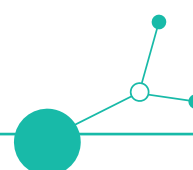


D.2.5.1 - FINAL REPORT INCLUDING COMMENTS OF THE EXPERT PANEL IN WHICH REQUIREMENTS ARE DOCUMENTED



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Project Coordinator	Dr. Ilia Lashkov
Organisation	Technische Universität Dresden
E-mail	Ilia.lashkov@tu-dresden.de
Telephone	+49-351-463-42413

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Contributor(s)	Francesco Varone (SINA), Andrea Piscini (SINA), Vanesa Kuzma (BP Akademija)
Reviewer(s)	Martin Hauptman (CESTEL)

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List of abbreviations

ACC: Accelerometer

BIM: Building Information Modeling

DT: Digital Twin

GVW: Gross Vehicle Weight

MEMS: Micro Electro-Mechanical Systems

SHM: Structural Health Monitoring

TUD: Technische Universität Dresden

WIM: Weigh-in-Motion



1. Introduction

The Deliverable 2.5.1: “Final report including comments of the expert panel in which requirements are documented” consolidates the feedback, recommendations, and documented requirements gathered through a series of transnational workshops carried out during the project implementation phase.

The workshops were held in an online format, ensuring broad participation across Central European regions. In addition, three key workshops were conducted in hybrid mode, combining online participation with physical meetings held in Dresden (Germany), Rakičan (Slovenia), and Turin (Italy). These hybrid settings enabled more dynamic interaction among participants and stakeholders and facilitated richer dialogue on the project's progress.

The purpose of this report is to present a structured synthesis of the insights gained during these workshops. Inputs were collected from a diverse set of stakeholders, including members of the Expert Council, public authorities, and project partners (PPs). These engagements provided valuable opportunities to reflect on the results achieved thus far, validate the approach, and gather targeted feedback to support refinement and improvement of the project outcomes.

Each workshop served as a forum to demonstrate and explain the current results, discuss potential implications, and receive feedback that would support future project phases. The open format encouraged constructive contributions, enabling stakeholders to express their needs, concerns, and expectations, thus helping to steer the project in a direction that remains aligned with its overall objectives and regional relevance.

This report brings together the collective outcomes of these engagements and the comments provided by the expert panel. It aims to serve both as a reference for internal evaluation and as a foundation for the development of future activities within the BIM4CE framework.

2. Action Plan for implementation and uptake.

Action	Responsible organisation(s)	Timing	Required resources	Expected result
Maintain and further operate the InfoHub cloud platform and digital-	Schüßler-Plan Digital, with ICT partners	After project closure	Existing platform infrastructure, technical maintenance and hosting resources	Continued access to bridge models, sensor positions and monitoring data



Action	Responsible organisation(s)	Timing	Required resources	Expected result
twin environment				
Maintain and further use the monitoring systems at the pilot sites	Relevant bridge owners/operators and technical partners	After project closure	Existing monitoring equipment, calibration and maintenance resources	Continued reference monitoring and additional data collection
Apply the harmonised sensor-installation, calibration and data-management methodology in future deployments	TU Dresden, CESTEL, ZAG and engineering partners	During future projects and commercial deployments	Technical staff, equipment, site access and project funding	Replicable implementation of the BIM4CE monitoring approach
Promote the pilot sites and final solution as reference cases	All partners	Post-project period	Communication, workshops, website and partner networks	Increased awareness among infrastructure owners and service providers
Prepare future funding applications and commercial offers	Project partners	During the three-year post-project period	Staff time, proposal preparation and partner cooperation	Potential follow-up projects and future investment opportunities



3. Sensor systems adopted for structural health monitoring

A central point discussed during the workshops was the technological setup of the structural health monitoring (SHM) systems employed within the project. The consortium has implemented a combination of standard sensors – including accelerometers, inclinometers, and temperature sensors – to monitor critical parameters relevant to infrastructure safety and performance.

However, a distinctive highlight of the sensor suite, and a topic of particular interest during the Dresden consortium meeting, was the introduction of an innovative, low-cost water leakage detection solution: the Flexible Leakage Sensor Foil, developed by TUD.

3.1. The Flexible Leakage Sensor Foil

The Flexible Leakage Sensor Foil represents a novel approach to water ingress detection within SHM frameworks, directly supporting the overarching objective of enhancing infrastructure resilience across Central Europe. This sensor is characterized by:

- **Operating principle:** It employs capacitive sensing, where the presence of water leads to a measurable change in capacitance. This change is quantitatively related to the water volume through a calibration curve, enabling detection of leakage volumes as small as 0.1 ml.
- **Physical features:** The sensor is built as a thin, flexible film, facilitating seamless integration into existing monitoring installations. Its robust design ensures high mechanical flexibility and excellent durability, even under significant thermal stress.
- **Safety and range:** Designed for low-voltage operation, the sensor minimizes electrical risks and maintains reliable performance across a wide temperature spectrum.

3.2. Demonstration and application during the workshop in Dresden

During the consortium meeting held in Dresden – conducted in a hybrid format to accommodate both in-person and remote participants – the Flexible Leakage Sensor Foil was not only presented in detail but also physically demonstrated. This hands-on session allowed participants to directly observe:

- The sensor's immediate capacitive response upon contact with small amounts of water.
- The ease of embedding the foil into existing structural setups.



Furthermore, the meeting provided an opportunity to discuss the practical application of this sensor technology on the IDA-KI viaduct, where the sensor has been installed to monitor potential water infiltration points. Observations from this pilot implementation were shared, generating valuable discussions on calibration accuracy, long-term stability, and integration with the broader data acquisition system.

3.3. Technical Specifications of the Sensor Foil

Parameter	Value
Foil Dimensions	200 × 5 cm
Foil Thickness	125 µm
Connector Type	EtherCAT
Measured Quantity	Capacitance (F)
Tensile Strength (Longitudinal)	260 MPa
Tensile Strength (Transversal)	260 MPa
Elongation at Break	100% (both directions)
Shrinkage (150°C, 30 min)	0.2% (longitudinal), 0.3% (transversal)
Operating Temperature Range	-20 °C to +140 °C
Sensitivity / Resolution	0.1 ml of water
Hardware Weight	26 g



4. Installation and validation of monitoring systems on pilot sites

As part of the BIM4CE project activities, two innovative concepts were developed: the Flexible Leakage Sensor Foil and the derivation of natural frequencies of the bridge from accelerometers. Both of these allowed the consortium to assess the applicability and performance of complementary monitoring technologies in addressing different aspects of infrastructure safety.

The installations, validation processes, and key findings were thoroughly discussed during the workshops, with particular emphasis placed on lessons learned and recommendations for further development.

4.1. Leakage monitoring system on IDA-KI bridge

The leakage monitoring system was designed and implemented by TU Dresden and installed under the IDA-KI bridge. This system employs the innovative Flexible Leakage Sensor Foil, which changes its capacitance upon contact with water. This capacitance variation is processed by the acquisition electronics, resulting in a measurable frequency shift that directly indicates the presence of leakage.

Key system features include:

- Acquisition unit: Based on an ESP32 microcontroller paired with a Raspberry Pi, providing local processing and data storage, as well as wireless IoT data transmission capabilities.
- Environmental integration: Complemented by a weather station that continuously records ambient conditions (rainfall, humidity, temperature), enabling correlation between leakage events and external factors. A leakage monitoring system developed by TU Dresden, validated on the IDA-KI bridge.

Installation highlights

During the installation phase under the IDA-KI bridge, several sensor foils were strategically positioned in locations deemed susceptible to water ingress. These positions were identified through preliminary visual inspections and structural assessments.

This installation was presented and discussed in detail at the Dresden workshop, where participants had the opportunity to review the setup, understand the rationale for sensor placement, and examine preliminary data outputs.



Validation results

The system demonstrated its effectiveness under realistic bridge conditions, including during subzero temperatures:

- Leakage detection: The sensors successfully detected leakage events in strong correlation with recorded rainfall.
- High sensitivity: In some cases, sensors responded to elevated humidity levels even before direct rainfall occurred, indicating a high sensitivity that, while beneficial, also led to occasional false positives.
- Persistent leakage monitoring: Notably, Sensor 6, installed directly beneath an identified leakage point, consistently registered elevated readings even after rainfall ceased, confirming water accumulation.

To enhance system precision and reduce false positives due to humidity alone, upcoming validation phases will incorporate:

- Testing with larger, less sensitive sensor foils.
- Controlled experiments in an environmental chamber to fine-tune sensitivity and calibrations.

Conclusions and stakeholder feedback

During workshops, including sessions in Dresden and later discussions in Turin, stakeholders acknowledged the system's ability to detect leakages in real-time and under varying environmental conditions. Experts highlighted the need to balance sensitivity to avoid over-detection and recommended exploring redundancy (multiple sensor types) for more robust assessments.

4.2. Accelerometer-Based Monitoring System (ZAG Laboratory)

The second benchmarking test involved an accelerometer-based structural health monitoring system deployed by ZAG within their structural testing laboratory. This installation focused on capturing changes in the dynamic behaviour of structural elements under progressive damage conditions.

The system comprised:

- MonoDAQ-E-gMeter and IOLITEi-3xMEMS-ACC-S accelerometers, selected for their high resolution and EtherCAT protocol integration.
- Coupled force and displacement transducers to provide comprehensive monitoring during load application.



Testing Details

Two salvaged bridge beams were subjected to controlled cyclic loading until failure, replicating typical structural degradation scenarios:

- Beam B1: An intact pre-stressed concrete beam without a slab, serving as a reference for distributed cracking damage.
- Beam B2: A beam with a reinforced concrete slab intentionally weakened by cutting select pre-stressing cables, introducing localized stiffness.

Dynamic measurements focused on tracking changes in natural frequencies across progressive loading stages (cracking, yielding, near-collapse).

Validation Results

- Frequency shifts: The system effectively identified changes in the beams' dynamic properties corresponding to damage evolution.
- Damage type sensitivity:
 - Beam B1, which experienced distributed cracking, exhibited more pronounced frequency reductions, particularly in the first bending mode due to load concentration at midspan.
 - Beam B2, despite the localized damage introduced by cutting cables, showed minimal frequency shifts, consistent with theoretical expectations on localized stiffness loss having limited influence on global dynamic properties.

Conclusions and expert's feedback

Results presented during the consortium meetings underscored the accelerometer system's capacity to detect structural degradation via frequency monitoring. However, discussions pointed to the importance of:

- Normalizing frequency variations with respect to temperature to avoid environmental confounding factors.
- Incorporating mode shape analysis and potentially additional dynamic parameters for a more holistic damage characterization.

4.3. General Conclusions

Overall, discussions with the Expert Council and participating stakeholders confirmed the promising performance of both monitoring systems within their respective contexts:



- The leakage monitoring system showed excellent correlation with environmental data, validating its suitability for real-world bridge conditions. Optimization of sensor design and sensitivity was identified as a priority for reducing false positives linked to humidity.
- The accelerometer-based system reliably tracked structural degradation under laboratory-controlled damage scenarios, laying the groundwork for future in-situ applications that will also consider environmental effects and advanced modal analyses.

These collective insights will guide the next phase of refinement within the BIM4CE framework, ensuring that monitoring solutions are both technically robust and practically aligned with the needs of infrastructure stakeholders across Central Europe.



5. BIM-based digital twin platform

The development of a BIM-based digital platform integrates real-time data from the installed monitoring systems. This platform effectively creates a Digital Twin (DT) of the monitored bridges, aiming to enhance infrastructure management and predictive maintenance across Central Europe.

5.1. Data collection and integration into the Digital Twin

To feed the Digital Twin, various sensors were installed on the pilot sites, particularly on the Tomačevó Bridge in Slovenia. These include:

- Bridge weigh-in-motion (WIM) sensors, which record vehicle weights and both air and concrete temperatures.
- Accelerometers, capturing vertical vibrations to track changes in natural frequencies that could indicate structural issues.
- Leakage sensors, detecting water presence below joints to identify potential corrosion or deterioration risks. Bridge Weigh-in-Motion (WIM) sensors: Measure gross vehicle weight (GVW) and temperature (air and concrete).

Data from these systems is collected continuously, processed to calculate relevant indicators (such as natural frequencies or overload events), and uploaded daily to Infohub, the project's central data platform.

5.2. From BIM to Digital Twin

Starting from detailed BIM models of the bridges – built from 3D scans and enriched with semantic data according to the LOIN framework – the project developed a fully functional interactive Digital Twin, integrating:

- The geometric and structural model of the bridge converted into IFC format.
- Sensor positions and live readings mapped directly onto the model.
- Historical and real-time monitoring data, viewable in both graphical and 3D model formats. DewesoftX software is used to synchronize and collect data from all sensors.

The result is a digital interface accessible via Infohub, where users can:



- Select a specific bridge and timeframe,
- Explore sensor data visually in the 3D model,
- Analyze charts (for acceleration, temperature, leakage, and more);
- Receive alerts when thresholds are exceeded, such as for excessive vehicle weights or abnormal frequency shifts.

5.3. Benefits highlighted during the workshops

Throughout the consortium meetings (in particular from 10 to 19), the Digital Twin concept was discussed in deep and was recognized as a strategic tool that:

- Provides an integrated and up-to-date view of the bridge's structural condition.
- Enables faster, more informed decision-making by public authorities and infrastructure operators.
- Lays the groundwork for predictive maintenance planning, reducing both costs and the risks associated with unexpected failures.

In summary, the Digital Twin platform developed under BIM4CE serves as a practical example of how a BIM environment enriched with live monitoring data can support smarter, data-driven infrastructure management. It paves the way for a more proactive approach to safeguarding bridge resilience across the Central European region.



6. Feedback from Stakeholders

Feedback from stakeholders was collected during the workshops and through specific requests and is explained in more detail in Deliverable 2.5.2: “Minutes of Meeting and Questionnaires”. Opinions on the topics covered and developed in BIM4CE are briefly collected in the following paragraphs.

6.1. Sensor systems adopted for structural health monitoring

Stakeholders positively consider the adoption of systems jointly composed of traditional and innovative instrumentation. The use of instrumentation in conjunction allows obtaining information in parallel from different technologies, ensuring reliable monitoring of the structure, thanks to traditional sensors, and the development of innovative techniques, thanks to the possibility of correlating the different data with each other.

The use of accelerometers as traditional instrumentation is reflected in the widespread use of this technology for continuous monitoring of structures by evaluating the evolution of the dynamic behaviour of bridges.

The use of innovative sensors with low impact for real-time diagnostics of possible situations that trigger degradation, such as the presence of leakage, would allow identifying and managing possible degradation phenomena at the outset.

6.2. Installation and validation of monitoring systems on pilot sites

During workshops, including sessions in Dresden and later discussions in Turin, stakeholders acknowledged the system’s ability to detect leakages in real-time and under varying environmental conditions. Experts highlighted the need to balance sensitivity to avoid over-detection and recommended exploring redundancy (multiple sensor types) for more robust assessments.

Results presented during the consortium meetings underscored the accelerometer system’s capacity to detect structural degradation via frequency monitoring. However, discussions pointed to the importance of normalizing frequency variations with respect to temperature and incorporating mode shape analysis and potentially additional dynamic parameters for a more holistic damage characterization. In fact, frequency shift of structures is very small even if severe damage occurs and thus stiffness change and frequency change is small, even if damage is high.



6.3. BIM-based digital twin platform

Stakeholders agree that the use of a bim-based digital twin platform is very positive for structural monitoring purposes.

A tool of this type allows to manage a large amount of data, perform analyses and draw conclusions useful for carrying out the diagnostic service of the monitored structures. To this end, experts suggest implementing in the platform tools for the visualization of risks related to the context in which the bridge is located (seismic, hydraulic, landslide risk maps) and additional data regarding environmental conditions (data from public weather stations, public accelerometric network for earthquake recognition, rainfall network, watercourse level, satellite interferometric monitoring, etc.). At the same time, it would be very useful to be able to directly visualize any defects on the digital twin, with attributes such as photos, anomaly recognition date, defect evolution, and associated risk.

The use of the BIM-based digital twin methodology also allows the optimal management of the monitoring systems themselves. The platform could be useful for the development of system maintenance plans and the correct and real-time identification of problems and anomalies in the functioning of the systems. The opportunity to view installed equipment could simplify the localization of sensor problems and therefore the scheduling of extraordinary maintenance activities. Experts recommend, for this purpose, inserting attributes on individual sensors and other components into the BIM platform, such as sensor data sheets, calibration certificates, dates of production, calibration, installation, calibration period, configuration parameters, etc.

6.4. Additional insights from stakeholder questionnaires

Complementing the workshop discussions, targeted questionnaires were distributed to stakeholders, yielding further valuable input. Inspectiondrone SRL (Italy), a company offering AI-based drone inspection services, reported that in their experience, bridge conditions are most commonly assessed through a combination of sensors, visual inspections, and drone-based approaches. They identified cracking and humidity as the primary defects contributing to deterioration, issues often compounded by the lack of systematic maintenance programs. While acknowledging leakage sensors as one among many useful solutions for early-stage detection, they stressed the need for a diversified monitoring strategy, tailored to the specific age and characteristics of each infrastructure.

Inspectiondrone also highlighted a key challenge: convincing engineering firms to adopt new technologies, tools, and methods. They believe that introducing robust digitalization methodologies and simulation capabilities would represent a major



step forward, enabling better monitoring practices and more effective maintenance planning.

DARS, the Slovenian motorway operator, confirmed that the condition of their bridge network is primarily monitored through regular and main inspections, with structural health monitoring systems installed on select critical structures. They cited delamination, corrosion, cracks, and leakage as the most common defects. Regarding leakage sensors, they noted that such technologies could be particularly useful on strategically important bridges, where maintaining the highest condition level is essential.



7. Conclusions

The jointly developed Action Plan consolidates the technical results, pilot experience and stakeholder feedback obtained during the BIM4CE project. It defines agreed measures for the continued implementation, transfer and uptake of the BIM4CE bridge-monitoring solution, which combines flexible leakage sensor foils, accelerometers, Weight-in-Motion data, cloud-based data management and BIM-based digital twins.

The solution was validated through pilot activities in Germany, Slovenia and Italy. The completed pilot sites provide reference cases for infrastructure owners, public authorities, engineering organisations and service providers. The Action Plan supports the continued use of harmonised procedures for sensor installation, calibration, data integration, monitoring and maintenance planning.

The project partners will continue cooperation through their established networks and will use the Action Plan, pilot experience and Business Plan as a basis for future research, funding applications, commercial offers and transfer activities. The plan therefore provides a practical foundation for the further uptake of cost-effective, data-driven bridge monitoring in Central Europe.



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