Requirements analysis for a digital road infrastructure twin

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Abstract: Road infrastructure represents a complex system encompassing various interdependent subsystems. Its management and maintenance require an excellent condition assessment of any asset involved. The concept of a Digital Twin has become established for capturing complex systems with their condition changes over time. A digital road infrastructure twin for management and maintenance requires a concept that considers the integration of all relevant subsystems, including their interdependencies. Existing software systems that are nowadays used to maintain road infrastructure in the state of Bavaria, Germany, consider specific aspects of one system. This article discusses the challenges of defining and using a digital twin based on existing road infrastructure management data. Furthermore, a structured requirements analysis is performed. For this purpose, use cases of a digital road infrastructure twin will be identified and described. These examples are taken as a starting point to determine how and which information sources must be incorporated to solve the use case requirements. Their implementation requires a linked evaluation of different distributed data. For this purpose, the proposed system links the required information available in the respective subsystem and evaluates them depending on the use case.

Keywords: Digital Twin, infrastructure, road network, requirements analysis

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1 Introduction

Road infrastructure systems are of particular importance, as they are essential for various social and economic aspects on the one hand and have a major impact on the ecological footprint during construction and operation on the other. To be able to ensure that, it is important to know the current condition of the existing infrastructure and to enable predictive maintenance with the best possible utilization of the existing infrastructure.

The basic idea of a digital twin (DT) is to describe physical reality with the help of a digital replica [1]. In doing so, the concept of Building Information Modelling (BIM) is extended to include recording

current conditions and condition changes. Accordingly, a digital twin not only represents its physical counterpart at a certain point in time but depicts its condition changes in a temporal manner. Therefore, Digital twins are ideally suited to represent the complex road infrastructure system in operation and support its maintenance.
It is viable to note that road infrastructure is already managed. Hence, extensive data sets are already captured and stored in different database systems. Thus, the research objective can be further narrowed down to whether and how this data can be used to create a digital twin. To answer this, this paper briefly defines the general characteristics of a digital road infrastructure twin. After that, existing approaches for managing road infrastructure used in Bavaria are presented. Subsequently, several use cases for a digital twin are proposed, and their possible implementation is discussed as an example using the data available in the Bavarian infrastructure administration. Furthermore, a concept is derived that meets the resulting prerequisites. Finally, research gaps are outlined.

2 Characteristics of a DT for road infrastructure and related research

A significant challenge in the conceptual design of a digital road infrastructure twin is the integration of the various subsystems of structures (e.g., bridges and tunnels), roads, and equipment into the overall road infrastructure system. Different abstraction models have been established for these distinct parts of the built road infrastructure. As an essential part of a road infrastructure system, there are structures that, with their comparatively complex structure, can be well represented with the help of digital building models, e.g., by using the Industry Foundation Classes (IFC). These structural assets are located on roads. The structure of roads is less complex and can be captured well with a few descriptive attributes. At the same time, however, roads have a much larger spatial extent than buildings. Therefore, data models describing geographical data structures, such as GML or GeoJSON, are much better suited than building models to capture the essential characteristics of roads. In addition to structures and roads, road equipment elements such as traffic lights, lanterns, or signs are also part of the road infrastructure system. Equipment elements are similar to structures in the complexity of their construction but do not have their unique character. Instead, the same element type occurs repeatedly along a road. Depending on the subsystem under consideration, this results in different suitable data models. At the same time, however, the subsystems also influence each other so that data from one subsystem may well be relevant for the status description in another subsystem. Broo, Bravo-Haro, and Schooling [2] consider the integration of the various subsystems using the systems of system perspective. For this, the approach of Alam and Saddik [3] is applied, but it focuses strongly on the communication between the systems and neglects the consideration of the infrastructure system as an overall system. Hagedorn, Liu, König, *et al.* [4] present a model-based approach to managing infrastructure systems based on information containers and Semantic Web technology. This is well suited for linking heterogeneous infrastructure data from various subsystems and would allow consideration at the infrastructure system level. However, only use cases that link data within one subsystem were investigated. Considering the need for linking the different subsystems could extend the approach presented.

3 Infrastructure management using the example of Bavaria

3.1 Organisational structures

As depicted in figure 1, the management of the road infrastructure system can be divided into two categories: short-term maintenance on the one hand and long-term and large-scale repair and replacement planning on the other hand. The road maintenance service is responsible for measures that ensure the road network's short-term and local functionality. It assesses the condition of the roads and structures during regular inspections [5]. Negative changes in the condition of roads, e.g., damage caused by traffic accidents, storms, or pollution, are documented. On structures, visible negative changes in condition, e.g., impact damage and undetectable changes in condition, are documented as positive inspection results. In addition to road inspection, winter maintenance is also the responsibility of the road maintenance service.

The medium to long-term maintenance is taken over by other institutions specialized in the respective subsystem. Accordingly, these departments mainly collect data primarily relevant to their objectives. The condition assessment is carried out in more detail and contains a finer degree of damage, capacities, and utilization according to the characteristics of the respective subsystem. In road management, larger road sections are considered over long periods. Characteristics of individual road sections are recorded, such as lane widths, number of lanes, and type and age of surface course. In addition, traffic and accident statistics are determined. Damages are recorded by regular inspection drives. Condition information of the road surface is collected and mapped into a numerical assessment classification (ZEB) for each section of road [6]. The individual infrastructure assets are recorded with their respective construction characteristics for construction management. The condition is examined for each component as part of regular manual structural inspections. Any damage found is documented and assessed individually. The documentation and the assessment result in condition scores for individual assemblies, which are combined into a key value describing the condition of the entire structure.

In summary, different aspects of road infrastructure management are carried out by different authorities. These record the assets with their conditions in their area of responsibility in different ways and with different update cycles depending on the aspect under consideration.

3.2 Systems used in Bavaria, ASB

The different institutions use different, separate systems for infrastructure management as shown in figure 1: The medium to long-term management of the Bavarian road network is carried out in an application called *BAYSIS*, an extended GIS system. *BAYSIS* is based on an SQL database system, as seen from [7], where road network-related data collected by various agencies is stored centrally. According to [8], using a system called *EQUBAR* is planned for the digital documentation of material test results of materials used in road cross sections. *EQUBAR* will also be based on a relational database. The administration of the structures is done with *SIB-Bauwerke*. The structures are recorded in *SIB-Bauwerke*, with their properties and condition descriptions determined during

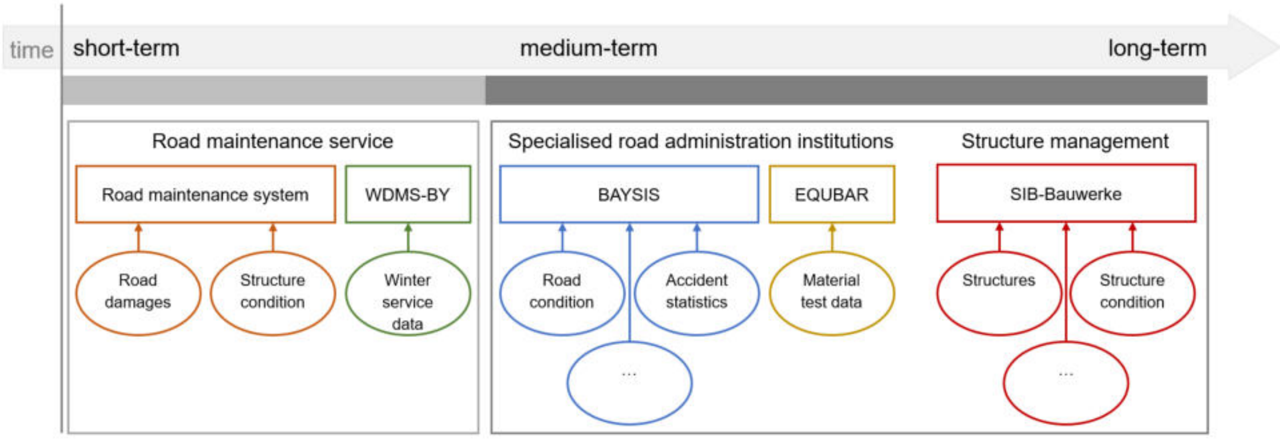

Figure 1: Organization of road infrastructure management in Bavaria, Germany

the structure inspection. The system also uses a relational database system to store the data [9]. The short-term condition recording of roads and structures in the area of responsibility of the road maintenance service is still partially paper-based but also related to the road network. A GIS system is being piloted, enabling the digitalization of damage documentation and management. This system will also be based on an SQL database system. As described in [10], the winter service in Bavaria is organized in the winter service management system *WDMS-BY*. This is also a GIS system in which requirements are estimated on a network-related basis, and the organization and documentation of winter service measures take place.

The individual systems are not connected. However, the underlying database structures consider the standard for infrastructure-related data collection (Anweisung Straßeninformationsbank - ASB). The ASB defines a network as a structuring system. All data sets must be referenced in this ASB network. The ASB network consists of 2 main elements: Nodes as point objects and sections as line objects, each bounded by two nodes. The nodes are uniquely numbered and form the basis for the stationing in a section. All data sets associated with the route network must be assigned to the network through geometry objects. Possible geometry objects are road points or route sections consisting of various route sections. A road point is uniquely located in the defined ASB network by the obligatory specification of a section and a station. Route sections are assigned to the ASB network by specifying start and end points, each referenced like road points. [11]

The description of the data structure of the individual data records then takes place in the supplementary sub-segments of the ASB. A particularly extensive sub-segment is the ASB-ING. It contains the data structure to be implemented in systems to manage infrastructure structures [12]. In addition to the ASB-ING, there are 13 other sub-segments, which define more or less detailed different data structures for different aspects of road infrastructure, e.g., for the road structure or aspects of road traffic.

In summary, infrastructure management-related data in Bavaria is stored in various distributed systems, which, as far as is known, are all based on nonconnected relational database systems. But all infrastructure-related data sets are referenced in the ASB network. Apart from this, however, the underlying data structures of the systems differ depending on the associated subsegment of the ASB.

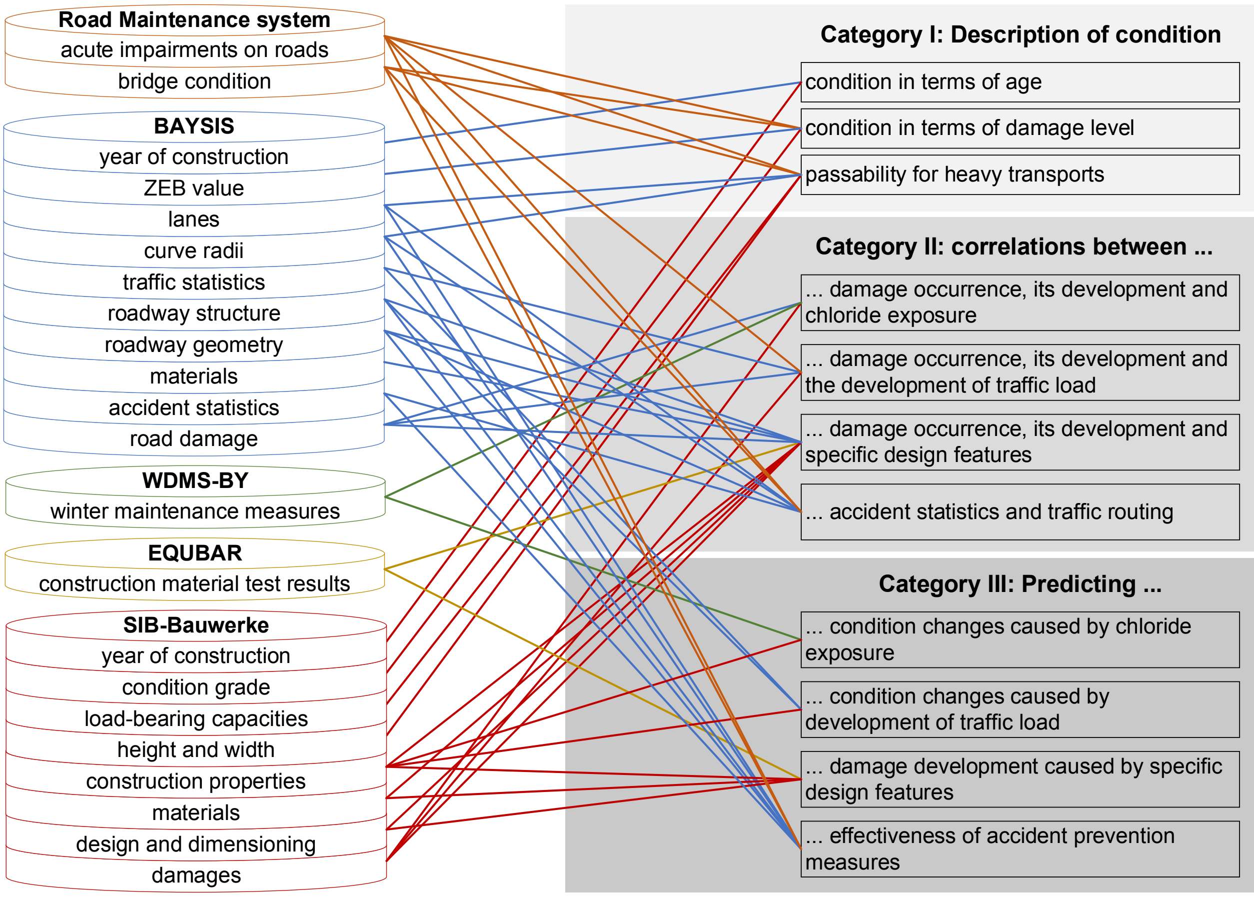

Figure 2: Required data to evaluate exemplary use cases

4 Use case analysis of a digital road infrastructure twin

4.1 Description of use cases

The overarching use case of a digital twin for operating a road infrastructure system results from the definition of obligation to construct and maintain (Baulast). According to [13], the objective is to ensure functionality at the current and future levels. This requires statements on the system's current condition and expected changes. This results in three use case categories:

1. Describing the current condition
2. Investigating correlations through the analysis of data from the past
3. Forecasting changes of condition based on known relations

The description of a road infrastructure system's current condition has to consider the overall system's composition from several subsystems. Therefore, the overall condition must be derived from the conditions of the subsystems in the section under consideration. Possible conditions that could be analyzed would be the age, the damage level or the passability for heavy transports.

A search for correlations in documented condition data is carried out to analyze (sub)system properties and impacts concerning their effects on the functionality of overall or subsystems. The knowledge gained with the help of this use case group on correlations between the collected data provides a basis for the third use case group. In this case, condition changes are predicted by extrapolating known cause-effect relations to comparable issues. The aim is to better estimate the effects of specific boundary conditions on the condition or functionality of the system based on known relations. The known relations can come from the use case category two analysis or recognized engineering knowledge. Possible impacts to be analyzed are, e.g., exposures such as the chloride load or the development of the traffic load. Potential system properties to be investigated are, e.g., materials generally used and the standards on which the design is based. For structures construction properties or in the case of roads, roadways properties of traffic routing or roadway geometry could be interesting. Relevant indicators for describing the effects on the functionality or condition of the road infrastructure system are, for example, damage occurrence, damage development, accident statistics, and traffic flow analyses. The analysis results can then be used, for example, to support decision-making or for predictive maintenance. Some exemplary use cases can be taken from Figure 2.

4.2 Requirements derived from the use cases

Figure 2 shows which data are required to answer some exemplary use cases. Which of the systems used in Bavaria contains the required data is shown on the left. Some examples per use case category are listed on the right-hand side. As shown in figure 2, in assigning the required data to the use cases of the 1st use case category, the required conditions are stored in a distributed manner in different systems. Where the corresponding condition property is found within a subsystem depends on the subsystem's underlying data structure and therefore differs from the different subsystems in question. The use cases of the 2nd and 3rd categories evaluate different impacts on the structures. One way of recording the impact is the use of sensors. But, the existence of sensors on infrastructure objects (e.g., in the context of structure monitoring) is rather rare. However, some impacts can also be derived well from already recorded statistics. For example, traffic statistics indicate the development of traffic loads, and the chloride load in a specific section of the road can be derived from documented winter maintenance measures. As in the 1st category, differently structured data must be evaluated in a linked manner to implement the use cases in the 2nd and 3rd categories. For example, impacts recorded as a property of a section of road must be associated with properties of damage to specific component groups of structures located in the related section of the road.

5 Results and discussion

Data from the different existing systems can be used to answer the use cases described above. Therefore, different structured and distributed available data must be linked and evaluated. Which data is needed from which subsystem and how this data needs to be linked depends strongly on the use case in consideration. The required links can therefore be described as highly flexible and use-case-oriented. At the same time, the subsystems to be integrated have very heterogeneous characteristics that lead to different suitable data models for abstraction. Therefore implementing the link between the subsystems is best done by an overarching system that queries data from the respective subsystems and then links them. In this way, the most suitable representations can be found for each subsystem without limiting oneself to the lowest common denominator of all subsystems when developing a common model that aims to incorporate all existing resources. As an approach for linking these data, referencing all data sets to a network can be used. In the case of the Bavarian infrastructure data, the ASB network could be applied as a potential topological foundation. Because the location of every recorded data set in the ASB network, which is obligatory due to the ASB, relates the heterogeneous data sets to each other. For the implementation of the use cases, this would mean that for each route section to be investigated, the corresponding network area in the ASB network is first determined. With the help of this network area, the data assigned to the area can then be queried in the different systems depending on the requirements of the use case to be answered.

6 Conclusion and Future Work

The challenge in generating a digital twin with already existing data lies in the flexible evaluation of heterogeneous data distributed in predominantly relational database systems, which different specialized institutions usually maintain. One approach to connecting distributed heterogeneous data is using methods of linked data as described in Beetz, Pauwels, McGlinn, *et al.* [14]. Therefore the existing legacy data must be converted into a graph-based representation. For the data contained in SIB Bauwerke, Göbels [15] already presents an approach. However, a counterpart for converting road condition data from the other Bavarian systems and the ASB network as a linking element is still missing. It will be part of future investigations.

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