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The Concept of the Digital Twin to Revolutionise the Infrastructure Maintenance: the Pilot Project smartBRIDGE Hamburg

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Abstract

The infrastructure of our transport network is ageing. At the same time, the requirements to the infrastructure increase regarding the development of autonomous and connected transport systems. To ensure the function and the availability of the transport network, the importance of frequent and digitally enhanced structural maintenance increases continuously. In order to save time and resources it also becomes necessary to optimise the maintenance process and to implement predictive functionalities. The concept of the digital twin can be the key to achieve this transformation. The aim of this paper is to present the concept of the digital twin and its realisation on the Köhlbrandbrücke in Hamburg, Germany.

Keywords:

Digital Twin, infrastructure

1. Introduction

The backbone of a strong economy is a functioning, highly available, efficient and safe infrastructure. With an ageing transport network and a constantly increasing volume of traffic on both, road and rail, Germany is currently facing a major challenge: the condition of old bridge structures must be precisely assessed, appropriate and correctly timed maintenance work must be performed, existing bridges must be repaired or replaced, and new transport routes must be built to meet current demands.

Regarding the current challenges in our society, this aim of a powerful infrastructure should be harmonised with requirements regarding financial limitations, saving human and material resources and reducing our carbon footprint. This can be reached by extending the service life of existing assets while maintaining the high safety requirements for the infrastructure operation and its robustness, in present and in future. Currently, a large part of the existing infrastructure in Germany is deficient due to a high degree of deterioration, increased traffic demands or outdated structural design. The current maintenance procedures often cannot keep up with these developments. It is therefore necessary to improve the current maintenance processes for our infrastructure by enhancing structural assessment and by enabling the transition from the currently applied reactive maintenance to a mostly digital predictive maintenance.

The digital transformation and its impact on civil engineering offers excellent opportunities to make this transition in infrastructure maintenance become reality. By equipping infrastructure assets with well selected sensors connected to IoT-systems, by aggregating and synthesising measured data and blending those automatic generated data with classic inspection data, it becomes possible to generate a sufficient data history to evaluate the current condition precisely and forecast its evolution. The rapid development of technologies paired with an increasing interest and awareness from asset owners will lead to a significant progress in this field in the next couple of years.

The aim of this paper is to show how the concept of the digital twin can help us in collecting, analysing and aggregating different types of data in order to improve the data basis to evaluate the current condition of a structure and predict its future development. The different key steps on the way to the digital twin of an infrastructure asset will be demonstrated based on a real-life bridge within the pilot project smartBRIDGE Hamburg.

2. Status Quo about the Maintenance of Bridges in Germany

For bridges, the manual, cyclic inspection according to DIN 1076 [1] has been state-of-the-art since 1930. Since the 1990s, the inspection according to the standard RI-EBW-PRÜF [2] is usually documented electronically in the SIB-Bauwerke programme system (a federal databank system for infrastructure), in which the structure and scope of the structural information are defined by the code document ASB-ING [3]. Together with the RPE-ING [4] (guidelines for structural maintenance), Germany has a uniform, conceptually coherent, proven, and accepted system for the maintenance of engineering structures.

The inspection is performed by qualified inspection engineers, who assess the structure based on visible or audible (by tapping with a hammer) damages. Every six years a major bridge inspection is necessary, where also almost inaccessible parts of the structure are inspected by hand using, if necessary, inspection equipment. Three years after a major inspection, a minor inspection shall be carried out as an intensive, extended visual inspection, usually without the aid of inspection equipment.

The aim of this cyclic procedure is to detect and repair damages promptly before more serious consequences occur. This procedure allows for a reactive maintenance of the assets based on existing and distinctively detectable damages. However, if a serious damage occurs, its origin must be investigated first after which refurbishment measures can be planned and carried out. Meanwhile the structure must often be restricted for heavy traffic or the number of lanes needs to be reduced which causes major traffic obstructions over an extended period. Therefore, to improve efficiency, predictability, controllability and coordination of maintenance measures, asset owners benefit from shifting to predictive maintenance. The classical inspection needs to be complemented by a continuous, automatic sensor-based monitoring to generate a sufficient database for a subsequent complex analysis of the condition and condition forecast. Although, this approach was already part of a research project cluster “Intelligente Brücke” (Intelligent Bridge) from the Federal Highway Research Institute of Germany (BASt), which has been launched in 2011 [5], it has yet to be implemented with a real-life large-scale structure.

3. The Concept of the Digital Twin

The concept of the digital twin already has different industrial applications. Because of the development of Building Information Modeling (BIM) and Internet of Things (IoT) in civil engineering and the subsequent emerging data quantities, the concept of digital twin is just beginning to be adopted in civil engineering.

Similar to BIM, the digital twin should not be understood as a technology but as a process. Since “digital twin” is an unspecific phrase, the *Digital Twin Consortium* defined it as follow: “A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity. Digital twin systems transform business by accelerating holistic understanding, optimal decision-making, and effective action. Digital twins use real-time and historical data to represent the past and present and simulate predicted futures. Digital twins are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge, and implemented in IT/OT systems” [6].

Regarding the aforementioned aims concerning maintenance improvement of bridges, the digital twin is a principally suitable and attractive concept to map them. The concept is sufficiently flexible and powerful to combine information coming from classical inspection, from monitoring and from Building Information Modeling and to process them with simulations or models in a continuous efficient digital process chain. The concept can also be extended to include financial data from investment or operation, allowing to prioritise maintenance activities and to improve the long-term maintenance strategy.

A digital twin can be composed of several digital twins and digital twins can be networked. This is a very important feature for infrastructure operators since they do not only want to analyse individual objects but need network analyses and analyses of asset classes to develop overall solutions from a strategic point of view [7]. Furthermore, regarding the mobility of the future (Mobility 4.0), the accurate, current and networked infrastructure information will be a crucial prerequisite to allow autonomous and connected driving.

It should be noted that a Building Information Model is not a digital twin, because a digital twin is a dynamic, networkable model of an asset and has a persistent link to the real world (see Fig. 1). Building Information models are static models that cannot be changed without manual intervention and cannot be networked. BIM is not designed for real-time operational reactions, which limits its usability in the context of maintenance management but is an imperative basis for the digital twin.

Efforts are therefore being made to expand the BIM capability map [7].

To enable the concept of the digital twin become reality, several prerequisites must be met:

- the methods for the implementation of an optimal monitoring concept, for the automatic data analysis, for the aggregation of data to key indicators, for the integration of inspection information, and for the deduction of a life-cycle-management strategy must be developed,
- the existing hardware and software solutions must be adapted, or new solutions must be created,
- the acceptance of the concept by the stakeholders must be generated.

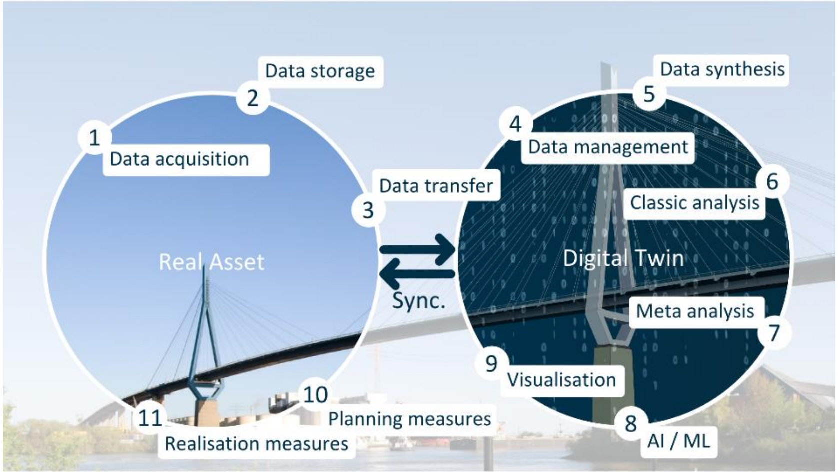

Figure 1 - Interaction between real and digital twin

4. The Pilot Project smartBRIDGE Hamburg

The city of Hamburg and the Hamburg Port Authority (HPA) are working intensively on optimising their maintenance strategy, because the port, as multimodal transport network has to cope with considerable volumes of traffic every day requiring the high availability of its infrastructure. Content of the project *smartBRIDGE Hamburg*, initiated by HPA is the creation of a large-scale demonstrator to implement and experience the concept of the digital twin aiming an innovative improvement of the maintenance for bridges regarding the transferability to other asset classes.

The Köhlbrandbrücke in Hamburg (Fig 2) is one of the port's most important bridges connecting the western part of the harbour and the motorway A7 with the eastern part of the port and the motorway A1. Because of its size and the diversity and complexity of its structure, this bridge is the ideal showcase to test the concept of the digital twin. The Köhlbrandbrücke thereby allows to show the scalability of the concept and to demonstrate the technical possibilities and the benefit with regard to the bridge maintenance.

From the technical point of view, the project is focussed on the monitoring of the structural condition by sensors and the extraction of aggregated key figures called *condition indicators* through a complex evaluation process to allow a quick overview on the bridge condition.

Because of the complexity of the project, a multidisciplinary team consisting of Marx Krontal Partner, customQuake and WTM Engineers was appointed by the sponsor to realise the pilot project. In the project duration of about two years until the ITS World Congress in Hamburg, the expertise in the fields of bridge construction, maintenance and inspection, software architecture, monitoring, data science and usability must merge to enable the expected innovation.

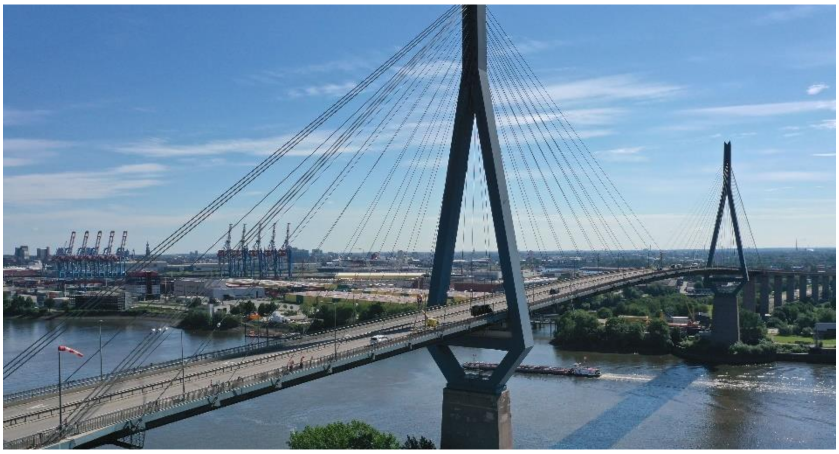

Figure 2 - View on the Köhlbrandbrücke in the harbour of Hamburg (Foto: HPA)

5. The Different Steps on the Way to the Digital Twin of a Bridge

For the realisation of the digital twin of an infrastructure asset, six decisive steps, which will be presented in the following sections, have been identified.

5.1. Structural Health Monitoring (SHM) as a major source of condition information

The monitoring of the structure and of its components with different, well selected and optimally placed sensors is the key to generate the required historic database to objectively and precisely evaluate the actual bridge condition in real time and to forecast its future development. Permanently installed sensors allow for continuous monitoring but are usually limited to a local area. For this reason, sensors are an important addition to the classical and integral inspection but cannot replace it. With regard to bridge maintenance, the following additional use cases and advantage of SHM can be identified:

- the data history allows for a better analysis of the cause of observed damages during inspection and a target-oriented determination of necessary maintenance measures,
- the influence of changes of use or special uses (heavy goods transports, overloading) can be tracked,
- the continuous automated monitoring in dedicated areas (e. g. damaged areas or areas difficult to access) can relieve or replace an inspection,

- the effectiveness of compensatory measures can be monitored or optimised,
- The data can be used to identify additional dysfunctions, damage or critical developments of damage that need to be assessed during an inspection.

However, to reach those advantages, the Structural Health Monitoring needs to be planned and implemented carefully. The questions that need to be answered in the conception phase are:

(1) Which parts of the structure need to be monitored to identify the structural behaviour and to detect changes?
(2) Which sensors and which layout is adapted to measure the structural response?
(3) Which analysis processes are necessary to derive the expected features from measured data?

In the project smartBRIDGE Hamburg, this process was carried out for the different types of structures (cable-stayed bridge and prestressed concrete bridges) and for the different structural elements of the Köhlbrandbrücke (cables, bearing devices, superstructure, etc.). Of the three, the most complex but also most important question is (1) because the quality and effectivity of the SHM depends on this analysis and on the identification of the critical parts. But due to the size of a bridge, its uniqueness, its service life of up to 100 years, and the slow damage rate, a differentiated sensitivity analysis of the structure must be performed. The identification of “weak points” bases on the following analysis of the bridge: (a) model-based analysis, e. g. recalculation, (b) condition-based analysis considering inspection results, (c) design-based analysis, comparing present design to similar designs documented in literature and (d) experience-based analysis considering the know-how of the asset manager.

To prioritise the investigation zones, the results of the sensitivity analysis were analysed following the method of FMECA (Failure Mode and Effects and Criticality Analysis).

5.2. The aggregation of the measurement data, the key to generate consumable information

While traditional bridge inspection of structures in accordance with DIN 1076 [1] evaluates existing damages, design calculations and recalculations of existing constructions are used among others to identify calculative safety deficits and deficits in structural design and thus potential damages. Sensor based monitoring can be used in support for both classical bridge inspection and numerical analysis.

In the first case, damages and damage scenarios can be directly monitored by sensors as a support for classical inspection. Existing damages can be monitored to detect degradation or to predict a point in time for maintenance measures (e. g. for elastomer bearings). Calculative safety deficits that might lead to ductile or brittle failure can be monitored by checking structural stresses against predefined stress limit values or by calculating the probability of failure by means of probabilistic analysis. In the second case, sensor-based data can be used to verify the structural model or to derive custom structural action models, e. g. for traffic, wind, or temperature.

The question is now how monitoring data of a multitude of different sensors can be aggregated to generate consumable information. The task is to aggregate numerical data (stress values, utilisation) into a semantically accessible structural indicator (e. g. good condition / bad condition). A possible failure of a structural component can usually be caused by various damage scenarios (e. g. buckling, fatigue), which are to be identified in a first step. The condition evaluation of a structural component is then a result of various partial evaluations for each damage scenario (e. g. check against buckling, check against fatigue) which are carried out in a second step. Each partial evaluation is then subject to a rating system (e. g. numerical value ranging from 1.0 to 4.0). Thus, in the third step, the partial evaluations are rated such that this rating grade indicates the partial condition of a structural component (PCI: partial condition indicator). This partial rating grade can be directly linked to a semantically accessible rating (e. g. 1.0: best possible condition to 4.0: severely structurally deficient). In the last step, the various partial condition indicators within a structural component are aggregated into a single rating value, a so-called condition indicator (CI).

Fig. 3 shows a schematic overview of the aggregation process from measuring data to a condition indicator. In general, the measured data are time-varying electrical signals, that are generated by physical processes from their environment. To interpret these signals a data cleansing and conversion into physical values is carried out. Furthermore, these physical values need to be transformed into engineering values, so called result data (e. g. strain into stress), which are then needed for condition rating. For a unified rating of measurement-based PCIs and PCIs from the inspection, the rating method for the measuring-based PCI is selected following the rating method of [1] and [2]. Every PCI consists of a rating concerning the three classifications S (structural safety), V (traffic safety) and D (durability). In total the aggregation of the raw data can be summarized by the following three aggregation levels (see also Fig. 3):

1. Data Aggregation and Evaluation: raw data are processed and evaluated against failure or damage scenarios
2. Partial Rating: The results of the failure assessment are rated to obtain a partial condition indicator for each potential failure
3. Condition Aggregation: partial condition indicators are aggregated into a condition indicator.

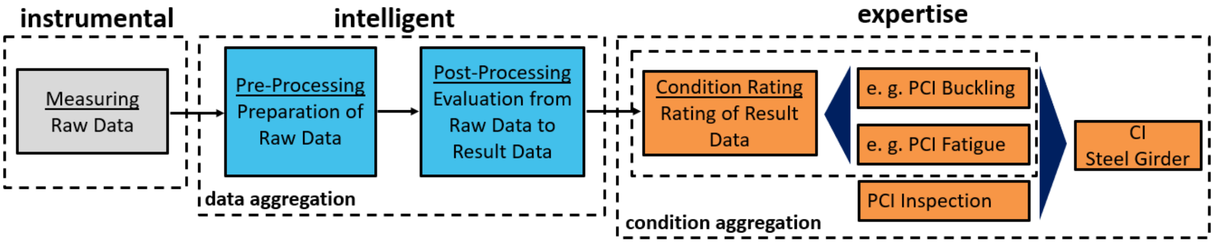

Figure 3 - Aggregation process from measuring data to condition indicator

As an example, one of many measurement-based partial condition indicators is the PCI "plate buckling" of the condition indicator CI "steel girder". Because of a possible destabilizing effect on the whole structure, the steel stresses are monitored to assess the buckling risk. Strain sensors are applied at critical spots, where the buckling check showed the highest utilisation $\eta = E_d/R_d$. From the monitoring data, a custom design value for variable actions $E_{Q,d}$ can be derived by statistical analysis. In combination with the permanent stresses obtained from numerical calculations $E_{g,d}$, the measured design action can be compared to the code design resistance R_d. The degree of the new measurement-based capacity utilisation is then used for the condition rating of the partial condition indicator "PCI buckling". In combination with other PCI, including the PCI from the inspection, the condition of the steel girder is rated. A more detailed explanation to the method of measurement-based buckling verification is given in [8].

Even if a component group is not monitored by sensors, the condition indicator of a component group is at least rated by the PCI of the inspection. This makes the method applicable to every component group of every structure (downward compatibility).

5.3. The fusion of information coming from conventional bridge inspection and from SHM

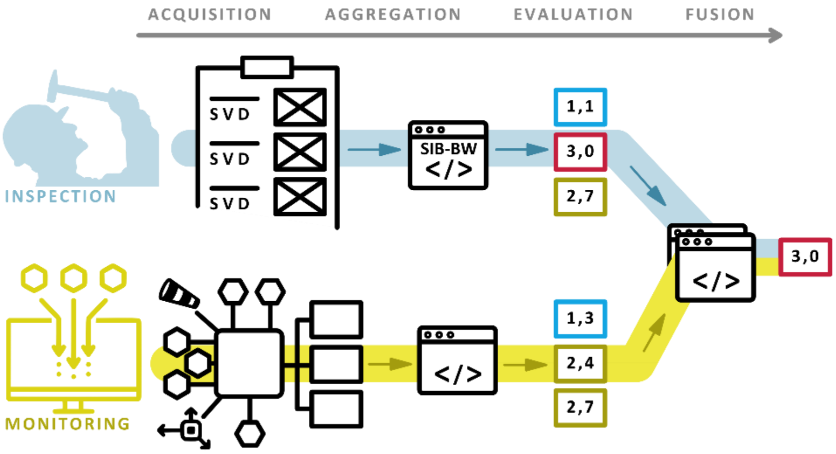

Figure 4 - Data fusion from conventional bridge inspection and from SHM

The most important benefit of this project is the parallel acquisition of cyclic inspection data (3/6 years) and real time monitoring data enabling an objective, complete, and real-time evaluation of the bridge condition. The different data are heterogeneous: manually detected damages, measured and analysed data, loading information etc. The aim of the project is to compute and merge all those data to obtain a general and objective information on the bridge condition.

The evaluation of damages according to the current maintenance strategy is standardised in [2], documented in [9] and implemented in the software SIB-Bauwerke. This evaluation process leads to a relatively simple grading of the damages / structural components / component groups / structure with scores between 1.0 (good condition) and 4.0 (insufficient condition). The overall evaluation is based on the recorded damages.

This rating method, accepted by engineers and asset owners, shall also be applied to the evaluation of measured data (Fig 4). The new determined partial condition indicators (PCI) which are aggregated information derived from measured data are treated as damages with regard to the evaluation. Then these PCIs coming from both inspection (damages) and monitoring are merged to a condition indicator (CI) of a component group. Each component group and structure get a score between 1.0 and 4.0. With this method it is possible to improve the evaluation of the bridge condition by increasing its quality, objectivity and currency without changing the known output format.

5.4. The role of BIM in realising a digital twin

The Building Information Model (BIM) has a key role within the project and its technical solutions: it is the basis for the digital twin. But as mentioned in Sec. 3, a Building Information Model is not a digital twin, because a digital twin is a dynamically linked model of an asset to the real world with highly current condition data. The Building Information Model does not provide this type of data. The strengths of BIM lies in the visualization of geometries and the linking of static information to 3D objects. Therefore, BIM is used for exactly these purposes within the scope of this project according the following use cases (see also Fig. 5):

- Bridge geometry representation for front-end visualisation (as designed but expandable to as build, e. g. by using LIDAR or other acquisition techniques)
- Structural classification that follows the ASB-ING standard [3]:
  It is used for front-end filtering, navigation and highlighting individual parts of the structure
- Damage localisation from the structural inspection over time
- Sensor localisation

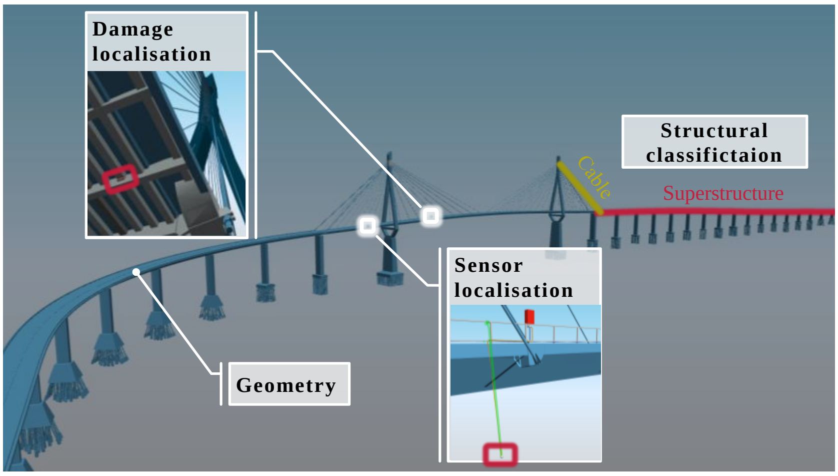

Figure 5 - Use Cases of BIM within the digital twin

In addition to front-end navigation, the BIM provides the ability to put the generated information (condition indicators, structural damages) into a temporal and spatial context.

Today, many new infrastructure construction projects are already being realised using BIM. Thus, a transferability of the concept to other projects / structures is guaranteed and promising for the future.

5.5. The data architecture and data management as technical backbone of the digital twin

To feed the digital twin of the Köhlbrandbrücke with all the necessary content, data from different and heterogeneous data sources (measurement data, infrastructure data, manual inspection reports, IoT devices and many other data sources) must be merged.

All the necessary information for processing and visualisation is loaded from a unified database, in this case an OGC Sensorthings server. Through several specific interfaces to this Sensorthings server, IoT devices can write data directly to the system. Currently, an MQTT or http connection is available for data transfer from IoT devices. The redundant storage of measurement data can thus be omitted for many measurement tasks. Processing is performed by a processing engine that is infrastructurally oriented to an Extract-Transform-Load (ETL) framework. The individual data processing steps are controlled and executed via the processing engine and consist of microservices, each of which contains a small part of encapsulated specialized logic. By chaining these microservices, processing pipelines can be created. If the same calculation or preparation process can be applied to different data, these pipelines can be used several times in parallel with the associated configuration parameters and input data.

All necessary process steps for refinement and aggregation can be mapped via this processing structure. In addition, each data source imported into the system requires a special adapter to bring the heterogeneous data structure into a uniform and smartBRIDGE-compliant structure. After data unification, further processing steps follow to refine and aggregate data. The goal of this processing is to calculate the PCI and CI (see Sec. 5.2). In this process, different data for determining the condition of the structure can be processed and combined with each other. The intermediate and final results produced during the calculation are also stored on the Sensorthings server. To find the desired data in the Human Machine Interface at any time, the configured process chains for processing the data can be executed via event-based, time-based or manual triggers.

Access to each data aggregation level is guaranteed via two different Human Machine Interface, as presented in the following section.

5.6. The Human Machine Interface: key of the success and acceptance of the digital twin

To be consumable, all the information of the digital twin, the interconnection of data as well as their reference to time and space must be transported to the persons dealing with that information and deriving decisions from them. Therefore, a multi-level Human Machine Interface (HMI) has been designed to consider different requirements from different user groups. The main task in the development of the HMI was to make the user interface intuitively consumable despite the enormous complexity of the underlying data while making it possible to dive into the depths of the data at any point.

conditionCONTROL is the overall interface based on the 3D model of the monitored asset showing geolocated key figures and contextually added data allowing a quick capture and complete overview of the current asset state on a high aggregation level to enable rapid decision (Fig 6). The navigation can be explorative by moving within the geometric twin (explore mode) or guided by using the menus (tour mode). Both modes are interlinked allowing a drill-down from asset level to detail component or damage level. The related software architecture is designed to handle multiple service-oriented front ends allowing classical browser-based representation as a combination of WebGL and HMTL5 as well as Augmented Reality (AR) or Virtual Reality (VR) displays.

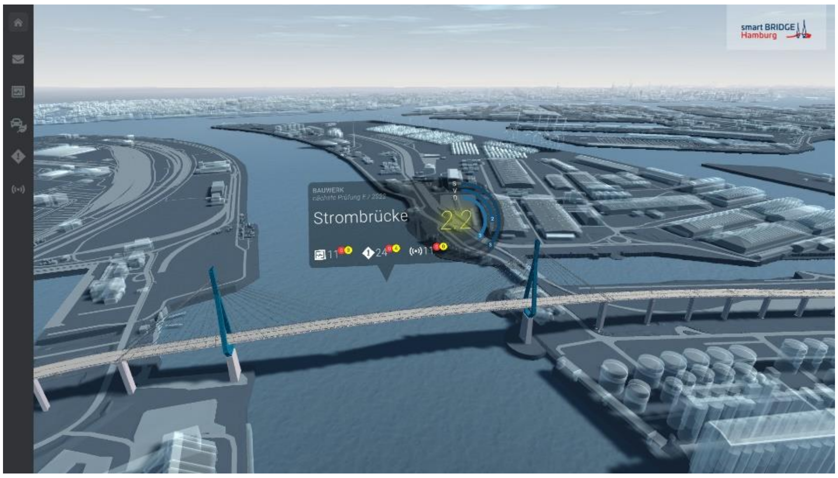

Figure 6 - Overview on the web-interface *conditionCONTROL*

expertCONTROL is the structured visualisation for the detailed data with access to the different aggregation levels from initial measured data to intermediate steps enabling to retrace the development of the computed data.

This way the HMI establishes a single point of access to the digital twin, allowing it to benefit from the advantages of the digital twin concept. By giving a high priority to the usability of the interface, the methodology of data aggregation and fusion is expected to be easily conveyed to different user groups while enhancing the acceptance of the digital twin concept and guaranteeing its success to revolutionise the maintenance of bridges.

6. Conclusion

To optimise the maintenance of bridges, it is necessary to support the work of the inspection engineers for detecting anomalies and damages and analysing the bridge condition by monitoring the structure with sensors. This enables the acquisition of data in real time and the collected data history is the basis for a predictive maintenance. The concept of the digital twin implemented on a bridge structure is an innovative development to optimise maintenance. The concept presented in this paper has the following key features:

- Fusion of data coming from classical inspection and from sensor-based monitoring
- Aggregation of different data sources to condition indicators with uniform evaluation method
- Technological convergence of BIM, SHM and IoT into a powerful concept based on a unified database
- High usability requirements for navigation

The project, as presented in this paper, is a first realisation of the concept demonstrated on a bridge. But the concept is powerful enough to be extended to other infrastructure assets and to support the integration of further innovation, e. g. automatic generation of a 3D model with photogrammetry or LIDAR technology, automatic data-based anomaly detection (self-inspection), application of artificial intelligence (AI) to analyse measurement data and make forecast. This development is necessary to meet the requirement of the transport network of the future.

References

1. DIN Deutsches Institut für Normung (1999). *Ingenieurbauwerke im Zuge von Straßen und Wegen, Überwachung und Prüfung, DIN 1076*, Berlin, Beuth Verlag GmbH.

2. Bundesministerium für Verkehr und digitale Infrastruktur (2017). *Richtlinien für die Erhaltung von Ingenieurbauten (RI-ERH-ING) – Richtlinie zur einheitlichen Erfassung, Bewertung, Aufzeichnung und Auswertung von Ergebnissen der Bauwerksprüfungen nach DIN 1076, RI-EBW-PRÜF.*

3. Bundesministerium für Verkehr, Bau- und Stadtentwicklung, Abteilung Straßenbau (2013). *Anweisung Straßeninformationsbank Segment Bauwerksdaten, ASB-ING.*

4. Bundesministerium für Verkehr und digitale Infrastruktur (2019). *Richtlinie für die Planung von Erhaltungsmaßnahmen an Ingenieurbauwerken, RPE-ING.* (Entwurf).

5. Schnellenbach-Held, M. et. al. (2014). Intelligente Brücke – Machbarkeitsstudie für ein System zur Informationsbereitstellung und ganzheitlichen Bewertung in Echtzeit für Brückenbauwerke, BASt Bericht B105

6. Olcott, S., Mullen, C. (2020). Digital Twin Consortium Defines Digital Twin, *https://blog.digitaltwinconsortium.org/2020/12/digital-twin-consortium-defines-digital-twin.html* (consulted 04.01.2021)

7. Ullerich, C., M. Grabe, M. Wenner, M. Herbrand (2020). smartBRIDGE Hamburg – prototypische Pilotierung eines digitalen Zwillings, *Bautechnik 97*, vol.2, pp.118-125

8. Herbrand, M.; M. Wenner; C. Ullerich; T. Rauert; G. Zehetmaier; S. Marx (2021). Beurteilung der Bauwerkszuverlässigkeit durch Bauwerksmonitoring – Probabilistischer Beulnachweis der Hamburger Köhlbrandbrücke, *Bautechnik 98*, vol.2

9. Haardt, P. (1999). Algorithmen zur Zustandsbewertung von Ingenieurbauwerken, *Berichte der Bundesanstalt für Straßenwesen, Brücken- und Ingenieurbau, Heft B22*