Linking Building Information Modeling and Structural Health Monitoring for Reliable Railway Infrastructure

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Linking Building Information Modeling and Structural Health Monitoring for reliable railway infrastructure

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Digitalization is the most important process of change affecting all areas of our society in this century. In the construction industry and especially in the infrastructure sector, these changes are still ongoing and are characterized by complex interactions and data management. Digital methods, in particular Building Information Modeling (BIM) and structural health monitoring (SHM), are increasingly being used. However, building operation and maintenance processes still follow conventional procedures mostly and are only reluctantly supported by digital databases. Within the wide field of different infrastructures, the railway sector specifically consists of rather aged methods and structures, components and devices, which need intense service. Research at Leibniz University Hannover investigates a basic concept for digitally supported maintenance of railway infrastructures, called shBIM, to enhance the reliability and safety of railway networks. The idea of shBIM is to combine strengths of both, Structural Health Monitoring and Building Information Modeling in order to provide a structured, data driven knowledge-base. Necessary methods and processes need to be defined and harmonized for different perspectives like supervisory authorities, infrastructure operators and monitoring service providers.

Keywords: Building Information Modeling, Structural Health Monitoring, Digital Bridge Maintenance, infrastructure management, reliable railway infrastructure, shBIM.

1. Motivation

German railway infrastructure is not only taking a key role for Germany's economy and public transport, but also for the European transportation market. Providing a resilient infrastructure is a challenging task with multidimensional complexity (Klemt-Albert 2016). Due to Germany's location in the center of Europe, six out of nine corridors of the Trans-European Transport Networks (TEN-T) will run across Germany by the estimated completion in 2030. The overall goal is to strongly support the Trans European Internal Market. (European Commission 2018).

With regard to rail, not only the development of new tracks will play a central role in the future. Indeed, retrofitting and especially the maintenance of tracks and engineering constructions like bridges, tunnels or retaining walls will become more and more important. The German railway network operator DB Netze AG is responsible for track maintenance and improvement including engineering constructions within the infrastructure network in Germany. This covers the responsibilities for more than 33,000 km tracks, 25,000 bridges and 700 tunnels (Deutsche Bahn 2018). The average age of Germany's railway bridges is around 73 years with a rising trend. It is common knowledge that with increasing bridge age the bridge condition will decrease significantly. To rate the bridge conditions, cyclical building inspections must be carried out. This binds material ressources as well as human ressources. Nowadays these inspections follow a defined rhythm in general, not regarding the condition of the actual bridge or tunnel. In Germany maintenance of engineering constructions is regulated in a national standard (DIN 1076). Further, there are specialized regulations with respect to the infrastructure operator (e. g. Deutsche Bahn, RIL 804). The established maintenance approaches do not envisage accompanying bridge monitoring or condition assessment. The maintenance is mostly reactive-oriented and results in expensive repair works. Applying condition-based and predictive approaches can be direct and sustainable counteracts.

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In order to meet the growing demand resource-wise and providing a rail infrastructure that fits the requirements in terms of stability, traffic safety and durability, innovative approaches for a continuous monitoring and intelligent health assessment are needed.

Data linking of Building Information Modeling (BIM) and Structural Health Monitoring (SHM) to an entire data platform with intelligent data organization and data analysis, can be a key for a performant status assessment. This approach will be defined as structural health BIM (shBIM) and includes data from different sources, e.g. construction information, sensor and operation data or weather conditions. The research aims on the development of a suitable data platform to fulfil interests of different stakeholders in the maintenance process and in the development and standardization in data structuring. Therefore, an investigation on existing data systems, roles and interfaces of German Railway is needed as well as the development of additional interfaces to foster interdisciplinary collaboration.

2. Concept of shBIM

2.1 Building Information Modeling

The digital method of Building Information Modeling (BIM) has become increasingly important in recent years. The development of data models and schemes to exchange product and object models started in the late 1980s (Sacks et al. 2018). With the adoption of Industry Foundation Classes (IFC) a neutral AEC-specific product data model was developed beginning in 1994, which represents geometric and semantic information along the whole building life-cycle with levels of detail according to demand. Since 2013 the IFC data scheme has become an international standard (ISO 16739:2013), a European standard in 2016 (EN ISO 16739:2016) and a national Standard in Germany (DIN EN ISO 16739:2017-4).

Driven by expected added values, the German Federal Ministry of Transport and Digital Infrastructure (BMVI) has announced the "Stufenplan Digitales Planen und Bauen" in 2015, which is a step-by-step strategy plan for BIM application in Germany (BMVI 2015). It calls for the mandatory introduction of BIM in all German infrastructure projects by the end of 2020. In addition, the Federal Ministry of the Interior, Building and Community (BMI) has issued an announcement to scrutinize the application of digital methods and BIM in their construction projects.

The BIM method grounds on three to n-dimensional building models. The digital image of an object serves as an information source and the whole model as a data hub for the cooperation for all users. The focus is on digital recording and networking of all relevant data for mapping the physical, functional, cost and process-related characteristics of a structure. The data can span the entire lifecycle and be used across phases. It transparently provides the actual status updates regarding any information linked to it. Object variation induces information updates and vice versa.

If the BIM method is used efficiently and consequently, it is particularly possible to achieve added value due to increased quality and improved action release, coordination and tracking. This is a result of consistent information management as well as a collaborative and transparent way of working. These benefits can be felt throughout all life cycle phases and in the long term feedback information from operations to future constructions. Information needed for operations can be documented, enriched and managed centrally during the previous project phases already.

The digital model (BIM model or BIM platform including several digital building models and corresponding documentation) functions as the one and only information source, the single source of truth (SSoT). Here, a so-called Common Data Environment (CDE) is particularly supportive (Klemt-Albert 2017). The use of the BIM model (or platform) as a SSoT is the logical and correct consequence of the implementation of digital approaches not only in railway transport, yet it requires an interchangeability of the model information, which enables continuous updating of information based on the central data hub between all project participants. The extensive specialization, characterized by various disciplines, represents a challenge for the collaboration of stakeholders, each working with digital tools specific to their use. With its own, open and world-wide developed data formats, the BIM approach integrates building information and integrated task and data management at high transparency with clear responsibilities. BIM standards and formats have not only started to spread within the Architectural, Engineering, Construction (AEC) sector, but also in connected industries. Especially in Germany or Finland the railway sector is mentioned as one of the first cross-industry appliers for BIM.

In general, it can be observed that the initialization of the requirement for the application of the method is assumed by most highly industrialized countries. This implementation is driven in particular by public bodies (e.g. building and transport ministries) and large industrial companies, yet it is mostly applied in design and with smaller respect in realization phases. Comprehensive approaches and thus life cycle phases with overlapping connections and benefits are only found rarely and yet not at all in surface transport modes.

2.2 Structural Health Monitoring

Structural Health Monitoring technology allows a continuous monitoring of state variables of the load-bearing structure of a building. The real-time data gathering can be used for an analysis of operation conditions. The concept is based on a hardware system, which consists of a comprehensive sensor system to record data sets, a data processing system to analyse the data and set the data in relation to different load cases or environmental conditions. Over the past twenty years, SHM has become much more attractive through the development of new measurement techniques and sensor types.

SHM systems can be cable-based or wireless. Wireless systems are easier to install and relatively low-cost, but there is a higher need in modelling to facilitate the documentation and the communication of monitoring-related information (Sternal 2017). Due to the high individualism of bridge constructions, a standard design of a monitoring system is not purposeful. Hovhanessian (2006) describes aspects that need to be considered for a good monitoring system, e.g. risk assessment approaches, maintenance manuals or automated measurements. Lin et al. (2018) define four parts for structural monitoring content for bridge operations:

- Environmental monitoring
- Structural response monitoring
- Durability inspection
- Loading monitoring

Monitoring systems have already been installed on several bridge structures of various bridge types, see Marx et al. (2015), Keil et al. (2015), Flamand et al. (2014), Jang et al. (2010), Li et al. (2016), Lin et al. (2018). The authors point out the relevance of data handling and data transmission. As mentioned in Flamand et al. (2014) it seems possible to close back on information about structural behaviour without requiring an enormous database. Different approaches for data consolidation and evaluation are introduced, but a user orientation for maintenance processes or approaches to integrate the supervising authority are not provided. The data acquisition and analysis of SHM systems are long-time oriented and focus stronger on single-value evaluation than on comprehensive consideration. An interdisciplinary and life-cycle-oriented dynamic data base with an integrated data evaluation system has not been developed yet.

However, there is still a strong need for data acquisition and cloud based analysis of large data. The following concept will introduce an approach for an improved data handling, combining the life-cycle-oriented methodology Building Information Modeling and structural health monitoring by providing user specific data sets in a common data environment.

2.3 shBIM concept

A key to an innovative digitally supported maintenance approach is a sensor-based continuous monitoring, which enhances and supplements the traditional manual inspection techniques and leads to a completely new quality of maintenance.

For this purpose, all information regarding inventory, manual inspection processes and building monitoring need to be linked intelligently. Based on linked data, it can be prepared, tailored and made available for the various process participants to enhance the reliability of the rail infrastructure.

The digital method Building Information Modeling provides an ideal conceptual and methodological basis for this collection, linkage and evaluation of multiple data sources and will be extended by the integration of structural health data (monitoring data, inspection data). This developed approach is called shBIM (Structural Health Monitoring combined with Building Information Modeling).

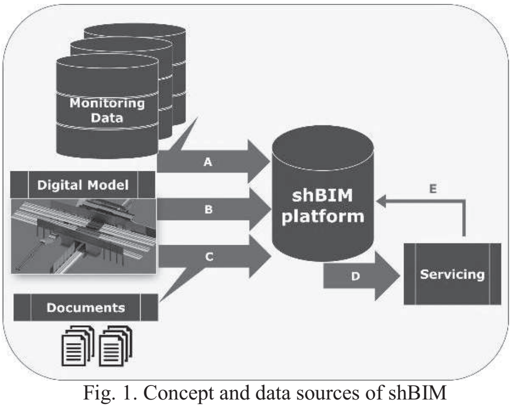

Fig. 1. Concept and data sources of shBIM

The overall concept of shBIM is shown in Fig. 1. The shBIM platform functions as a data hub and is fed by different sources. For generalization, these sources can be defined as three main sources:

First, monitoring data, which includes all data from SHM systems and dynamic data of the operation phase. The extensive data sets from different monitoring elements like acceleration sensors, strain sensors or temperature sensors will be pre-processed and appropriated for integration in the platform using suitable interfaces (A).

Second, the digital model, which includes the information of the infrastructure building and the installed monitoring systems. It contains the object information, geometric information as well as static semantic information and is the central element for the user interface, data visualization and user-oriented data preparation. The digital models require a suitable structure for part models and object classification to merge the information from the other data sources. In general, digital models need to be provided in open exchange formats to handle the manifoldness of the authoring systems (B).

Third, documents and further data bases, which provide a more detailed description of the construction object, like conventional drawings, photo documentations, reports or maintenance instructions. They are linked to individual objects or object groups within the shBIM platform (C).

It can be seen that structuring of the different data sources is strongly dependent on the data sources themselves. Especially for automatization in data analysis and providing a user-friendly platform, different requirements need to be fulfilled to make evaluations by means of artificial intelligence possible. Merging the information of different sources an evaluation on the health of the building can be drawn and can be provided to support the maintenance servicing processes (D). The automated and continuous analysis of the data is used for prediction of probability of occurrence of damage cases.

Finally, the information gathered during maintenance will be recirculated and is used for assessment of the maintenance processes. Further an inference on the quality of the maintenance and the bridge construction can be drawn (E).

The shBIM approach leads to a comprehensive and user-oriented monitoring data integration. All relevant information is fully integrated in the BIM model and linked to the building objects.

3. Composition of a demonstrator

To integrate shBIM in practical use, it is necessary to align the development of the model structure with existing structures of Deutsche Bahn. For health assessment, an infrastructure building is split into sub-parts, which are assessed separately. The object with the worst state determines the overall condition of the bridge. For the development of a suitable structure, a reference bridge has been selected.

The Grubentalbrücke (Fig. 2) is a semi-integral bridge with a span of 215 m and raises 35 m above the valley (Keil 2011). It was built in 2013 and is part of the new high-speed connection between Berlin and Munich, called VDE 8.

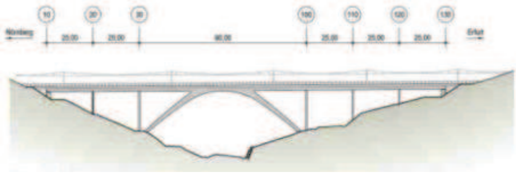

Fig. 2. Schematic view of Grubentalbrücke (Keil 2011)

It has been selected as a demonstrator to examine the underlying process chain, user-platform interaction and data integrity. Furthermore, the demonstrator enables the development of solutions for data merging from different sources and authors. The demonstrator concept provides open exchange formats and functional interfaces with respect to high compatibility, including large numbers of perspectives.

The reference building entails detailed information regarding design and construction. Additionally, an already installed SHM monitoring system delivers continuous data sets. This is complimented by railways operations data and potentially to be enriched with more information (e. g. weather data).

3.1 Development of the Model Structure

Following the maintenance standards at Deutsche Bahn, more than 40 individual components need to be checked in the course of a bridge inspection following the conventional way. Each component belongs to one out of four pre-defined bridge parts: superstructure, bridge abutments, bridge piers or bridge equipment. Each bridge part can consist of different types, e.g. the superstructure can be a slab-beam bridge or a bridge with a hollow section. Depending on the type of the bridge, the number and classification of the components are varying. An extract of the component structure is shown in Figure 3.

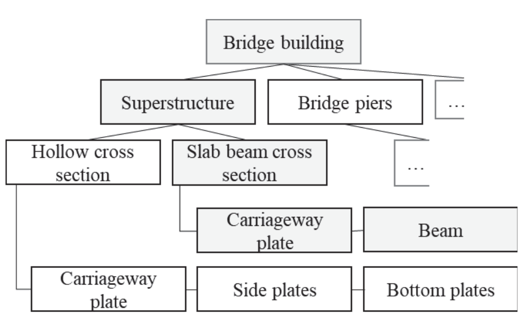

Fig. 3. Bridge Structure and derivation of object structure for digital model

The path of relevant objects for the superstructure is highlighted for the reference project. Overall there are 45 different object classifications in the model.

For each component, different state variables are analysed and documented during the maintenance process, e.g. component moisture or recarbonation. A breakdown of the digital models analogous to these specifications is necessary at minimum. In addition, the semantic information of the digital model must contain the state variables in the context of site inspections. In reference to this specification and the types the digital model can be divided in the following part models:

- Slab beam
- Electrification and signals
- Abutments
- Arc
- Piers
- Bridge cap and cornice
- Protection systems
- Track construction
- Technical equipment
- Terrain and Pavement

Usually, for bridge definitions and object classification systems, the objects of a structural health monitoring system are not taken into account, since it is usually not a part of bridges. However, the SHM system will be modelled during the design process and will include the relevant system components and information. All elements of the structural health monitoring system are linked to a base object in one of the other part models. For example, an acceleration sensor can be linked to a pier or to a component in the track construction. The sensor has a position within the component (e.g. pier head) and also in the global system of the bridge (e.g. bridge axis with coordinates x,y,z). For further consideration, a new part model of the SHM system will be introduced and will be made available as a separate part model for integration in the holistic coordination model. Each part model can be provided in a revised version, if geometric information or semantic information changes during the life-cycle. Due to the traceability of former versions, it is ensured that all information is available for the life-cycle-orientated assessment with high transparency.

The part model of the shBIM demonstrator consists out of nine different sensor types, which are connected to specific building objects. Hereby, basic principles of the BIM method are followed, e.g. object orientation and the integration of object relations to describe the interaction and interdependencies to other building objects. The sensors measure acceleration values, air or structure temperature or strains and shifts. Furthermore, the connection and data system is modelled in the SHM part model.

Another innovation to be considered in this context is the addition of dynamic data collection. Whilst the conventional way of inspection only generates static information at certain times, the use of structural health monitoring data will be generated and evaluated continuously. This requires an additional processor for data gathering and evaluation, to provide slim information in reference to the model objects. For data structuring there is a difference in these two data characteristics. Static information are information sets which change not or only to defined time stamps with a relatively wide temporal distance. The design related data, e.g. materials, cross sections or date of construction or date of the last inspection are typical static information. The single values can be handled as a direct object based information. In addition, SHM makes live data regarding physical parameters, e.g. acceleration or temperature values, available in real-time. These require a special handling for the linkage with the model. Two different approaches are viable:

A) The live data is gathered and the information is pushed permanently into the shBIM platform.
B) The live data is gathered external. shBIM pulls the relevant, consolided data in the platform by a user specific request.

Both approaches are integrated in shBIM, depending on the data source and further data processing. Thus, different interfaces are provided to meet the user and analysis requirements.

3.2 Model Performance

Following the definition of the project structure, subsequently the data performance is to handle and to improve. In general, all digital objects can be modelled in different resolutions. Depending on various use cases, a different geometric detailing is necessary to fulfil the requirements for data visualization, construction processes or design check approaches (e.g. clash detection). Especially external sensors are infinitesimally small in their geometric size compared to the dimensions of the overall building, yet they have no relevant effect to the bridge structure. This means an abstraction in the sense of the geometry seems to be acceptable without a loss of the overall quality for the digital model.

To determine the behaviour of the model capacity in terms of geometric representation and the model performance indicators, sensors are modelled in three different levels of detail: abstract design (A), conceptual design (B) and detailed design (C) (see Fig. 4).

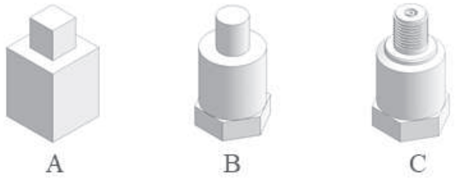

Fig. 4. Acceleration sensor in different detailing

Depending on the scope of monitoring, a structural health monitoring system can consist out of 250 individual sensors or more for a bridge in the size of the selected reference bridge (Grubentalbrücke). In creation of digital models, this can lead to considerable amounts of data that are difficult to handle with respect to amount, formats and further use.

To understand the behaviour of sensor modelling in the sense of data capacity, the sensors have been placed in the digital model of the reference bridge and were exported in IFC 2x3 format.

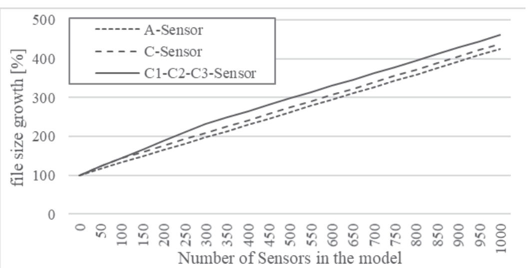

Fig. 5. File size growth in reference to the detailing

In Figure 5, three examined options are shown. First, all sensors were characterized by an A-detailing. The more detailed Sensor in C-detailing has higher demands on storage as well as processor capacity. In the C1-C2-C3 sensor the same sensor-detailing (C-detailing) was used, but as three individual components with different component affiliation interpreted. As it is shown, the requirements in terms of data capacity increase more significantly with the variation of the components itself. Even if the same level of detail and an absolute number of components exists, the overall IFC-file size growths more than by variation of the detailing. There is an almost linear growth in the file size by placing sensor components. The more variations there are in the components, the steeper the increase will be. This means in conclusion, it is more efficient to have an abstracted geometric representation for the sensors, thus capacity is very well controllable and links to a detailed type via the extended information.

4. Implementation

As already mentioned in the previous chapters, a first implementation of the concept has been conducted. Therefore, a Common Data Environment was set up and the part models were integrated in orientation to the introduced model structure. The digital models have been modelled in two native software solutions based on the drawings of the detailed design of the existing reference bridge. The models were exported in IFC2x3 format for validation of the model quality and the exported file structure in a neutral data format. The landscape model was provided as rough data in *.xyz format by a public geoportal. For integration into the platform it needed to be modified for further use. Therefore, a transformation of the *.xyz data format into a readable csv format was executed. Addtionally, a transformation of the data set from a PD83 coordination system into ETRS89 was conducted by using a transformation matrix. Based on the platform Squirrel a further extension, shBIM integration, has been developed. The platform is characterized by a focus on collaboration and process orientation as well as a comprehensive data integration.

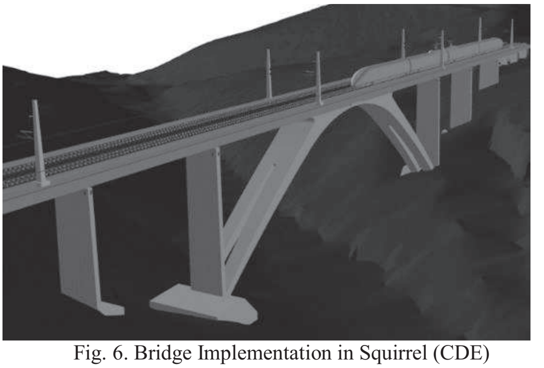

Fig. 6. Bridge Implementation in Squirrel (CDE)

As shown in Figure 6, part models are integrated in the platform and coordinated to a structured comprehensive project. Next to the viewing mode also the semantic information can be loaded and displayed, which is transferred via the IFC format. Research examined the development of suitable parameter sets, which do fit into the existing systems of Deutsche Bahn and allow a bidirectional data exchange. For this implementation exemplary data sets as extractions of the real systems from Deutsche Bahn were analysed and translated into an IFC-compliant structure.

Key is to structure the relevant information about the sensor in an appropriate way to make it available. Furthermore, this is necessary to link the dynamic data as an outcome of the continuous monitoring.

Having the data of the monitoring system linked to the building objects, deviations can be detected in reference to the normal state of operation. Compliance to limit criterions, which are anchored in the digital model, can be monitored. Further, impacts for the structural system can be simulated by qualifying the original design assumptions. The development of the measured quantities can be analysed automatically manually or combined in order to draw conclusions for the structure condition variables over time.

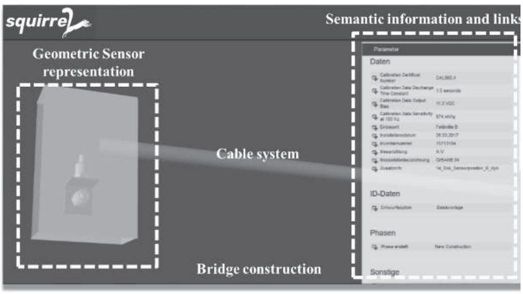

Fig. 7. Detailed view on sensor in shBIM

Figure 7 shows a view of the detailed geometric sensor and the abstraction of a sensor representation. The right half displays an extract of the property set, which includes all standardized sensor information and the part model of the monitoring system. This is where additional links to further databases or evaluations of the sensor data can be displayed for the user.

5. Conclusion and Outlook

The research has shown that it is promising to link the life-cycle-orientated method Building Information Modeling and Structural Health Monitoring using a digital platform. Having all the relevant data in one common platform enables combining and analysing the different data sets using intelligent approaches and artificial intelligence. Due to this procedure, it is possible to gain comprehensive information about the status of the building and to initiate suitable countermeasures at an early stage of damage. Having all data together, different variants for servicing can be efficient set up and evaluated to find the most economic. Once again, the importance of data structuring is increasing for the efficient evaluation of comprehensive data.

In further research, interests of regulatory authorities as well as of design teams will be taken into account to develop user-oriented processes. This require setting up and implementing a role concept with specific user rights and access permissions. This will also consider responsibility for data and the CDE consequently functioning as a SSoT for all operation-relevant data. This allows efficient and foresighted conclusions and data-based as well as data-linked decision making.

Acknowledgements

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