
Typical span length:	31 m
Number of traffic lanes:	2 (in each direction)
Average monthly number of HGVs (vehicles over 3,5 t):	21.141 (direction Ljubljana)

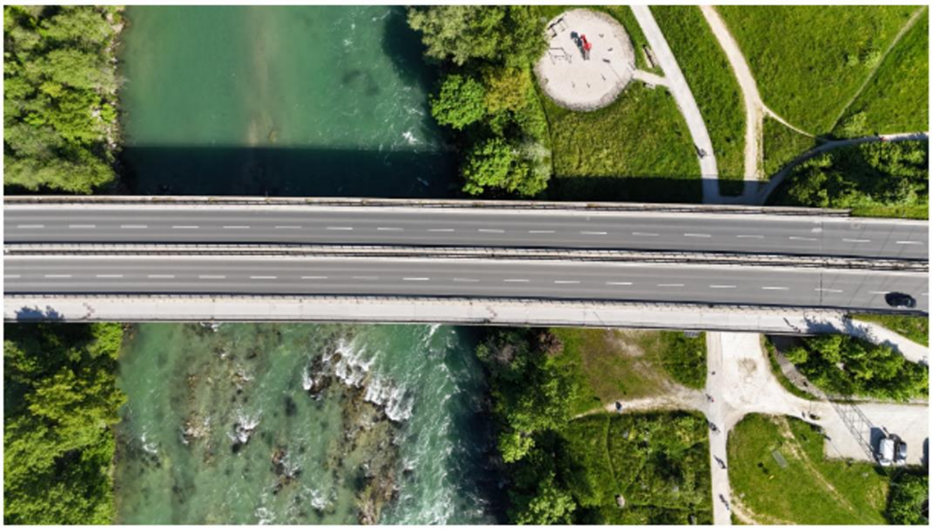


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Figure 21: General bridge information visualized on the DT platform.

To instantiate the sensors as generic objects within the model, the user selects the “Create Sensors” function (Figure 22). This action dynamically generates sensor IFC objects and places them accurately at their predefined positions on the bridge. These sensor elements are structured according to the IFC structure defined in chapter 3.2, ensuring proper hierarchical organization and seamless integration into the model (Figure 23).

Subsequently, by clicking the "Semantic Enrichment" function, the instantiated sensors are enriched with relevant metadata retrieved from the LOIN dataset (also illustrated in Figure 22). An example of an enriched sensor object, specifically a Bridge Weigh-In-Motion (BWIM) sensor, along with the defined PropertySets and its assigned attributes is shown in Figure 24.

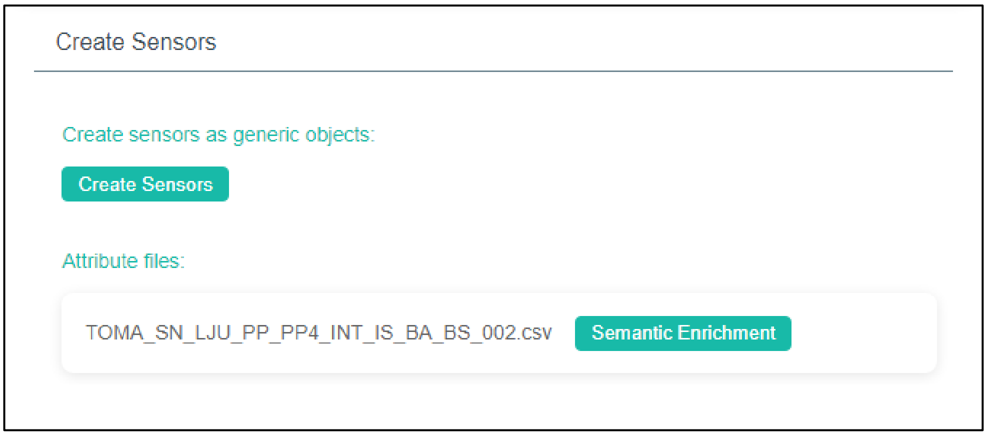

Figure 22: Buttons for creating the generic IFC sensor objects into the DT platform and semantically enrich them.

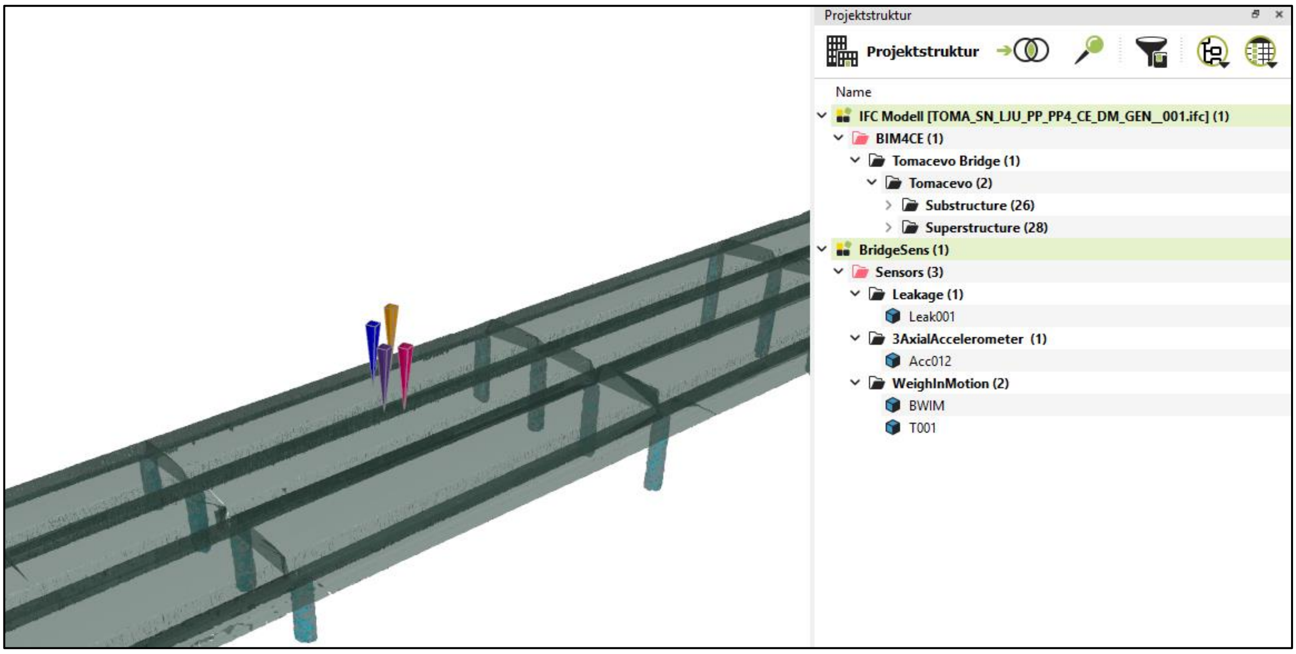

Figure 23: Sensor objects instantiated at correct positions with corresponding IFC hierarchy.

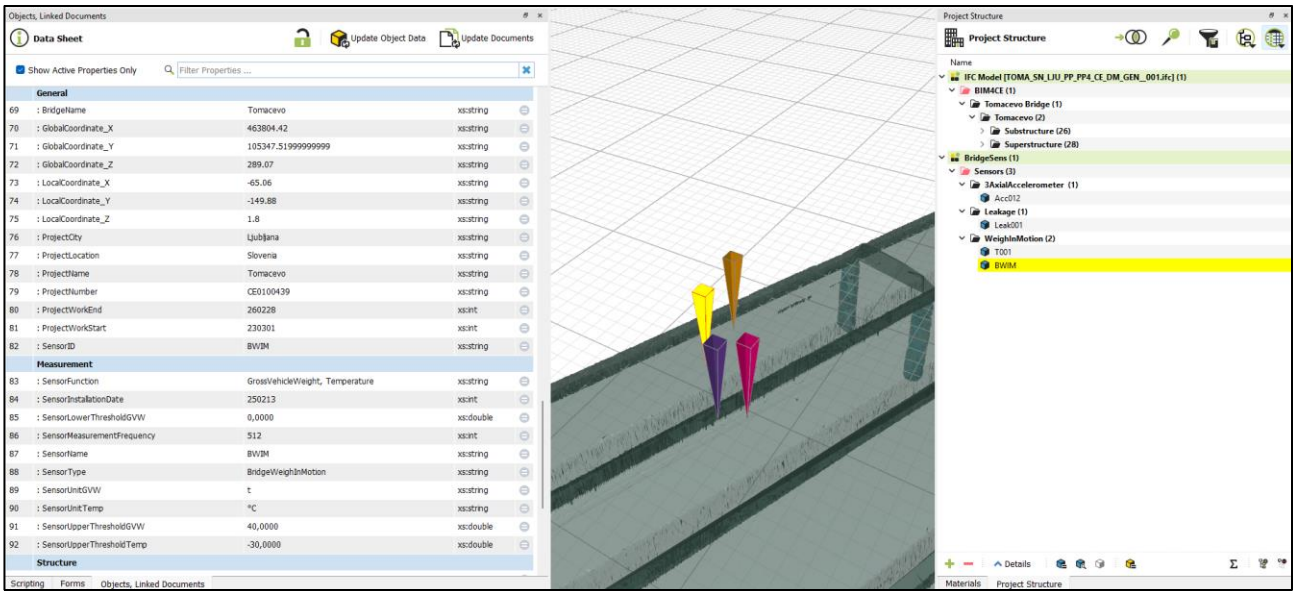

Figure 24: Example of a semantically enriched sensor object with assigned attributes.

In the next step, to view sensor data, the user begins by selecting the desired observation period, as illustrated in Figure 25. The interface distinguishes between two primary categories of sensor data: bridge-related and vehicle-related, as defined in Chapter 5.3.

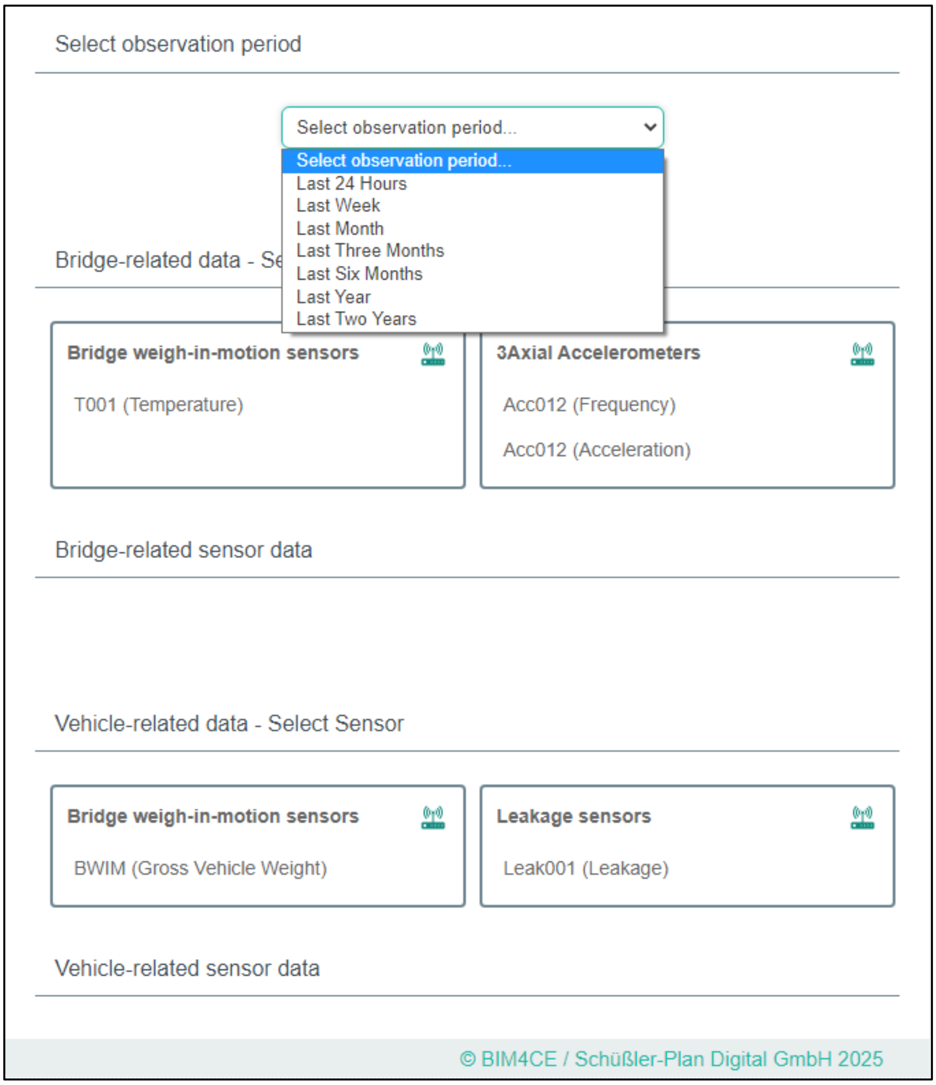

Figure 25: Selection of observation period and categorization of sensor data types on the platform.

Clicking on a sensor, either directly within the 3D model or through the list interface, displays its corresponding data in real time. For instance, in Figure 26, the observation period is set to the previous week, and a temperature sensor is selected. As a result, both the sensor in the 3D model and in the list interface are highlighted, and the temperature data from the selected period is visualized interactively.

Figure 27 provides a clearer view of the sensor data represented in a diagram format, allowing for more detailed analysis. Meanwhile, Figure 28 shows a better view of the 3D model alongside the project structure, illustrating the spatial placement of the sensor and overall file hierarchy.

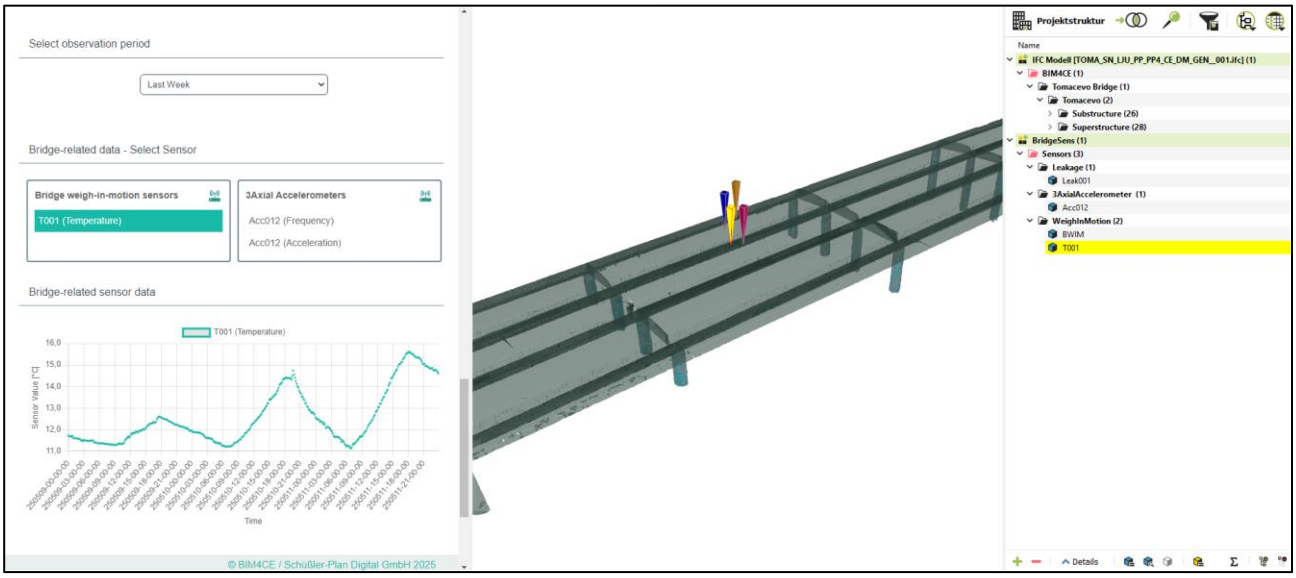

Figure 26: Interactive visualization of temperature sensor data and the 3D bridge model.

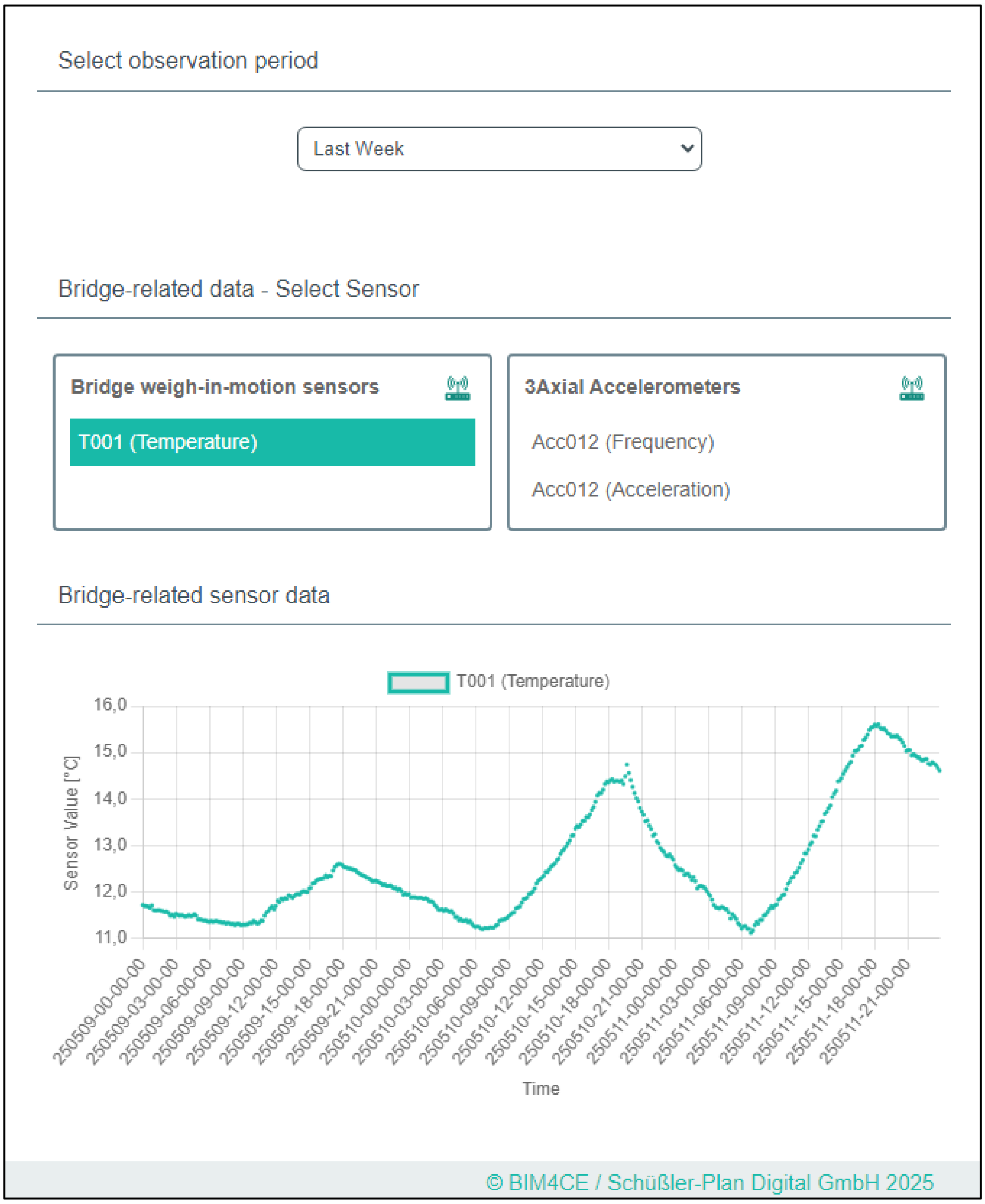

Figure 27: Weekly temperature sensor data illustrated in diagram format on the platform.

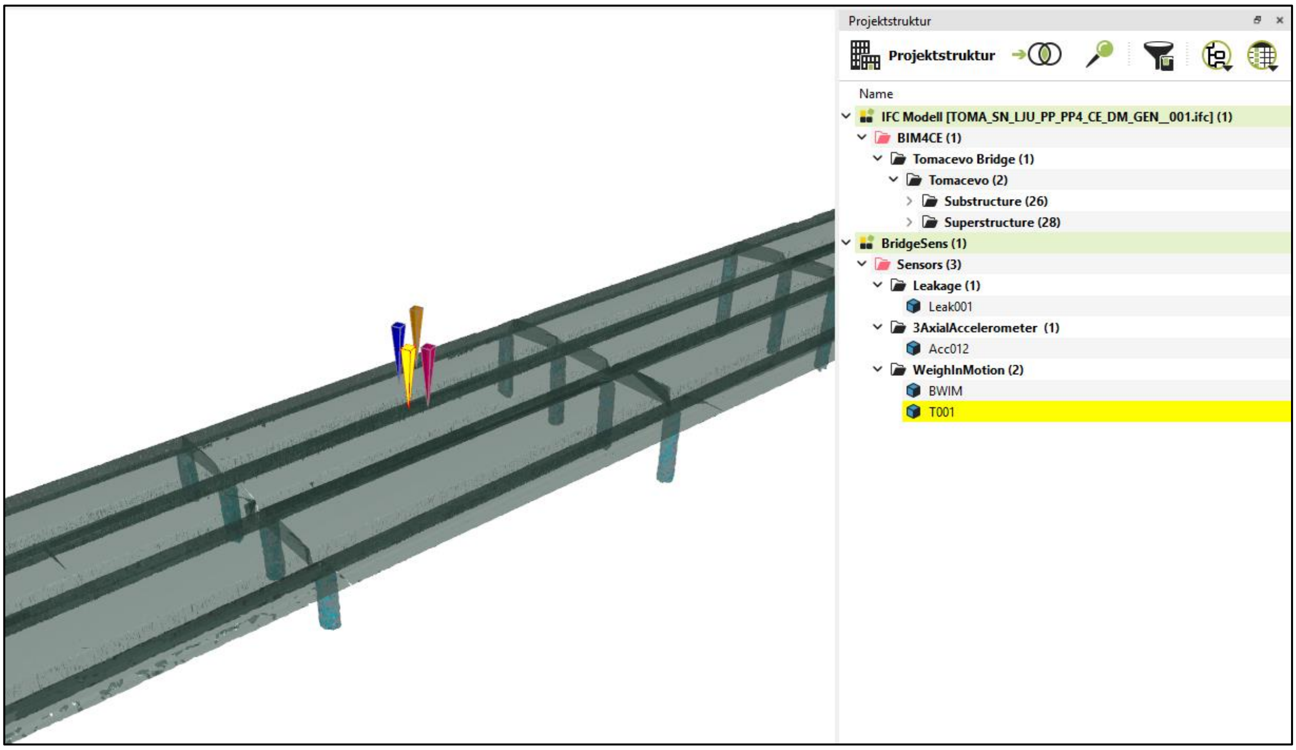

Figure 28: Overview of the 3D bridge model, sensor placements, and project structure.

For sensor data types with predefined thresholds, any values that exceed these limits are automatically highlighted in red, providing immediate visual indicators for potential maintenance or regulatory intervention. For example, in the case of bridge weigh-in-motion sensors, the maximum allowable load is set at 40 tonnes. As shown in Figure 29, vehicles exceeding this threshold are clearly marked in red, effectively alerting responsible authorities to take appropriate actions.

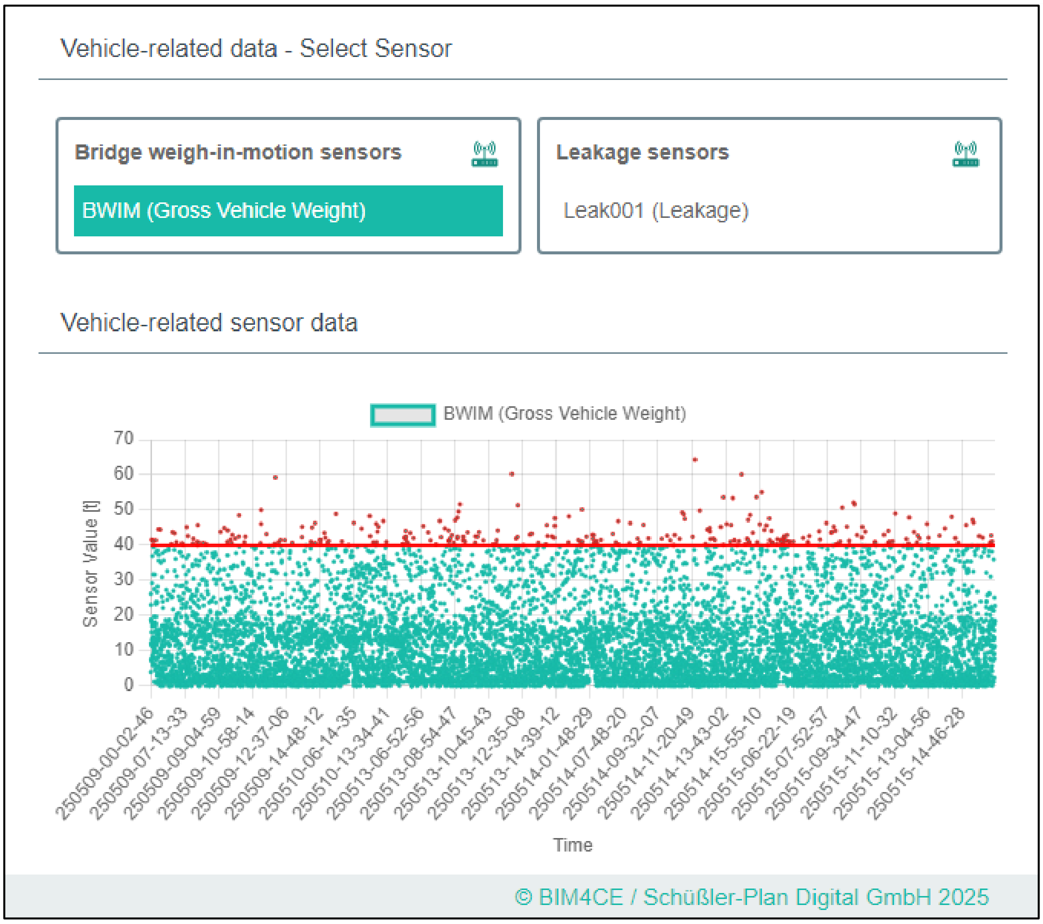

Figure 29: Visualization of BWIM sensor data showing threshold exceedances highlighted in red.

Other sensor data types, whether bridge-related or vehicle-related, can be visualized using the same procedure. This integrated workflow ensures structured data handling and model consistency, while also enabling an interactive, real-time monitoring system specifically tailored for effective bridge health monitoring and management.

7. Discussion, Limitations and Future Work

The current architecture of the structural health monitoring (SHM) system and its corresponding data pipeline, from raw sensor acquisition to integration within the Infohub Digital Twin (DT) platform, has demonstrated substantial versatility and scalability. The system is capable of processing and visualizing sensor data within a semantically enriched BIM model, providing a robust foundation for real-time infrastructure monitoring.

From a data integration perspective, the architecture allows for future expansion to accommodate additional sensor types. These could include strain gauges, extensometers, and other advanced sensors relevant for assessing structural integrity. Similarly, the system could be enhanced to incorporate more detailed vehicle parameters, such as axle loads and vehicle classification. These parameters are valuable not only for improving load effect analysis on bridges but also for broader applications in traffic engineering and transport policy.

A critical aspect for future development will be the involvement of domain experts in structural health monitoring. Their input will be necessary for determining which sensor types and data streams are most impactful for Digital Twin applications. Equally important is the definition of alarm thresholds and parameter limitations to enable predictive maintenance and actionable alerts. These decisions must be grounded in engineering standards, data obtained from actual bridge performance and bridge expert judgment, ensuring that alarm thresholds are both practical and structurally relevant.

The system currently doesn't enable live monitoring of traffic, which would be necessary if the data is to be used by the law enforcement agencies in enforcement of maximum gross vehicle weight and axle load regulation.

Another technical limitation relates to the quality of the 3D scan data. Poor scan resolution, noise, or incomplete capture of structural elements can negatively impact the accuracy of the resulting BIM model. This could, in turn, affect sensor placement precision and the alignment of sensor data within the DT environment. Ensuring high-quality data acquisition and implementing rigorous data validation protocols are therefore essential in future deployments.

Looking forward, several directions for future work are identified:

- Expanding the sensor network to include additional SHM devices.
- Enhancing the DT interface to support live monitoring features.
- Improving 3D scan workflows for higher model fidelity.
- Integrating advanced analytics, such as machine learning models, to forecast structural degradation.
- Strengthening stakeholder collaboration for better definition of critical parameters and response thresholds.

In conclusion, the demonstrator project has successfully established a robust foundation for a scalable and adaptable Digital Twin (DT) system tailored to bridge monitoring. By integrating real-time sensor data with a semantically enriched BIM model, the project showcases the practical application of advanced digital tools in infrastructure management.

The DT platform not only meets the technical objectives of data fusion and live monitoring but also demonstrates clear value for diverse stakeholders. Bridge owners gain a powerful tool for long-term structural health monitoring and predictive maintenance, while regulatory bodies can access vehicle-related data for compliance enforcement. The unified access to all relevant data through a single platform significantly improves transparency, coordination, and operational efficiency.

Furthermore, the demonstrator validates the effectiveness of combining openBIM standards, structured data pipelines, and modular sensor systems in a real-world setting. Successful sensor integration and seamless data visualization mark important success criteria already achieved.

As the platform evolves, its potential to enhance safety, optimize maintenance planning, and reduce operational costs becomes increasingly evident. It paves the way for broader adoption of Digital Twin technologies in bridge health monitoring across Central Europe and beyond.

Acknowledgement

The digital twin platform was completely developed by PP4, Schüßler-Plan Digital GmbH. The sensor data preparation and pushing them to the Infohub was done by PP6, Cestel. PP8, ZAG, supported the digital twin model's development by providing laser-scanning data of the bridge, fundamental geometry and instrumentation drawings, scripts for frequency-data processing (as part of the sensor data preparation workflow), and expert consultancy on the parameters and threshold values to be incorporated into the platform.

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List of Abbreviations

ABBREVIATION	DESCRIPTION
BIM	Building Information Modelling
BWIM	Bridge Weigh-In-Motion
CDE	Common Data Environment
CSV	Comma-Separated Values
DT	Digital Twin
IFC	Industry Foundation Classes
JSON	JavaScript Object Notation
LOD	Level of Development
LOIN	Level of Information Need
SHM	Structural health monitoring
WIM	Weigh-in-motion
3D	Three-Dimensional

List of Tables

List of Figures