Smart Bridge Monitoring: Digital Twins and Sensor Technology Against Structural Aging

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Abstract

The adoption of Industry 4.0 technologies beyond manufacturing is gaining traction in construction engineering, particularly through the use of digital twin technology for infrastructure monitoring and maintenance. Digital twins, originally developed for industrial systems, offer real-time digital representations of physical assets by integrating static data, such as design specifications, with dynamic data streams from embedded sensors. This paper presents a digital twin solution which integrates sensor data tailored for bridge monitoring, using the Asset Administration Shell (AAS) to enable interoperability and structured data management. By consolidating diverse data sources - from planning, construction, and operation phases, the system facilitates continuous structural health assessment and assists structural aging by means of predictive maintenance strategies. Central to this solution is the BBox toolset, sensor configuration, data ingestion, visualisation, and centralised knowledge management for network infrastructure such as bridges. The architecture enables both static data imports (e.g., CAB files, IFC models) and dynamic data acquisition (e.g., MQTT-based sensor readings) via a time-series database. Moreover, the architecture can be integrated with existing tools such as Bridge Management Systems (BMS) and Building Information Modelling (BIM), promoting a unified, data-driven approach to infrastructure management without displacing current engineering workflows.

Keywords: Digital Bridge, Asset Administration Shell, Sensor Integration, Structural Health Monitoring

1 Introduction

The integration of Industry 4.0 technologies into civil infrastructure systems is gaining attention, particularly in response to the growing challenges associated with aging assets, constrained public resources, and rising demands on structural resilience. Among existing technologies, *digital twins* offer significant potential for transforming traditional infrastructure such as bridges by enabling digitalised monitoring and maintenance practices [1]. Initially developed for applications in manufacturing, digital twins create a real-time digital representation of physical assets by combining static data with dynamic, sensor-derived information. This concept is now being extended to the domain of bridge infrastructure, where the need for continuous, data-driven condition assessment is both critical and urgent [2].

Bridges represent essential components of transportation networks, yet many are subject to degradation due to age, changing environmental exposure, and increasing annual traffic loads. Conventional inspection routines, often based on periodic visual assessments, are labour-intensive, scheduled at static intervals, and limited in their ability to detect evolving structural problems at an early stage. In this context, digitalisation presents an opportunity to support the transition toward predictive and lifecycle-oriented maintenance strategies. By using real-time data and integrating diverse information sources, digital twin combined with sensing technology can reduce operational costs and increase the safety and longevity of critical infrastructure assets such as bridges [2]. Furthermore, it can provide a powerful data foundation for monitoring and controlling the entire life cycle of a bridge [3].

This work builds on the digital twin-based approach for the monitoring and management of bridge structures presented in [4] and introduces the aspect of sensor integration. The proposed system integrates *static information*, such as design documentation, material properties, and construction records, with *dynamic data* collected through embedded and external sensor technologies. These sensors continuously monitor relevant parameters in term of structural health monitoring. The system is built upon the Asset Administration Shell (AAS) [5], a standardised data model designed to ensure interoperability across different systems and domains. The AAS enables structured data representation and facilitates the integration of the digital twin with existing infrastructure management tools, such as Bridge Management Systems (BMS) and Building Information Modelling (BIM) platforms.

Through the consolidation of heterogeneous data types, the digital twin enables structural health monitoring and the identification of potential anomalies within the structure, thereby supporting efforts to tackle structural aging. This allows for example a more targeted allocation of maintenance efforts and supports early intervention before severe damage occurs. Furthermore, when implemented during the construction or major rehabilitation phases, sensor systems can be embedded directly into structural components of a bridge, thereby protecting them from environmental influences, vandalism, and animals/insects. In existing structures, externally applied sensors provide a viable alternative, offering valuable insights without the need for invasive procedures.

In addition to improving the management of individual structures, the system architecture supports scalability and regional coordination. The use of standardised interfaces and interoperable data structures allows for the aggregation of data across multiple assets and administrative levels. This opens possibilities for centralised monitoring units to oversee bridge infrastructure at a municipal, regional, or national scale. Such coordination can improve the efficiency of inspection and maintenance operations by enabling resource bundling, comparative analysis, and strategic prioritisation.

By addressing both technical and organisational challenges in bridge monitoring, this work contributes to the development of a scalable, interoperable, and data-driven framework for infrastructure management. The proposed digital twin-based system, integrated with sensing technologies, supports a paradigm shift toward proactive maintenance and lifecycle optimisation, offering a practical and cost-effective toolset for public authorities and infrastructure operators facing increasing demands on performance, transparency, and sustainability.

2 Background and Motivation

There are more than 150,000 bridges in Germany, approximately 130,000 of these are road bridges. Of the more than 40,000 bridges in the German federal highway network, over 25% have a condition rating worse than 2.5 on a scale from 1 to 4 [5]. These ratings are based on structural inspections conducted for all road bridges in Germany in accordance with DIN 1076 [6]. Certified inspection personnel are evaluating the progress of existing damages and recording new damages, primarily through visual inspections. The outcome is an inspection report, which supplements the structure's record book—an official document that must be created for each bridge after its completion and contains essential information such as dimensions, materials, and structural properties. In Germany, the proprietary *SIB-Bauwerke* software [7] is often used for this purpose. The information is exchanged as a .CAB file, the human-readable information is transferred as a .pdf file. This process accompanies a bridge structure over the entire life cycle phase of operation. However, data is also generated during planning and construction [2]. If these phases are supported by digital tools, BIM models are maintained. All disciplines plan their installations together and collisions can be identified at an early stage using collaboration tools. Collaboration takes place in common data environments. These already offer the unification of data of all types and origins (e.g. drawings, structural calculations, images, protocols), but are proprietary and therefore not interchangeable. While the BIM model is intended to be used over the life cycle, they do not offer any possibility of connection, especially for dynamic data such as sensors, and damage management is also not possible. This is currently implemented using a linked data approach. The reason for this is that a dynamic component is imposed on a static program format [2] [8]. Central data management in a standardised, exchangeable, dynamic format is not feasible. Instead, the real time display of measurement data takes place via the connection of dashboards of the measuring device manufacturers, while the data is stored in an environment that may be unknown to the building owner. In summary, several key challenges remain: infrequent updates, isolated data silos, a lack of real-time insight, and the absence of dynamic, standardised, and interoperable solutions.

3 System Architecture of a Digital Twin for Bridge Lifecycle Management

To address the challenges associated with fragmented, heterogeneous data in bridge lifecycle management, a reference architecture for a digital twin-based system is proposed in [4]. This architecture supports the integration of both static and dynamic data sources across all life phases of a bridge - from planning and construction through operation and eventual demolition. The core objective is to enable seamless and interoperable data consolidation for structural health monitoring and lifecycle analysis, ultimately supporting more efficient and data-driven maintenance strategies. The system architecture as illustrated in Figure 1 is built on the AAS, a standardised digital representation framework developed under Germany's *Plattform Industrie 4.0* [9]. The AAS ensures semantic interoperability between digital systems by structuring asset-related data into modular Submodels. These Submodels represent aspects such as design specifications, inspection records, maintenance history, and sensor measurements. The AAS model complies with the IEC 63278 series and serves as the digital backbone for bridging domain-specific engineering models with cyber-physical infrastructures.

At the core of the implementation lies the Eclipse BaSyx middleware [10] [11], which provides the runtime environment for managing AAS instances and Submodels. It includes a registry for digital twins, repositories for AAS and Submodel instances, and standardised REST interfaces for querying and interacting with live asset data. This middleware supports the integration of live and historical sensor data, imported files (e.g., .CAB), and design models (e.g., IFC or BIM) into a consistent and interoperable digital twin infrastructure.

The digital twin system is accessible through the BBox [12] [4] graphical user interface, which acts as the central interaction layer for its users. Designed with usability and role-specific perspectives in mind, the BBox interface allows engineers, operators, and inspectors to visualise consolidated bridge data, configure sensor setups, and visualise upcoming inspections as well as past inspections assessments. Key components of the BBox toolset include:

- **CAB-Import Feature**: Enables automated conversion of legacy bridge data (in .CAB format, compliant with ASB-ING [13]) into standardised AAS Submodels. This process preserves the semantics of structural records and bridges the gap between proprietary systems and interoperable data management.
- **Network View**: Offers a geospatial overview of all managed infrastructure assets. Users can navigate across a map-based interface that visualises the condition status, inspection history, and sensor activity of bridges in a regional or national network.
- **IFC-Viewer**: Provides a 3D visualisation environment for BIM models. IFC models can be imported and linked to dynamic sensor data, enabling users to explore structural elements in context and observe live or historical metrics directly within the geometry.
- **Sensor Data Integration**: The architecture incorporates a multi-layered storage supporting scalable data management. Static data and metadata are stored in the AAS repositories, while dynamic data—such as time-series from sensors—is handled through an InfluxDB instance optimised for high-frequency environmental and structural monitoring. Additionally, S3-compatible storage is used for archiving long-term datasets and supporting scalability.

The data flow within this architecture is structured to support both batch and streaming paradigms. Legacy static data is uploaded and parsed via ETL services and linked to the corresponding AAS structures. Dynamic data from sensors can be ingested either via file-based imports (e.g., CSV) or through real-time streams using protocols like MQTT. All data is annotated with semantic metadata, including measurement context, units, and spatial locations—ensuring high fidelity in data interpretation and reuse.

The proposed system aims at a modular, scalable, and standards-compliant architecture, which offers a comprehensive foundation for building and maintaining digital twins of bridges. The integration of static and dynamic data not only supports current asset management needs but also creates a future-proof infrastructure for predictive analytics, AI-assisted diagnostics, and cross-domain interoperability.

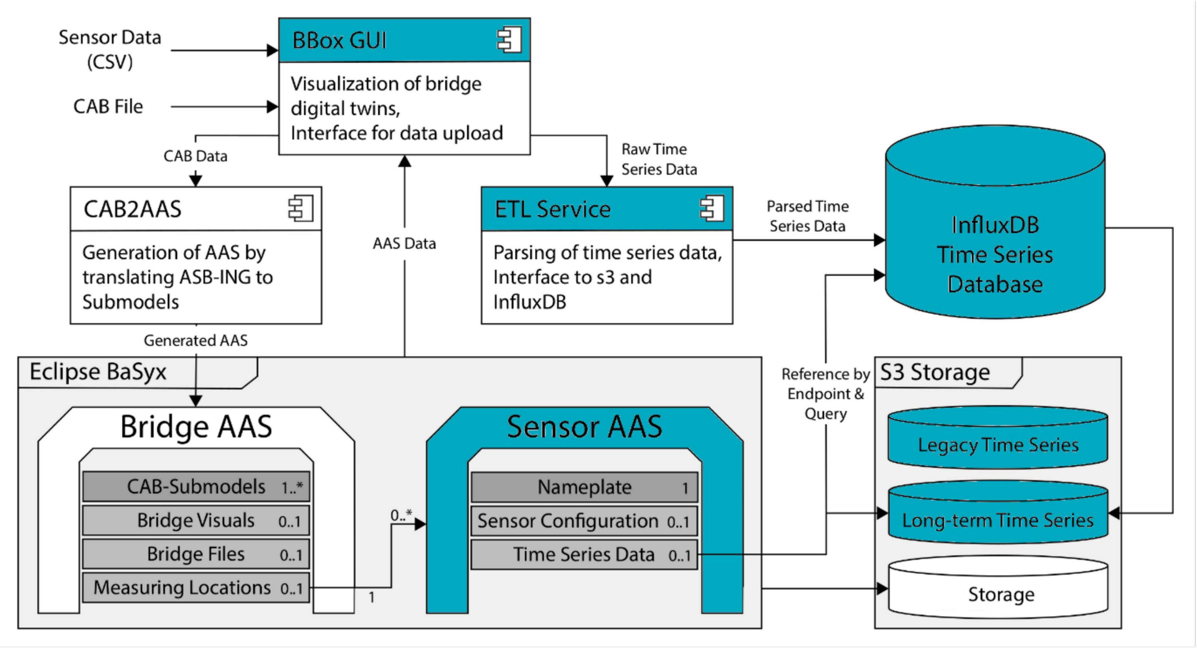


Figure 1: Architecture overview of a digital twin-based system *[4]*

4 Sensor Integration for Bridge Structural Monitoring

As previously discussed, a central component of the proposed digital twin-based architecture is the integration of dynamic data from physical sensors. The primary objective of collecting such dynamic data is to enable continuous structural health monitoring and to provide stakeholders with timely, data-driven insights that help prevent damage at the earliest possible stage, especially in aging structures. To facilitate traceable and real-time data exchange, the architecture implements a digital twin by means of AAS for each sensor, which then is mapped onto the structural model of the bridge through well-defined semantic references.

This chapter describes the sensor integration strategy in detail, focusing on sensor mapping, data importing mechanisms, and the linking of time-series data to the AAS Submodel(s). The core components involved in this process are illustrated in colour blue in Figure 1: Architecture overview of a digital twin-based system [4] Each sensor is represented as an individual AAS, which encapsulates the digital identity of the sensor including a nameplate (descriptive metadata), sensor configuration parameters, health or status information, and a dedicated Submodel for time-series data. This time-series Submodel does not contain the sensor data directly, but instead references a backend storage system—specifically, an InfluxDB instance—via a URI endpoint and a query specification. This indirection ensures a lightweight and flexible AAS model while enabling seamless access to high-frequency data streams. The ensure interoperability and among others here the IDTA standardised time-series Submodel is used and implemented.

Sensor placement within the digital twin is managed via the concept of sensor locations, which are created by selecting eligible structural components of the bridge (e.g., a bridge field or a support element). These locations are represented within the bridge's AAS by a dedicated Submodel that aggregates all sensor locations. Within this Submodel, a *ReferenceElement* links each sensor location to the corresponding bridge component's Submodel, ensuring contextual alignment and traceability. Once a sensor location is defined, one or more sensor AAS instances can be associated with it. Upon creation, a bidirectional reference is established between the sensor location and the sensor AAS, allowing both components to remain synchronised. This referencing mechanism supports modularity and reuse of sensor types across multiple bridge assets while maintaining structural traceability.

The proposed architecture supports different approaches for sensor data collection and processing. Such flexibility in crucial due the challenge of heterogenous information around measurements in a bridge. Here we present two approaches, one for static data ingestion and one for dynamic data ingestion:

- **Sensor data over static ingestion** is based on manual uploads of CSV files generated by the sensors. These files are processed through an ETL (Extract, Transform, Load) service available via the BBox frontend. The ETL service parses the CSV content, enriches it with metadata, transforms it into a time-series compatible structure, and stores it in the InfluxDB. The Submodel of the sensor's AAS is then updated with the access information for the newly ingested dataset, maintaining referential consistency.
- **Sensor data over dynamic ingestion** enables continuous, real-time data collection by connecting active sensors that support protocols such as MQTT to a central broker. An ingestion service, implemented using Telegraf, subscribes to relevant sensor topics and streams the measurements directly into the time-series database. This setup ensures low-latency monitoring and supports time-critical applications such as damage detection or load monitoring under varying operational conditions.

In both approaches, time-series data remains accessible either through the AAS time-series Submodel or via direct API calls to the database, depending on user roles and system configuration. The AAS framework ensures that even third-party applications can interact with the data through interoperable, standards-compliant interfaces, enabling advanced analytics and decision support systems—such as predictive maintenance or anomaly detection algorithms—to be integrated within the broader ecosystem.

Regarding the setup and configuration of sensors, the initial onboarding of a new sensor type into the system requires user-defined specification of the sensor's data format. This includes identifying the sensor type, manufacturer name, the location where the sensor is installed, and more. Figure 2 illustrates the configuration interface. In the case of CSV-based data, defining the structure and semantics of the file—such as the column layout and the meaning of each field is necessary. For sensors transmitting data via MQTT, users must configure the relevant broker endpoints and specify the appropriate topics for data retrieval. This configuration process is designed to be straightforward and is performed through the graphical interface provided by the BBox interface.

By tightly coupling physical sensor data with semantically structured digital representations, the system supports scalable, maintainable, and standards-aligned sensor data integration. The inclusion of both static and dynamic data ingestion approaches ensures adaptability to diverse sensor technologies and operational constraints across bridge infrastructure networks. The following chapter presents some practical use cases, demonstrating how various types of data have been integrated into the digital twin framework and how this data is systematically ingested and managed within the overall system.

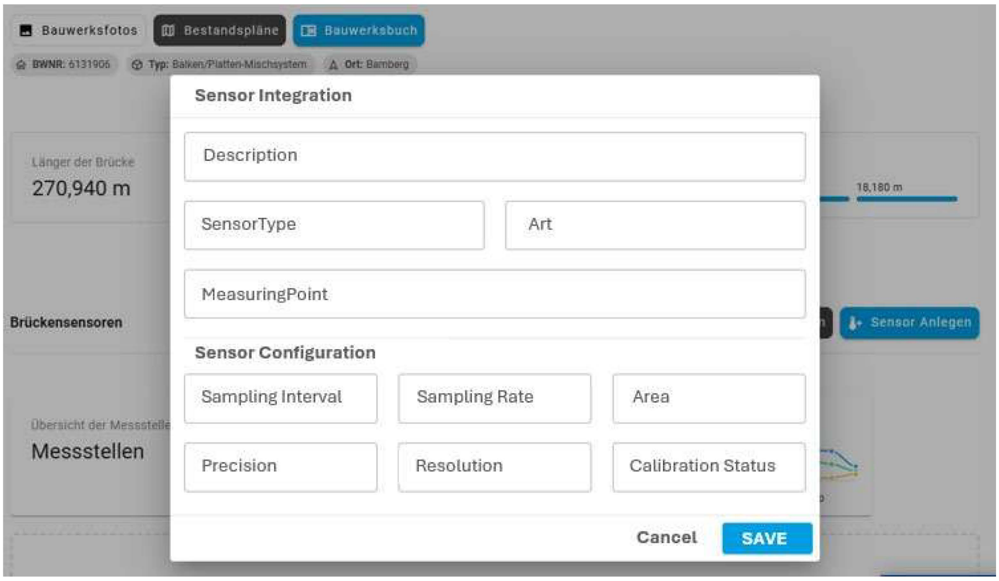

BWNR: 6131906
Typ: Balken/Platten-Mischsystem
Ort: Bamberg
Länger der Brücke 270,940 m

Figure 2: Sensor configuration over the BBox UI

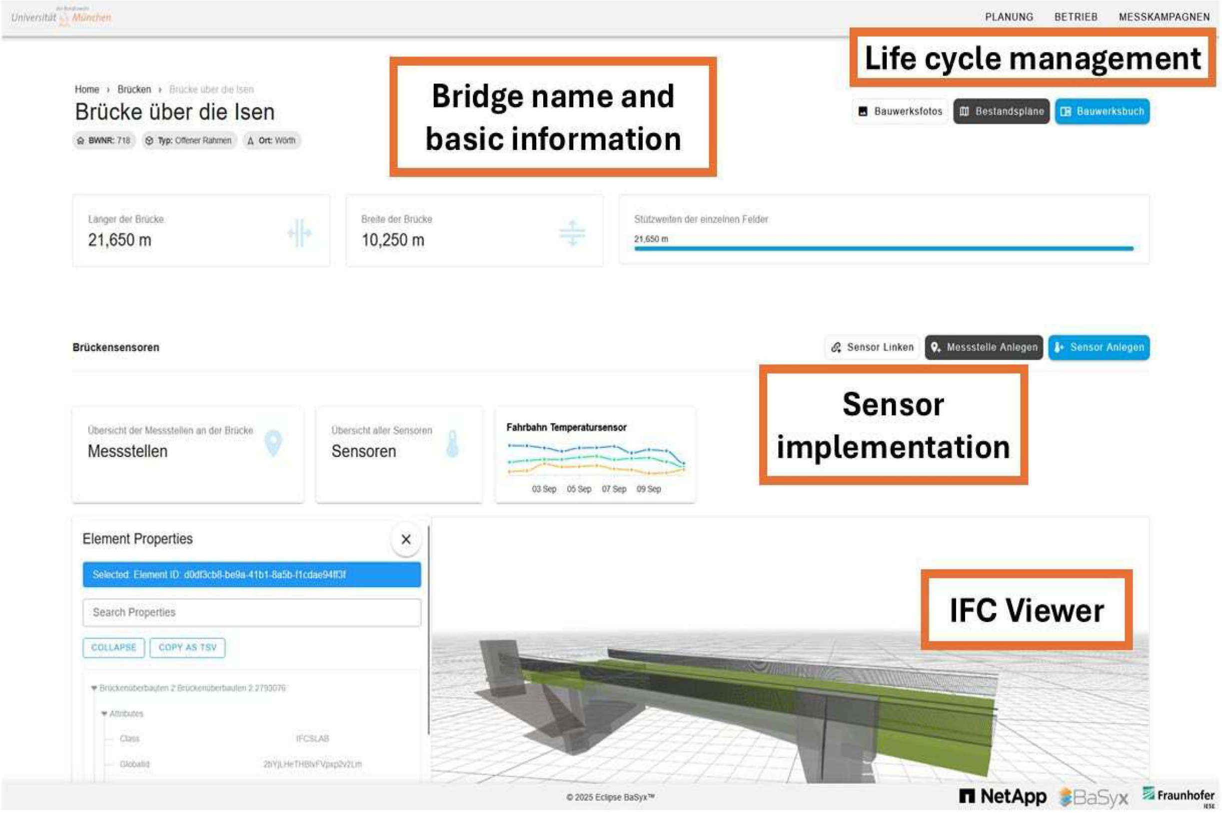
5 Case Study: Bridge Schwindegg

A demonstrator was created for the Isen Bridge in Schwindegg (Germany). The structure was built in 2022 as a single-span frame bridge made of prestressed precast reinforced concrete elements with in-situ concrete additions and has a span of approx. 21 m. It carries the MÜ22 district road over the River Isen in the inner village. In the course of the new construction, the structure was equipped with approx. 140 sensors. Strain, temperature, inclination, earth pressure, acceleration and settlements have been measured almost continuously since December 2022. A technology block was installed on site to ensure power and internet supply [14] [15].

The planning and construction phases used static data that was stored locally. This included 2D planning, certificates for building materials, and protocols. A 3D laser scan was also carried out during the construction phase. To record the data in time for the opening to traffic, an AAS was created manually, the measuring points added, and the sensors connected. The IoT router in the technical block is used to transfer measurement data via MQTT [16]. After completion and the first bridge inspection, the construction log and thus the .CAB file were transferred. This was then used to complete and finalise the AAS. In the operation phase that now prevails, the data is collected, and new conclusions are continuously drawn from evaluations.

An important data-specific task is plausibility checking. Data scientists need information from an engineer on the reliability and functionality of a sensor. The plausibility check was carried out in [17] and noted in the sensor's AAS. A sensor in a bridge can be plausible with regard to traffic, temperature or other environmental influences. If a quantitative statement is to be made about the traffic load, the sensors must be calibrated. The calibration test results were presented for this structure in [17]. Furthermore, the results are used to implement evaluation algorithms for a real-time traffic load model in the AAS [18].

A BIM model was derived from the point cloud of the 3D laser scan. This is also displayed in the AAS configurator and supports visualisation. Not only the bridge level, but also the network level for the infrastructure owner is also mapped. The bridges can be displayed in a map module with the most important information such as name, size, bridge condition, etc. Since BBox was designed to make all types of data accessible for all types of road bridges, further pilot studies have already been launched. For another case study, a highway bridge is monitored by satellites and a local monitoring system, the data is also combined and evaluated in the BBox [19].



Home › Brücken › Brücke über die Isen

Brücke über die Isen

BWNR: 718 Typ: Offener Rahmen Ort: Wörth

Länger der Brücke 21,650 m

Breite der Brücke 10,250 m

Stützweiten der einzelnen Felder 21,650 m

Brückensensoren

Übersicht der Messstellen an der Brücke Messstellen

Übersicht aller Sensoren Sensoren

Fahrbahn Temperatursensor

Element Properties

Selected: Element ID: d0df3cb8-be9a-41b1-8a5b-f1cdae94ff3f

Brückenüberbauten 2 Brückenüberbauten 2 2793076

Attributes

Class IFCSLAB

GlobalId 2bYjLHeTHBlvFVpxp2v2Lm

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Figure 3: User Interface (Dashboard) to configurate and display a brief overview of a bridge

6 Conclusion & Outlook

This paper has presented a digital twin-based framework for the structural monitoring and lifecycle management of bridges, with a strong emphasis on the integration of sensor technologies. By combining static data from planning, construction, and documentation phases with dynamic data streams from embedded and external sensors, the system enables continuous and reliable structural health monitoring. The system is built upon the Asset Administration Shell (AAS) and operationalised via the BBox toolset, the architecture supports interoperability, scalability, and centralised knowledge management across all bridge lifecycle phases.

The implementation showcases how standardised interfaces, modular Submodels, and semantically linked data streams allow for effective monitoring, visualisation, and decision-making. Both static (CSV-based) and dynamic (MQTT-based) data ingestion approaches were demonstrated, supporting a wide range of sensor types. The use case of the Schwindegg Bridge illustrated the real-world applicability of the proposed system, validating its capacity for sensor integration, plausibility checks, and real-time performance monitoring. Additionally, BIM integration enables intuitive 3D visualisation and georeferenced representation of sensor and infrastructure data.

This work contributes to the transition from traditional, reactive inspection methods to a proactive and predictive maintenance strategy. By doing so, it helps address the challenges associated with structural aging, rising infrastructure demands, and limited public resources. The integration of digital twins with sensing technology offers public authorities and infrastructure operators a practical, cost-effective, and a pragmatic toolset to ensure the long-term safety, functionality, and sustainability of bridge assets.

For future developments, ongoing sensor-related research is further expanding the capabilities of the digital twin. Current developments focus on the georeferenced integration of non-punctual data sources. Distributed fiber optic sensors represent a promising class of technologies capable of providing linear or even meshed monitoring coverage. Additionally, acoustic measuring systems have revealed that the location of data acquisition (e.g., microphones) may differ from the spatial scope of the information collected (e.g., signals indicating cracked prestressing steel). These advancements shall enrich the spatial resolution, diagnostic capability, and predictive power of digital twins of bridges, transforming future infrastructure management at both the structure and network levels.

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