ce/papers Proceedings in civil engineering
Ernst & Sohn A Wiley Brand
ORIGINAL ARTICLE
EUROSTRUCT

Interoperable, platform independent structural health monitoring with long-term availability

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Abstract

Within the FFG-project PreMainSHM the area of preventive structural health monitoring is raised to a new level of networked systems. This applies not only to the networking of self-sustaining sensors and their sensor data, but also to the networking and utilization of relevant information for the building condition assessment and building management. The paper presents and discusses the basic considerations in terms of data models and interfaces of cloud-based systems to guarantee interoperability between different software systems and long-term-availability and accessibility not only of raw but also of and relevant meta and analysed data. The starting point for further developments is provided by the existing technologies of the involved partners, which is a GIS based infrastructure asset management system and wireless as well as fibre optic sensor systems from the authors. In order to obtain information relevant to the building management, suitable analysis and prognosis procedures are discussed. Data models and analysis tools are developed and integrated into an interoperable software framework in order to provide relevant status information that can be either assessed directly by web user interfaces in form of a georeferenced digital twin or that can be used in building management systems.

Keywords

Digital Twin, Interoperability, Structural Health Monitoring, FAIR data, Cloud-based SHM Software Systems

1 Introduction

With the "Intelligent Bridge" project cluster launched in 2011, the Federal Ministry of Transport and the Federal Highway Research Institute (BASt) in Germany are pursuing the goal of designing the necessary modules for a structural condition assessment in the context of a service life prognosis and maintenance, and of developing an adaptive system for providing relevant information for a holistic assessment. To date, various sub-topics have been investigated and presented in several research projects in the "Intelligent Bridge" project cluster [1].

Up to now, sensor-based condition monitoring with regard to condition assessment and maintenance planning has not been systematically considered in design and management tools such as BIM. Rather, information is currently collected in separate systems and mostly analysed by bringing in expert knowledge and further software-based tools to obtain relevant characteristic values for the assessment and maintenance planning [1], [2], [3]. This is time-consuming and bears the risk of misinterpretation and a progressive loss of information over time, especially due to the temporary analysis results provided by the expert knowledge and the associated reduction of the complex data basis to a few measures to be set. In addition, it has been shown that forecasting models often have insufficient accuracy. In the past, this circumstance led to the application of probabilistic concepts, which in turn can lead to very conservative lifetime forecasts [4]. Many examples can be found here, e.g. for estimating corrosion due to carbonatisation [5] and/or chloride exposure [6], [7] or fatigue [8].

A promising approach to a more reliable condition assessment and prognosis is sensor data-based analysis. However, this requires the use of reliable sensor technology or sensor systems and corresponding analysis methods. The requirements for sensor technology for structural monitoring can be considered extremely high, as measured values are to be recorded and evaluated, in part with high resolutions under harsh environmental conditions, perhaps over a period of several decades. Although a large number of robust sensors have been developed for the building industry and have also been used successfully in the past (cf. [1], [8], [9]), it is likely that the typology of sensor

https://doi.org/10.1002/cepa.2055
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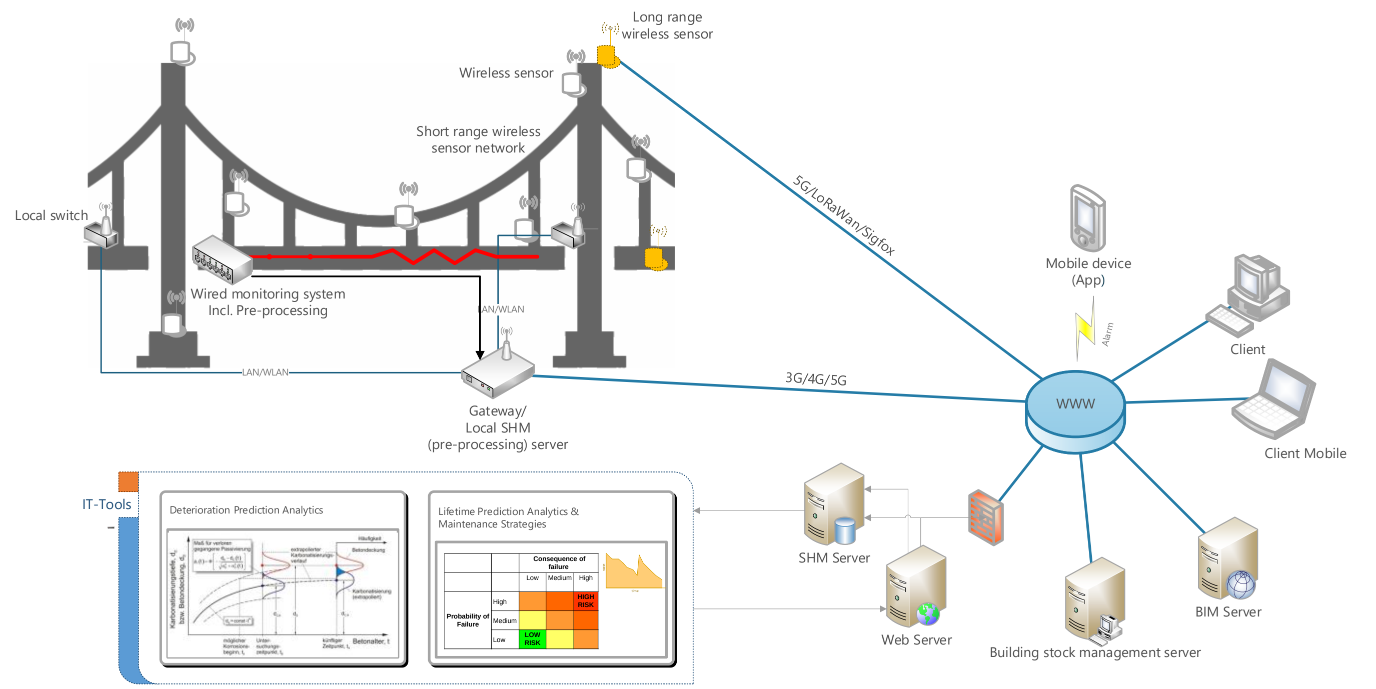

Figure 1 Concept of intelligent building monitoring with corresponding system components

technology will change in the future. For example, major advances in wireless sensor networks have now resulted in billions of connected Internet of Things (IoT) devices, and IoT applications can also be found in the construction sector [9], [10]. Advantages of such IoT technologies are the often low price and the thus enabled increasing networking of a multitude of sensors and thus sensor data.

The project "PreMainSHM" (FFG project no. 886145), which is currently being worked on by the authors in co-operation with ASFiNAG, builds on the state-of-the-art in the field of structure monitoring and takes the field of preventive structure monitoring to a new level of networked systems (cf. Figure 1). This concerns not only the networking of autonomous sensors and their sensor data, but also the networking and utilisation of relevant information for systems (especially software programmes) of building condition assessment and building management. The main aim of the project is to further develop the components in the interaction of the various systems for several exemplary application scenarios and to integrate them into a cloud-based, scalable, but at the same time highly efficient and practicable system.

An essential aspect is the utilisation of the monitoring data or the findings from it in GIS or BIM systems or other systems such as sensor data-based structural modelling and recalculation or maintenance and management systems [11]. Corresponding standardised software interfaces and suitable protocols or data formats for automated data exchange as well as standardised attribute definitions are to be specified, evaluated and implemented. If done properly, such simple attributes in connection with object models can also be used in BIM systems to characterise temporally variable structure states and the results can be used in structure management systems (e.g. the IMT "Cockpit" system of ASFiNAG) across all structures.

2 From isolated solutions to networked, adaptive and interoperable systems

Currently, there are mostly only proprietary monitoring system solutions that often only provide pure measured values. Interfaces to other systems, such as GIS or BIM systems, are missing, and analyses are often carried out outside the monitoring system solution used. This is due to the fact that analysis and assessment methods require other expertise or tools and data from other sources (e.g. building inspection) must also be included in an assessment. The field of building management is occupied by different actors, the building owners, the monitoring experts and monitoring system experts as well as technical building inspectors [12]. Although initial approaches to holistic systems for the exchange of information between the various actors have already been tackled in the past (see e.g. Brimos, www.brimos.com) or are being partly anchored in guidelines [12], [13], [14], [15], there is a need for a more holistic approach [1]. With newer approaches such as OSIMAB [16], and other approaches [17], these deficits should be eliminated. As discussed before, BIM systems are increasingly playing a central role in this context, but practice is far from providing BIM data for all structures with the appropriate level of detail. Moreover, it also does not make sense to merge all systems with each other. Rather, data exchange by means of open, standardised data models and suitable communication interfaces is required (see e.g. [18] or the management shell bbox - Bridge Box in [19]). The information content must also be specified (e.g. current carbonation depth and/or predicted start of possible corrosion, etc.) and does not only have to provide just measured sensor values [20]. Schemas used in BIM, for example based on the IFC standard, contain extension options that allow user-defined information to be stored in subclasses (e.g. IfcProperty) for objects with the help of dynamically generated properties [21], [22]. However, BIM software is a planning software which is operated manually on demand and actually does not operate autonomously with dynamically generated information from continuous monitoring. So far there are just three different integration strategies, which are [11]:

i. information integration directly in the semantics of the object (embedded data), e.g. geometry and status metadata (attributes) are implemented directly in the BIM model
ii. information directly linked to the semantics of the object (linked data), e.g. a web link is stored in the attribute, which for example provides a photo of the object or any other relevant information needed for the assessment
iii. use of the attributes for linking to external data sources. E.g. a database query can be created from the attributes, which contains further metadata (linking of systems).

2.1 Sensor data formats and standards

Observing FAIR data principles (FAIR data are data that comply with the principles of findability, accessibility, interoperability and reusability) is essential in data acquisition and data management, which means using established standards or expanding existing standards accordingly and making each sensor data record uniquely identifiable (e.g. via a UiD). There are no such generic standards for the multitude of sensors or sensor types and different software systems used for structural health monitoring (SHM), but there are for temporal and spatial information (cf. Table 1). Through temporal as well as spatial referencing, it is possible at any time to filter, provide, exchange, retrieve, assign and analyse data in a platform-independent way, which is not possible with just a unique identifier (UiD). How the UiD is defined, on the other hand, must be determined and documented on a system-specific basis. In this context further data fields (attributes) are required to ensure reproducibility as well as interoperability, e.g. for the sensor type, the measured unit, the accuracy class and much more. Here many different concepts have been developed already and standardisation is ongoing (e.g. OGC Sensorthings API [23], IFC [24] etc).

Table 1 Minimum platform-independent metadata definition requirements to ensure interoperability

Metainformation	Standard
Unique identifier (UiD)	-
Temporal referencing	e.g. UTC
3D georeferencing	e.g. WGS84 or ETRS89

2.2 Data exchange formats

When monitoring data is analysed in a 3D context, the 3D data should also be available in an exchangeable format. Contrary to new construction where a BIM is already available from the planning phase of a structure, structural health monitoring is often applied to decades old existing structures where no 3D models are available and even drawings might be missing or are incorrect. In such cases the geometry of the structure has first to be captured e.g. by structure from motion (sfm) or laser scanning techniques. Typically, laser scanners capture the data in a proprietary format. These scans are usually imported into a registration software where scans from different setup points are registered into a homogeneous point cloud which can also be transformed into a project specific or global coordinate system. These point clouds can be exported into generally accepted ASCII (*.xyz, *.asc) or binary (*.las, *.laz, *.E57) point cloud formats. However, point clouds are not well suited for monitoring data overlays and are usually processing intensive. Textured 3D models are more appropriate as the huge amount of data is reduced to geometric primitives like cylinders, spheres or triangles. For more natural appearance these models can be textured with images. Common data exchange formats for structured models are *.obj files with textures in jpg format or *.ply files.

The integration of 3D models of real structures with sensor data in game engines enables the creation of immersive virtual environments. These environments can be viewed using 3D viewers or augmented reality applications, allowing for virtual inspections and interactions with the monitoring data [25]. However, the incorporation of object-oriented ontology still requires the use of specialiced software. Initial attempts indicate that artificial intelligence can assist in generating object-related information and semantics to develop complete BIM models [26]. Despite this, the process of creating 3D digital twins remains laborious and resource-intensive.

3 Simplified approaches for bridge monitoring

In many use cases a simplified approach to setting up a monitoring system onsite, which is used firstly for quick and efficient documentation of the installation but also configuration of the monitoring system itself without the need to use special software, is still missing. I.e. most monitoring systems are limited to data acquisition systems with very proprietary configuration possibilities. To make such systems more practicable, especially in the context of using monitored data in digital twins, two key factors must be considered:

i. information enrichment with semantics and object relationships and
ii. guaranteed interoperability of data between different software systems.

3.1 Taxonomy on demand

As there will always be diversity in software systems, scalability and interoperability must be ensured without adding complexity to the processes or the necessary software development. A simpler approach will result in higher acceptance. However, to maintain the usability and long-term accessibility of monitoring measures, basic semantic considerations and hierarchical and multi-level inheritance must be taken into account already during data acquisition [18], [21], [27], [28], [29]. Otherwise, the data from the monitoring system may become inaccessible, creating a "data graveyard" where it will be unclear in the future what information was provided and how to use it.

To address this issue of "taxonomy on demand", it was decided to adopt the methodology of regular bridge inspections for structural health monitoring as well. The procedures of the regular bridge inspections are well established and are updated regularly to meet the changing needs (e.g. RVS 13.03.11 [14] and RVS 13.04.11 [15] for Austria or DIN 1076 in Germany). As the actual project was considered for Austrian infrastructure, the taxonomy of RVS 13.04.11 was chosen, which is much simpler compared to that of SIB-Bauwerke in Germany. This taxonomy divides the structural system of bridges into 8 main structural elements and various detailed structural elements, which are hierarchically associated with the main elements. These detailed structural elements can then be further subdivided in elements related to structural design, including attributes like used materials etc. In some cases, it is useful also to use further sub-levels (e.g. for a prestressing steel bar etc.).

For bridge inspections, the object-related hierarchical structural system is complemented by inspection elements based mainly on the detailed structural elements. This level of detail allows for the identification of "hot spots" related to a deterioration type and its assessment, i.e. the deterioration and thus the actual condition is a property of a structural element. There is a catalogue of several structural element-specific deterioration types defined in the RVS 13.04.11 for bridge inspection, but there aren't some for structural health monitoring.

In Austria monitoring issues related to bridges and other engineering structures are addressed in RVS 13.03.01 [12]. Although the RVS is a guideline that provides some explanations on the monitoring procedures, the planning and the implementation of monitoring measures incl. measured variables and appropriate sensor types for different application scenarios, it misses information on how to use the information from the monitoring for bridge assessment and maintenance in other software systems.

At first glance, it might seem that this is not necessary, as the monitoring measures are usually carried out as a supplement to a building inspection or as a recommendation from the building inspection. It is often assumed that the evaluation of the results from the monitoring is therefore carried out in the course of the building inspection, from which then bridge maintenance actions are derived. However, it is also quite reasonable to make data from the continuous monitoring directly usable, be it for an immediate damage report or for the continuous reporting of changes in condition, which form the basis for a service life assessment or maintenance planning. This requires that the data from continuous monitoring is processed in a suitable manner and, ideally, through automated processes, and that it be converted into a report that is easy for the user to understand. For structural monitoring, this means that the recorded data is transferred via suitable "assessment schemes" into a feature space that can be used in structural management.

In the context of a desired taxonomy, inspection elements can also be treated as monitoring elements and the deterioration types defined in RVS 13.04.11 can be used accordingly or can be supplemented with further types specifically addressing monitoring issues. It is also of advantage if the monitoring system itself, i.e. the system components and the sensors are handled as objects with additional attributes in the data model. This makes the monitoring system independent from the structure. Depending on the purpose the monitoring system and sensors can be assigned to a location as well as to individual or to several structural elements. If done properly, also any sensor readings are automatically allocated to structural elements.

However, the sensor readings are just measured values that need to be processed either by special software (e.g. static software etc.) or by routines that continuously analyse the acquired data. If special software is required for further analysis, the sensor data must be exported in a software-compatible format. However, in the case of continuous analysis in 24/7 operation, it is advisable to combine suitable routines with monitoring system components, the structural elements and the data stored in an overall software system. Therefore, the output of the analysis becomes a property or feature of the structural elements. The routines resp. algorithms for data analysis can be generic and can for example provide statistical data or model-based data for deterioration types and its assessment or lifetime prognosis (e.g. fatigue, corrosion etc.). It is also possible to provide the output in form of a grading system like it is done already for bridge inspection and also a rating can be inherited to higher level elements. However, since the results of analysis routines can often be very complex and subject to gradual changes, a suitable graphical presentation is indispensable in most cases.

The appeal of utilising such easy-to-use "assessment schemes" on the basis of generic models and supported by appropriate visualisations and component mapping is that they can be applied to a wide range of structures and thus be used as another decision-making tool for the managing and maintaining assets. However, it is important to keep the data basis in a suitable form for the long term. This makes it possible to modify models or even apply new methods of analysis.

In summary, monitoring measures that take FAIR data principles and the use of the outcome in digital twins into account, should reflect the following taxonomy considerations:

- Structural system should be hierarchically structured into 3 to 4 levels of detail, including the main structural system, main structural elements, and detailed structural elements or subparts if necessary
- Condition assessment should include:
  - Inspection/Monitoring elements (linked to a specific object of the structural system)
  - Monitoring system elements (associated to Inspection/Monitoring elements)
  - Monitored data (linked to monitoring system)
  - Assessment scheme (linked to monitored data, degradation/damage type and structural system)
  - Degradation/damage type and severity (linked to the structural system as a property through Inspection/Monitoring elements)

In order to create a most simplified digital twin, it is not necessary to generate all structural elements and details of the monitored structure. Instead, it is more beneficial to focus on those structural elements with object related attributes, which are being monitored and have relevance to damage assessment, findability and smooth exchange of information between building management software. By limiting the scope of the digital twin to these key elements and attributes, a simplified approach can be achieved while still maintaining the principles of FAIR data.

4 Software implementation

4.1 Basic considerations

The increasing demand for safe, reliable, and cost-effective infrastructure has driven the need for advanced monitoring technologies that rely on sensor data. However, currently, monitoring systems are primarily used as data acquisition systems, and data analysis and interpretation are left to experts. With the growth of the Internet of Things (IoT), wireless monitoring has become a popular and efficient method of collecting large amounts of sensor data, enabling efficient real-time analysis when data acquisition and analysis routines work together.

However, the lack of interoperability between different data acquisition systems and data analysis tools often limits the effectiveness of wireless SHM systems. This fragmentation makes it difficult to integrate data from multiple sources, share data between stakeholders, and combine data with other relevant information. To overcome these challenges, the development of an interoperable, cloud-based platform for SHM and data analysis is proposed. For an interoperable, cloud-based platform for SHM and data analysis to be successful, it must meet several critical user requirements, including:

- Interoperability: The platform must be able to integrate data from a wide range of systems and technologies, regardless of the underlying protocols or formats used (see also Figure 1). This will allow easy sharing of data between stakeholders and integration of other relevant information. Adherence to the FAIR data principles (Findable, Accessible, Interoperable, and Reusable) will ensure that the data is managed in a way that maximises its utility, portability, and longevity, and that the data is easily discoverable and usable by other researchers and organisations.
- Data analysis capabilities: The platform must include a powerful data analysis engine that enables users to perform various analyses, including real-time monitoring, periodic reporting, and advanced data analysis techniques such as machine learning and artificial intelligence [30], [31]. The data analysis engine should be accessible through a user-friendly interface and capable of handling large amounts of data.
- Scalability: The platform must be highly scalable, allowing it to accommodate large amounts of data and supporting the needs of organisations of all sizes.
- Data security: The platform must include robust security features to ensure the confidentiality and integrity of the data stored on it. This includes features such as user authentication, and access control.
- User-friendly interface: The platform should include a user-friendly interface that makes it simple for users to access and analyse data, perform complex analyses, and visualise results.
- Reliability and availability: The platform must be reliable and available at all times, ensuring that users have access to the data they need, when they need it. This includes features such as redundant systems and disaster recovery plans.

In conclusion, an interoperable, cloud-based platform for SHM and data analysis has the potential to transform the way we monitor and assess the performance and integrity of structures. By meeting the requirements above, such a platform can provide a cost-effective and efficient solution for collecting, analysing, and sharing data from structures.

4.2 Software/system architecture

The developed SHM system can be accessed through a web application, which allows for remote viewing and analysis of collected data. The web application also facilitates configuration and management of the SHM system and its components. The sensor data collected by the SHM system is stored as continuous streams in a time series database. The database is optimised for storing and querying large amounts of time-stamped data and provides automatic aggregation functions, allowing the data to be easily analysed over time. Metadata and configuration information for the SHM system is stored in a relational SQL database. This includes information about the structures being monitored, sensor locations, and other relevant data as described in chapter 3.1.

Real-time data analysis, periodic reporting, data acquisition through 3rd party providers and alerting are performed by independent services similar to the microservices concept report by Behrens & Mayer [16]. These individual services communicate through a distributed event streaming platform, which is a key component of the system. All services, as well as the used event streaming platform are designed for redundancy through replication to ensure that the system remains operational even in the event of hardware failures.

4.3 Data and system visualisation

As visualising data is a crucial aspect of data analysis, the platform provides users with a powerful set of tools for creation of interactive charts, graphs and dashboards. With the desired platform, users can create interactive charts, tables and graphs that provide rich insights into the data, helping them to identify trends, patterns, and anomalies. The built-in chart types, including line charts, bar charts, scatter plots, and more, are highly customizable and can be adjusted to suit the specific needs. This includes setting custom thresholds and triggers, which help highlighting important data points.

The platform also includes a dashboard feature that allows users to create custom dashboards to display their data near real-time. Dashboards can be configured to display multiple charts and graphs in near real-time, and they can be customised with different widgets, including text boxes, images, and more. Users can also control the layout of the dashboard, adjusting the size and position of each widget to create the ideal viewing experience. The dashboards are also designed to act as a reporting tool, i.e. dashboards can be archived or exported to other software systems.

The system also provides a comprehensive representation of the monitored objects and areas in the form of a simple 2D digital twin, for which the object data can either be imported from other software or can be created directly in the system by the user. The digital twin utilises georeferencing, polygonal representation of areas, hierarchical and

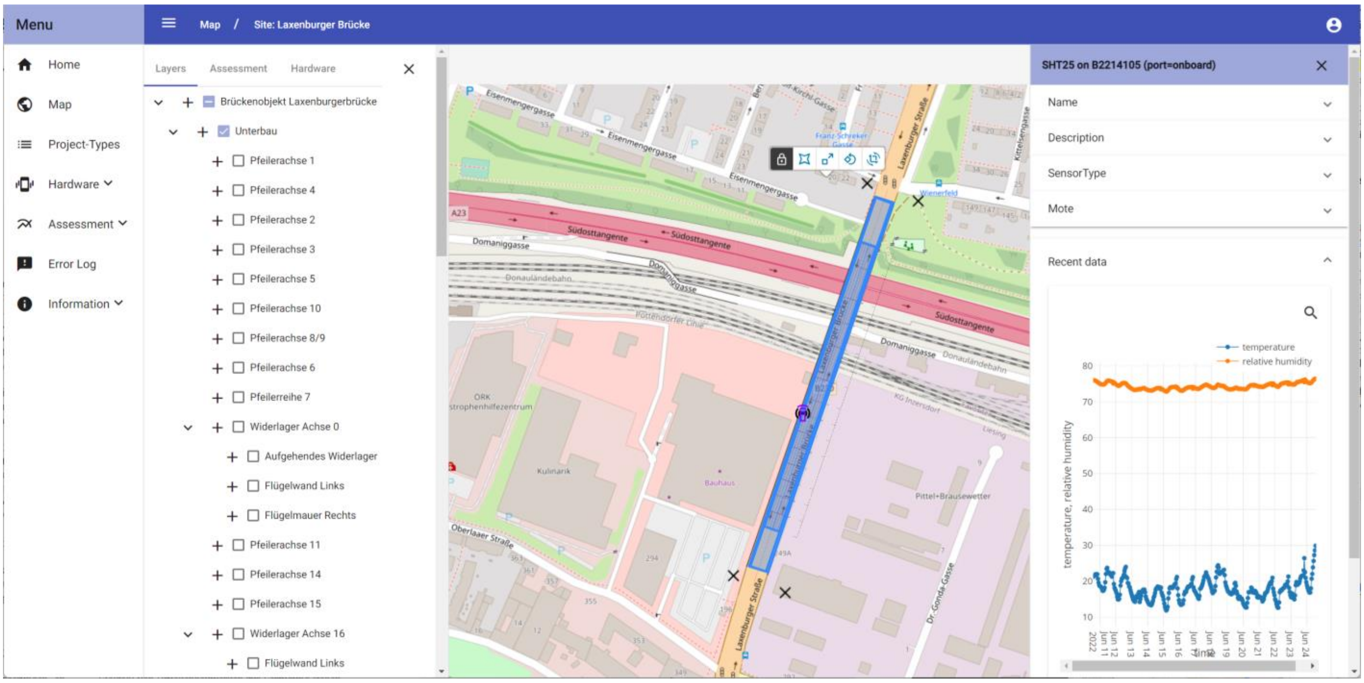

Figure 2 Web-based software framework with integrated data analysis tools and georeferenced 2D visualisation of key building elements, sensors and sensor data. Source: TU Graz & TTI GmbH

multi-level inheritance for structural elements etc., and provides a geographical context for data analysis, all represented in a map view. The hierarchical structure and map view offer an organised and visual way to understand the relationships and locations of objects within the system and provide the semantics to assure the FAIR principles (see Figure 2 and also chapter 3.1). This concept is especially of benefit for using it for Austrian highway infrastructure, as ASFiNAG is actually using a GIS based infrastructure asset management software.

4.4 Data assessment

The data assessment follows the concept of providing relevant analysed data (resp. data on the condition) and not just sensor readings. Data assessment and prognosis are at the forefront of the developed cloud-based platform. To achieve this, a visual scripting language called "blueprints" is utilised. Blueprints can be customised to perform specific computations on multivariate inputs and are used to assess the condition of monitored objects.

The versatility and flexibility of blueprints enable users to define the type of analysis they want to perform, including predefined modules such as statistical models and machine learning algorithms. In this way meaningful insights and predictions can be generated that give users a clear understanding of the data collected from the monitored objects. When the evaluation procedures are coupled with the visualisation tools (see chapter 4.3), they result in easily understandable and flexibly applicable "assessment schemes" (see chapter 3.1), which can be stored as templates for further use. If these assessment scheme templates are now linked to the objects (resp. structural elements) and the object relevant sensors, a direct assessment of the structural elements can be carried out. This means that the assessments are performed on an object-based level, grading the condition of each monitored object. This saves time and effort while ensuring consistency and accuracy in assessments.

Additionally, alerts and notifications can be set up based on the results of these assessments, allowing users to respond quickly to potential issues before they escalate.

4.5 System reliability issues

The developed solution addresses reliability issues through a combination of technical and operational approaches to ensure system reliability and scalability. Key features of the platform include:

- Redundancy: All services are designed to be highly available and reliable, with data streams being replicated across multiple servers to ensure that data is always accessible, even if a single server fails.
- Data Backup and Recovery: Regular backups of all data are taken and stored in secure off-site locations, ensuring that data can be recovered in the event of a disaster.
- Monitoring and Maintenance: The platform is monitored 24/7 to identify and resolve any issues that may arise, including proactive monitoring and maintenance to prevent problems from occurring.
- High Availability Architecture: The platform's architecture is designed to ensure high availability, with load balancing and failover mechanisms in place to ensure that the platform remains responsive and available even during periods of high demand.

Overall, the platform is designed to be highly reliable, and a comprehensive approach is taken to ensure that it remains operational at all times. The technical features and operational practices employed, such as redundant data streams and regular backups, provide a reliable platform that customers can depend on.

5 Summary

Monitoring systems must be designed taking into account cost aspects as well as durability aspects. Software and hardware components must be scalable and the data must be checked for plausibility for further use. However, efficiency is only significantly achieved through intelligent data aggregation and analysis and the visualisation of the results as well as interoperability with other systems. Partially automated and fully automated analysis procedures using AI methods are therefore often developed and integrated without neglecting model-based approaches based on scientific knowledge. The data is visualised using suitable 2D or 3D models and other graphical tools via web services, which also allow the configuration of the monitoring systems. Finally, digital twins are created by linking to building management systems or by considering concepts for the creation of digital building models (IFC (BIM), City GML or similar), which enable sustainable monitoring-supported building management [25].

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