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# BIM-models of bridges in the operational phase: use cases, phase model and reference architecture

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**Abstract**

For several years, the use of the BIM method has been mandatory for public new construction and replacement projects of the transport infrastructure in the Federal Republic of Germany. As a result, about 20 use cases (UC) for the application of digital models have been defined. Most of them focus on the planning and execution phase. Despite the importance and long duration of the operational phase, there are isolated definitions for use case for operational phase and therefore underrepresented in the overall context. Moreover, none of the published use cases so far consider the specifics of bridge structures. For this reason, a further definition of specific BIM use cases for the operation of bridge structures is needed. In this article, BIM use cases for the use of digital models of bridge structures in the operation and maintenance phase are defined based on a qualitative empirical study. First, the current state of the art is elaborated by means of a literature analysis. Based on this, a expert interviews are conducted and systematically evaluated. The BIM use cases for operation are derived from the results. In addition, requirements and artifacts are defined. This results in a further specification of the use of BIM models in the operational phase of bridge structures and promotes the digitalization of maintenance management.

**Keywords**

Building Information Modelling (BIM), Use Cases, Bridge Structures, Operational Phase, Phase model, Reference architecture

## 1 Introduction

Bridge structures are complex, need to be resilient and have a special significance for the economy and society [1–3]. Especially due to the long operational phase of bridges, the maintenance of bridge structures is of particular importance [4]. In the German transport infrastructure network, there are a total of about 40,000 road bridges [5] and approximately25,000 railroad bridges [6]. The majority of these bridges are currently in a condition that requires rehabilitation [7]. At the same time, a future service life of more than 100 years is targeted for the bridges [7, 8]. In order to achieve this goal and to establish a predictive maintenance management for existing bridges, it is necessary to use new digital methods and technologies [9, 10].

A key element for the digitalization of bridge operation is the method of Building Information Modeling (BIM) and the use of digital building models along the complete life cycle. The use of BIM in the infrastructure sector has been given priority in recent years and is to be implemented across the board in a step-by-step approach by 2025. To this end, specific guiding documents and strategy papers have been published in all transport sectors in recent years, such as the “Stufenplan Digitales Planen und Bauen” [11] or the “Masterplan BIM Bundesfernstraßen” [12]. Within these documents, implementation procedures and different possible uses of digital BIM models are presented in the form of use cases. So far, these use cases mainly address the planning and execution phase. Despite its relevance and duration in the life cycle of a bridge structure, the operational phase is currently still given too little attention in the context of BIM. The research article fills this research gap and will define specific BIM use cases for the operational phase of bridge structures and develop important framework conditions and reference models.

## 2 Related Works

In recent years, the establishment of BIM in the construction sector has intensified [9]. In this course, unified structures and requirements have been established. The association buildingSmart International, for example, has established the BIM Use Case Management. This serves to record the necessary application options and specifications



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for digital models in the infrastructure domain [2, 13, 14]. According to the VDI guideline 2552 sheet 2, the implementation of the BIM method involves a specific process or work step using a digital 3D model to achieve defined goals [15].

In the German construction sector, various BIM use cases with a focus on the complete life cycle for building construction and infrastructure construction have been developed in recent years within research, but also by public administrations and private companies. Deubel et al. present a catalogue for BIM UC in construction [16, 17]. Equally, specific BIM UC for federal buildings were defined in the strategic publication "Masterplan BIM für Bundesbauten" [18].

In contrast, individual BIM UC were also defined for the infrastructure sector. Based on the step-by-step plan for digital design, construction and operation, a total of 20 BIM UCs were published by BIM4Infra at the national level in the first phase, covering the entire operational phase in one scenario [19]. With the publication of the "Masterplan BIM Bundesfernstraßen", a total of 8 UC are defined for the construction of federal infrastructure systems. Thereby, only 3 UC consider the operational phase [12, 20]. However, these are not specific to the requirement of the operational phase, but apply generically to several phases in the life cycle. In contrast, the "Deutsche Einheit Fernstraßenplanungs und -bau GmbH (DEGES)" has defined a total of 19 of its own UC for the use of BIM in the life cycle of structures in road construction. In this context, the operational phase is also only considered in a single use case [21]. In a study by the Federal Highway Research Institute (BASt), the use of BIM in the operational phase of road bridges was also examined in more detail. Seven scenari-os for the use of BIM in operation were also considered and defined in more detail [22]. Due to the many different definitions of BIM UC of the companies and public institutions, a standardization for the life cycle both in building construction and for infra-structure construction (road and rail) was undertaken at the federal level and sample cases were published as a guideline. For road and bridge construction, a total of 17 UC were published. In this context, the operational phase is addressed by six UCs - (i) operation, (ii) maintenance, (iii) traffic management, (iv) area management, (v) environment, and (vi) budgetary management. [23]

Although there are already first approaches for the specification of use cases in the operation of bridge structures, important disciplines of maintenance management, such as structure inspection, diagnostics, monitoring or recalculation are not yet addressed. For this reason, this article attempts to unify and specify the BIM application for the operation of bridge structures in the road and railroad sector. This is done by integrating a practical view with expert knowledge.

## 3 Methodology

After a review of the status quo through an analysis of existing literature, the main part of the article defines the BIM use cases for the application of digital models in the operational phase of bridge structures. For this purpose, an explorative approach is carried out by conducting qualitative, guideline-supported expert interviews. This methodical procedure serves the integration of the profound practical knowledge of the participating experts for the definition of relevant artefacts for science and practice. In the context of this procedure, a total of 31 experts were interviewed in 25 sessions. As a prerequisite for participation in an interview, an expert had to have a total of more than three years of experience in one of the areas - bridge construction, bridge design, bridge operation, structural inspection, structural diagnostics, BIM for bridge structures. The experts were selected to include all relevant parties involved in the operational phase of bridge structures. Thus, persons from bridge operators (asset owners), public institutions, engineering offices were involved in the interviews. The results of the interviews were systematically evaluated by the qualitative content analysis according to Mayring [24] and the relevant BIM use cases were derived. The BIM UC for the application of digital models of bridge structures in operation are generally defined for the areas of road and rail transport. These are presented in detail in the following step. Furthermore, a phase model, a uniform outline structure for digital bridge models and their minimum se-mantic requirements are defined. In addition, a reference architecture is developed. At the end of the article the results are discussed, critically reflected and an outlook on further research results is provided.

## 4 Development of the BIM-Uses

### 4.1 Quantitative Studies

Experts are persons with many years of experience and area-specific knowledge as well as a high level of expertise [25, 26]. A total of 31 experts are interviewed in 25 Sessions, who also serve as knowledge providers for the definition of the use cases. Table 1 shows the assignment of the interviewees to 3 different expert groups. This allows the topic to be viewed holistically from different perspectives.

**Table 1** Expert groups in the interview series

| Expert-group-No. | Name | Amout of persons [pcs.] |
|---|---|---|
| 1 | Bridge structure operator (asset owners) | 12 |
| 2 | Engineering offices for bridge construction (planning, maintenance, structural inspection & diagnosis) | 6 |
| 3 | governmental institution | 13 |

For the structured and systematic acquisition of the existing expert knowledge, a guideline for the interviews is used as a main document [27–29]. The guideline and the integrated question are based on national standards and technical regulations from the domains of road and railroad construction in Germany. This included a total of four main categories - (i) potentials, challenges and requirements, (ii) definition of detailed phases of digital models in operation, (iii) definition of UC in the operational phase and (iv) minimum information requirements - each with specific guiding questions. The interviews were conducted in a semi-structured format and generally had a duration of approximately 80-90 minutes. In the context of the scientific article only the main categories of the definition of the detailed phases, the use cases as well as the minimum information requirements are considered. All other topics will be defined in further research work of the institute.

### 4.2 Definition of a phase model for the the operational phase

The already existing BIM use cases for infrastructure systems with focus on the planning and execution phase are classified into the service phases according to the “Honorarordnung für Architekten und Ingenieure (HOAI) [20, 30].]. To ensure that the UC defined in the scientific article for the operational phase are also classified along the operational phase, a phase model is defined based on the expert knowledge gained (s. Fig. 1). This is used to specify the operational phase for the use of the bridge structure as well as the BIM model developed. Moreover, it addresses the needs of bridge structures in both road and railroad construction. According to the evaluation of the expert interviews, no fixed time periods can be defined for the phases of bridge structures in the operational phase. This results from the individual circumstances of the bridge construction as well as specific load scenarios and reactions. Instead, the operation of a bridge structure is divided into three generic phases - (i) the warranty phase, (ii) the utilization phase, and (iii) utilization with restrictions. The warranty phase is the first subphase and represents the transition between construction and the operation phase. It is the only terminated partial phase and has a length of five years. After this, the bridge structure enters the actual utilization phase, during which the responsibility lies entirely with the asset owner. From that time on, no temporal definition is provided for the two phases still to be completed. Instead, the condition index is used as a significant parameter for classifying the structure in the different phases. This indicates the general condition of the bridge in a quantified value. With increasing age, the condition grade also progresses.

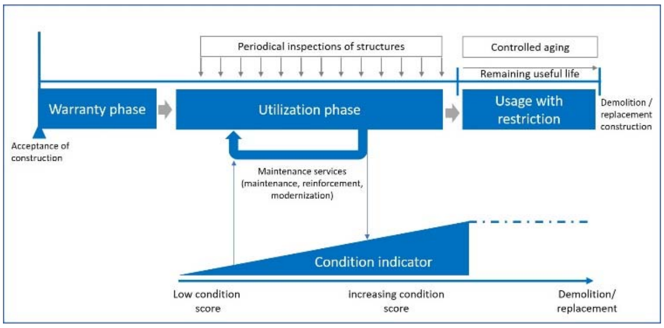


**Figure 1** Phase model for bridges in the operational phase

The duration of the utilization phase has no predefined period. With increasing age and condition scores as well as the resulting decreasing quality of the building structure, the regular implementation of maintenance, repair or modernization measures according to RPE-ING counteract the aging process. As a result, the service period can be further extended, the condition grade decreases and the quality increases again. This is represented in the phase model by the returning arrow. If the bridge is used too intensively with increasing age despite all maintenance, repair or modernization work, the transition to the third and final phase "use under restrictions" is reached. In this phase, a controlled aging of the structure proceeds, as well as a parallel planning of a replacement construction or demolition of the existing structure. The aim of the operational phase is to guarantee the operational phase as long as possible and to carry out continuous improvement works according to the RPE-ING [31]. This prevents the transition to the final phase and guarantees the continuous availability of the bridge structure and the associated traffic infrastructure. The corresponding data for the representation of the currently existing phase of the operation as well as necessary information, such as the condition grades, are displayed in parallel in the BIM model, as well as anchored in the minimum standards of the information level.

### 4.3 Description of the BIM Use Cases

The main focus of the conducted expert interviews is to define new use cases for the application of digital BIM models for the operational phase of bridge structures. For further specification of this phase, the knowledge of 31 experts was acquired within the scope of the guided interview series (25 interview sessions). The shared knowledge was processed, their contents analysed according to Mayring [24] and clustered. A total of 13 use cases could be defined, which are described below (s. Tab. 2).

**Table 2** BIM use cases for the operational phase of bridges

| Use-Case No. | Description |
|---|---|
| 01 | Bridge Inspection |
| 02 | Monitoring |
| 03 | Bridge structure diagnostics |
| 04 | Geotechnical analysis |
| 05 | Structural recalculation |
| 06 | Bridge structure maintenance |
| 07 | Road, rail and equipment maintenance |
| 08 | Deconstruction |
| 09 | Simulation |
| 10 | Sustainability assessment |
| 11 | Immersive technologies |
| 12 | Smart Service |
| 13 | Network Analysis/Cohort Evaluation |

BIM Use Case 01: Bridge Inspection

Cyclic execution of test procedures on the bridge structure to determine damage and damage progression according to valid standards and technical regulations (e.g. DIN 1076, ASB-ING, RIL 804, VDI 6200, etc.). The structural inspection is recorded and evaluated according to the criteria of durability, stability and traffic safety, and condition grades are assigned on this basis. The damage information obtained is integrated into a "damage" sub-model and continued during operation.

BIM Use Case 02: Monitoring

This use case implies the installation of a monitoring system for the bridge structure using sensor technology. In conjunction with this, the structure has a specifically oriented monitoring concept for the collection of different sensor data (static and dynamic) and reference to material and structural properties of the structure. The monitoring system collects structure-related data in a predefined time period for further analysis on the condition of the bridge. The collected data is linked to the model on a further data basis and is also made available in aggregated form in another specialized model "Monitoring" to the user in the operating phase.

BIM Use Case 03: Bridge structure diagnostics

Detection, evaluation as well as the condition prognosis of the actual condition of the structure using structural engineering test methods. Both construction and material properties are considered. Destructive, low-destructive and non-destructive testing methods are used in bridge diagnostics. The results are also made available in aggregated form in another specialized model "Diagnostics" to the user in the operating phase.

BIM Use Case 04: Geotechnical analysis

Preparation of geotechnical expert reports with regard to settlement and deformation behaviour, stability issues, (ground) drainage as well as for contaminated sites in accordance with current guidelines and standards. The investigation basis is formed by subsoil investigations, geotechnical field tests, vibration measurements and geotechnical laboratory tests. The data are embedded in a separate submodel “underground structure”.

BIM Use Case 05: Structural recalculation

Conducting a recalculation to assess the load-bearing capacity and serviceability of existing bridge structures in the event of serious existing deviations from design and construction in accordance with the relevant standards and technical guidelines.

BIM Use Case 06: Bridge structure maintenance

The operational use case "bridge structure maintenance" includes the administrative tasks as well as the planning of necessary measures to maintain and modernize the status quo of the bridge structure condition. This is also used to record the condition development of a bridge in order to develop preventive or reactive maintenance strategies as well as medium- to long-term implementation planning of measures at the execution level

BIM Use Case 07: Road, rail and equipment maintenance

Constructional and operational maintenance of road, rail and peripheral equipment (drainage, protective equipment, telemetry, etc.) of bridge structures in accordance with the current standards, technical regulations and recognized rules of technology of road and rail engineering. Structural maintenance includes "all minor structural measures to safeguard the structure, function and traffic safety. Operational maintenance includes appropriate care and maintenance work [31]."

BIM Use Case 08: Deconstruction

The deconstruction or partial deconstruction of the bridge includes the engineering planning and execution, considering various factors that influence the selection of the demolition method. A distinction is made between deconstruction variants such as blasting, mechanical deconstruction, crane deconstruction, use of lifting technology, floating out or combinations. The deconstruction ends the life cycle of a bridge and is usually connected with a new bridge structure or partial replacement.

BIM Use Case 09: Simulation

The simulation includes - separated from the recalculation - the design and verification of the behaviour of the bridge structure under cross-linking the digital bridge model with further external data sets in different scenarios (e.g. earthquake, load data, wind and weather data, etc.).

BIM Use Case 10: Sustainability assessment

Consideration of the operation of a bridge structure and associated maintenance measures under ecological, economic and social sustainability aspects. By linking the digital BIM bridge model with further sustainability data, multi-criteria analysis can be implemented for the evaluation and optimization of sustainability in the operational phase.

BIM Use Case 11: Immersive technologies

The use case "Immersive Technologies" serves as an extension of the use case 03 "Visualization" of the planning and execution phase of BIM4Infra [19]]. Here, a visualization is used for the visual preparation of a digital bridge model without interaction with the user. In the new use case "Immersive Technologies", there is the possibility of interaction with the digital BIM model by the user. Data can be displayed, edited and created within the immersive environment. This creates a bidirectional data exchange between the physical structure and digital model, integrating humans into the process chain.

BIM Use Case 12: Smart Service

Using intelligent algorithms based on artificial intelligence, demand-specific analyses, forecasting and decision-making bases are derived on the basis of the digital BIM model and other data containers of the considered use cases. The use case refers to the consideration of a single building structure and its existing database.

BIM Use Case 13: Network Analysis/Cohort Evaluation

A bridge cohort is formed by considering an infrastructure corridor. Digital BIM models of the bridge structures are linked together and holistic analyses and predictions are carried out along the corridor by evaluating the linked databases. In this way, analogies of structures in connection with operation (utilization possibilities, damage developments, etc.) can be identified and holistic measures in operation can be derived. In this use case, two or more linked bridge structures and their databases are applied.

The special feature of the use cases is the consideration of the operation of bridges in road and rail infrastructure. By covering both domains, the use cases are considered to be applicable in all domains. The BIM use cases focus either on the structure (bridge structure), on its structural equipment (e.g. road surfacing or rail alignment) or on more advanced scenarios of data usage based on the digital bridge model. All UC have a uniform minimum standard for the geometric and semantic information depth as basic data or minimum attribution.

The existing synergies and dependencies between the use cases should be emphasized. All use cases have a uniform minimum standard for the geometric and semantic information depth as basic data or minimum attribution. (illustrated in the following chapter). In addition, it is envisioned that each use case will once again have specific information requirements. These are not considered in the context of this scientific article. Use cases and their information points can be coupled as needed to obtain a higher depth of information for the operation. Nevertheless, the minimum attribution is always included in an operational model of the bridge. This approach is to ensure the performance of the model. Based on structure of the published use cases of the “Ministry for digital and transport (BMDV)” [20, 23], specific profiles are developed for each use case. These contain the parameters - (i) definition, (ii) occasion, (iii) benefits, (iv) stakeholders and implementation requirements, (v) data, models and formats, and (vi) information requirements. The catalogue with the elaborated fact sheets will be detailed in further publications of the institute.

## 5 Bridge breakdown structure and minimum attribution

In order to provide the digital models of bridge structures with a qualitative basis for their intended use in the operational phase, a minimum standard will be developed in the following for all predefined use cases. This includes the definition of a uniform structure and hierarchy of the digital bridge models as well as the specification of component-specific levels of detail. In addition, a basis for a minimum attribution of the geometric and semantic information for the digital models is created. These specifications are intended to be generally suitable for bridge structures from both road and railroad construction.

The first part of the specification is the definition of a basic model structure for bridge structures, a universally used Bridge Breakdown Structure. For the definition and subdivision, the relevant standards in road and railroad construction will be used and a unification will be determined. A submodel structure is chosen for the digital model in order to cover all relevant components of a bridge structure and to integrate the necessary data points specifically and according to requirements. The level structure (see Tab. 3) distinguishes in the first level between the structure of the building, domains of specific equipment, the environment as well as further, use case related models (e.g. damage model, monitoring model, diagnostic model, etc.). The 2nd level specifies the main models according to their possible submodels. For example, the main model Civil Structure is differentiated according to the components - superstructure, substructure, abutments, caps, transition structure and foundation. Table 1 shows a pattern for the breakdown of the model structure. Here, the models are even sub-divided up to the third level "object instance". In addition to the consideration of the civil engineering structure, the specification of the civil engineering equipment on the second and third level is then differentiated according to the specifics of the two domains road and rail. The model structure serves as a generic guideline and can be adapted according to the specifics of each individual project.

In addition to the development of a uniform submodel structure of the BIM models, the experts were also asked in the series of interviews about the necessary level of detail of the models at the geometric and semantic levels. According to the expert statements analysed, a high level of semantic detailing of the model is of great importance for the use of BIM models of bridges in the operational phase. This means that a lot of further alphanumeric as-built information needs to be integrated or linked.

**Table 3** Unified model structure digital bridge models in the operational phase

| 1st level (main models) | 2nd level (submodels) | 3rd level (object instance) |
|---|---|---|
| Bridge structure | Superstructure | Longitudinal structural elements |
| | | Traverse structural elements |
| | | Internal components (e.g. tendons) |
| | | Caps |
| | | Superstructure (roadway, rail track) |
| | Substructure | Columns (incl. form) |
| | | Wall structures |
| | | Arches |
| | | Etc. |
| | Abutment | - |
| | Brige caps | - |

| | | |
|---|---|---|
| | Foundation | - |
| Structural equipment<br>- road engineering<br>- rail engineering | Structural equipment | Railing<br>Poles<br>Luminaires<br>Road marking<br>Drainage system<br>Groundings<br>Signals & signage<br>Guard rails<br>Noise protection walls<br>Etc. |
| | Subsoil | - |
| Surroundings<br>(terrain model) | Drainage | - |
| | Pipeline | - |
| | Vegetation | - |
| | Surrounding structures | - |
| | Protective equipment | - |
| Use case related models | Damage model | Type of damage<br>Form of damage (punctiform, linear, areal)<br>etc. |
| | Monitoring model | Measuring sensors<br>Signal amplifier<br>Etc. |
| | Diagnostic model | Destructive test<br>Semi-destructive testing<br>Non-destructive testing |
| | Etc. | - |

In contrast, according to the experts, more abstract geometric representations can also be used in the geometric detailing. The definition of the "Level of Information Need (LOIN)" in the DIN EN 17412-1 [32] should be determined individually by the plant operator for the generation and use of digital bridge models in the operational phase. The definition of the individual LOIN of an existing bridge is also influenced by factors such as the size of the bridge, the type of bridge, the considered use cases and the level of detail and the actuality of the as-built documentation.

To ensure that the digital models with the unified bridge-breakdown structure can also be used effectively for operation, a minimum attribution is defined. This will be developed on the basis of technical standards and regulations as well as the findings of the expert interviews. The alphanumeric information serves as a guideline for a potential minimum attribution of the model or the individual submodels. Further attribution at component level for use in operations is recommended. In particular, it is necessary to provide the submodels with case-specific information according to the requirements. The minimum attribute set consists of ten generic attribute categories with a total of 51 semantic attributes including the representation of the data types (e.g. integer, float, boolean, etc.). A listing of the individual attributes would exceed the scope of the article, which is why the attribute categories and the number of attributes per category are listed in Table 4 below.

**Table 4** Generic representation of the minimum attribution of BIM models in operation.

| **Category No.** | **Name** | **Amount of semantic attributes)** |
|---|---|---|
| 01 | Identification information | 5 |
| 02 | Basic information about the building structure | 9 |
| 03 | Quantities | 8 |
| 04 | Condition assessment | 3 |
| 05 | Concrete values | 11 |
| 06 | Reinforcement and prestressing values | 5 |
| 07 | Temperature | 2 |
| 08 | Production and maintenance | 3 |
| 09 | Products used | 3 |
| 10 | Pavement specification (road / rail) | 4 |

## 6 Reference Architecture

The defined BIM use cases in the operational phase, as well as the requirements for the model structure and the minimum attribution, all focus on the level of the BIM model. In addition, the consideration of the integration of

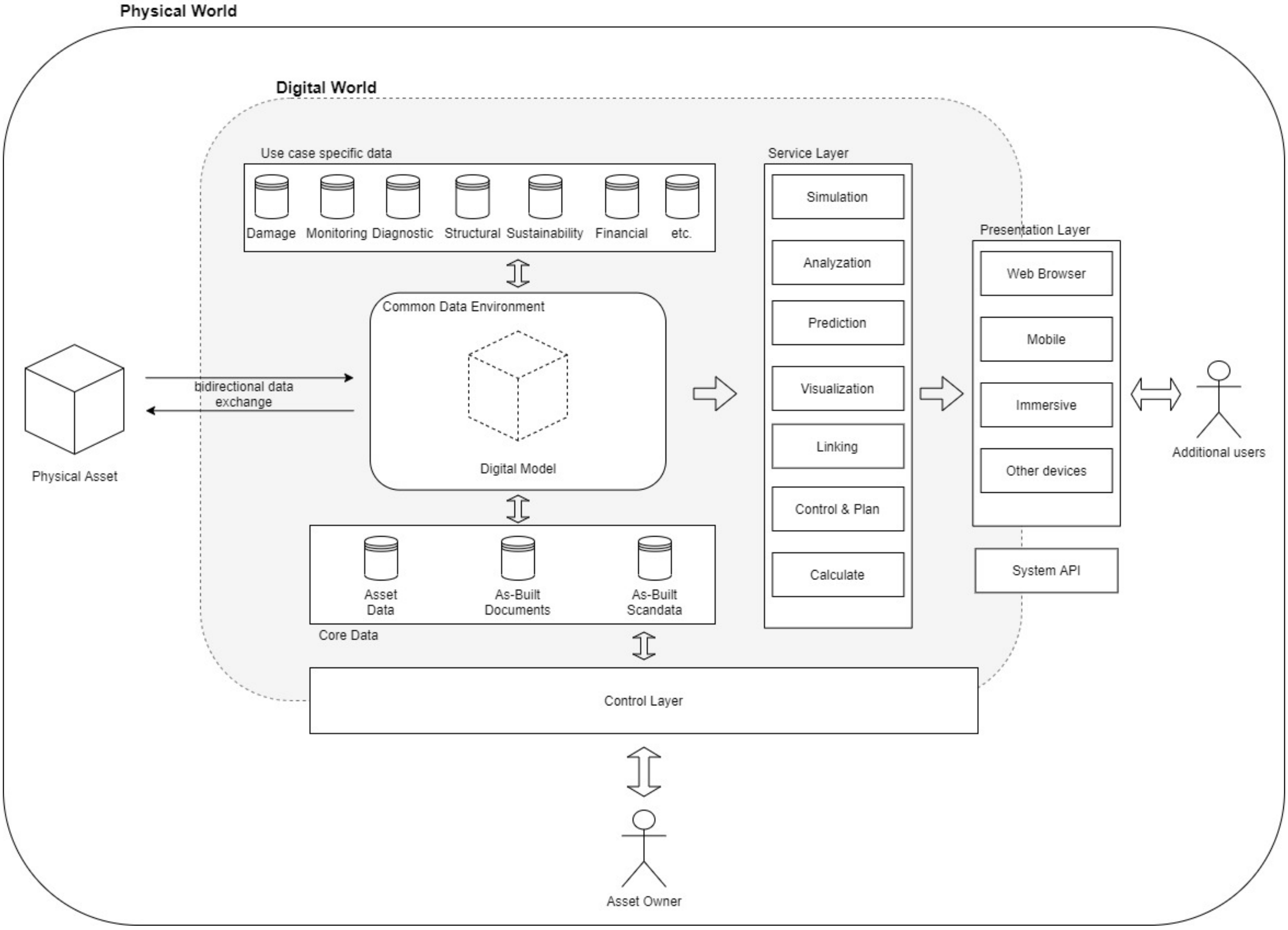


**Figure 2** Reference system architecture for the use of digital bridge model in the operational phase

the model into the existing structures of the system landscape of deployed application systems in operation. For this reason, a generic architecture for integration was developed as an additional artifact. It serves as a framework for optimal integration of the digital model as well as its efficient and interoperable use in the operational phase. The integration and linking of the digital model with the core data of the operation, as well as the possibility of the flexible integration of data sets specified for the respective use case are to be emphasized. The basic components of the reference architecture (see Fig. 2) are explained generically below:

Common Data Environment & Control Layer:

The generated digital model of the existing structure is managed in a Common Data Environment (CDE), acting as a single source of truth for the operational phase ("Operational-CDE"). The digital model has bidirectional data exchange with the real bridge structure, so that changes during the operational phase are also transferred directly to an updated model version. The administrator of the CDE is the asset owner. He can control the application system via a control layer. This allows new project participants to be created and read, access and editing rights to be assigned within the CDE.

Core Data:

The digital as-built model is linked to the basic as-built data sources via the CDE. Thus, relevant asset information is transferred directly into the digital model or linked to it. The inventory data represent the "core data" in the operational phase. It includes the alphanumeric as-built information, additional as-built data (e.g. plans, images, reports, etc.) and the laser scan data of the as-built bridge. The databases of the "Core Data" are managed by the plant owner and kept up to date continuously during the operating phase.

Use case specific data:

Each use case possesses a separate continuative database. The relevant data of the use case is managed in this database and is available for integration or linking with the model as required. Individual databases are set up for different use cases (e.g. damage, monitoring, diagnostics, construction, sustainability, finance, etc.). The databases of the specific "data sets" are managed either by the plant owner or by the parties responsible for the use case and are continuously kept up to date during the operating phase.

Service Layer:

The service layer is linked to the CDE and is used for further processing of the data. The relevant data within the model including the linked further databases are used for the different evaluation activities. Different services can be used for simulations, analyses, predictions, visualizations, linking, controls and planning, recalculations or others. Services are additional modules of the operational CDE. Intelligent algorithms for optimal data processing are integrated into these modules.

Presentation Layer:

The presentation layer is used for the user-centric presentation of the BIM model and the processing results via the service layer for the end user (additional user). In this context, the model and the data can be presented via different end devices. A presentation in a web browser on the PC, a mobile device (tablet or mobile phone), an immersive environment (virtual - and augmented reality) or other devices of choice are supported.

System API:

Another component in the architecture is an existing API for an interoperable linking of the CDE with further application systems (e.g. model authoring software, quality control systems, etc.) used by the project participants in the operational phase. This implies both the in-house application systems of the asset owner, as well as systems of external parties.

## 7 Discussion

This article presents new results to further specify the use of digital BIM models in the operation phase. Based on qualitative expert interviews and the integration of existing literature, standards and technical regulations, new BIM use cases for the operation of bridge structures are defined and a phase model is derived. Furthermore, a standardization of the model structure for digital as-built models in the form of a Bridge Breakdown Structure is evolved and a minimum attribution specified. To ensure that the digital models can be embedded in the existing IT infrastructure of the operational phase in a performant and interoperable manner, a reference architecture is also being developed. By defining the artifacts, a significant contribution is made to the optimized use of digital models in the operational phase of infrastructure structures. This provides all stakeholders with a framework for the future successful generation and implementation of digital models of existing bridge structures. On the one hand, this promotes the quality, transparency and consistency of data management and use, and on the other hand, it strengthens collaboration among the stakeholders. Furthermore, a significant contribution to the creation of a digital and predictive maintenance management is created. As a result, the life cycle of bridge structures can be extended and the critical infrastructure can be permanently kept intact.

In addition to the fundamental positive contributions for the improved generation and use of digital BIM models in the operation of existing bridge structures, there are also limitations in the research approach. A first limitation is the practicability and further verification of the results. Although these are based on existing standards and scientific literature as well as further expert knowledge, there is a need for further testing and verification. The further verification can be done, for example, by conducting an empirical study or an expert workshop. Practicability also can be tested by implementing feasibility studies or integrating them into pilot projects. Based on the results of the testing and verification cycle, an optimization can be conducted. Another limitation is the generic consideration level of the elaborated content. The results of the articles provide new insights on a strategic level. A specification of all contents on the operational level of the use cases is further necessary.

In future research activities, the results should again be subjected to an iterative testing and verification loop. This can be done using both qualitative and quantitative research methods. The involvement of practical experiences is target-oriented in this context and should be considered. Furthermore, the practicability should be tested in case studies, further practical feasibility studies and in pilot projects. Furthermore, the results should be integrated into further frameworks.

## 8 Conclusion

This article presents the definition of BIM use cases, a phase model, further model information and a reference architecture for the generation and use of digital models of existing bridge structures in the operational phase. First, the status quo is presented by means of a literature research. Subsequently, the basis for the definition of the models and architectures is established by holding a guideline-based series of interviews. In this context, 31 experts with experience in bridge operations and BIM are interviewed. Based on the derived results, a total of 13 use cases for BIM models in bridge operations are defined and a further phase model for their classification is generated. Based on this, the definition of a unified bridge breakdown structure for BIM bridge models in operation as well as their minimum attribution is established. In addition, a reference architecture is developed for the smooth integration of the BIM model into the IT infrastructure of the operational phase.

A future use of the results developed in the scientific article will make a significant contribution to the further integration of the BIM method in the national infrastructure. In the future, this will improve cooperation between the stakeholders involved and lay the foundation for predictive and digital maintenance management. In addition, the level of digitization and automation in the area of infrastructure construction will be improved and a significant contribution made to longer usability and increased resilience of critical infrastructure systems.

## 9 Acknowledgement

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## 10 References

[1] K. Klemt-Albert, R. Hartung, and S. Bahlau, “Enhancing Resilience of Traffic Networks with a Focus on Impacts of Neuralgic Points Like Urban Tunnels,” in *Resilience Engineering for Urban Tunnels*, Reston, Virginia, USA, 2018, pp. 55–70.

[2] J.-I. Jäkel, “Ein ganzheitlicher Systemansatz zur(teil-)automatisierten Generierung von digitalen Bestandsmodellen der Verkehrsinfrastruktur,” in *Tagungsband zum 31. BBB-Assistent:innentreffen Innsbruck 2022*, 2022, pp. 148–163.

[3] J.-I. Jäkel, R. Hartung, and K. Klemt-Albert, “A concept of an automated damage management for the maintenance of bridge structures in the context of a life cycle oriented approach,” in *Proceedings of the 2022 European Conference on Computing in Construction*, 2022.

[4] R. Hartung, R. Schönbach, D. Liepe, and K. Klemt-Albert, “Automatized Parametric Modeling to Enhance a data-based Maintenance Process for Infrastructure Buildings,” in *Proceedings of the 37th International Symposium on Automation and Robotics in Construction (ISARC)*, Kitakyushu, Japan, 2020.

[5] J. Bednorz, I. Hindersmann, K. Jaeger, and M. Marszalik, “Methoden zur Generierung von As-Built-Modellen für Bestandsbrücken,” *Bautechnik*, vol. 97, no. 4, pp. 286–294, 2020, doi: 10.1002/bate.202000011.

[6] H. Naraniecki, R. Hartung, S. Marx, and K. Klemt-Albert, “Zustandsprognose von Ingenieurbauwerken auf Basis von digitalen Zwillingen und Bestandsdaten,” *Bautechnik*, vol. 99, no. 3, pp. 173–181, 2022, doi: 10.1002/bate.202100100.

[7] R. Hartung, “Vorgehensweise zur Bewertung von Schäden an Ingenieurbauwerken auf Basis objektorientierter Bauwerksmodelle,” Dissertation, Gottfried Wilhelm Leibniz Universität Hannover, 2021.

[8] R. Hartung, H. Naraniecki, K. Klemt-Albert, and S. Marx, “Konzept zur BIM-basierten Instandhaltung von Ingenieurbauwerken mit Monitoringsystemen,” *Bautechnik*, vol. 97, no. 12, pp. 826–835, 2020, doi: 10.1002/bate.202000095.

[9] S. Stemmler *et al.,* “Multisource-data-fusion for the digitization of critical infrastructural elements,” in *Remote Sensing Technologies and Applications in Urban Environments VII*, Berlin, Germany, Sep. 2022 - Sep. 2022, p. 4. [Online]. Available: https://www.spiedigitallibrary.org/conference-proceedings-of-spie/12269/2634711/Multisource-data-fusion-for-the-digitization-of-critical-infrastructural-elements/10.1117/12.2634711.full

[10] A. Simroth *et al.,* “Digitale Instandhaltung von Eisenbahnbrücken: Schlussbericht,” Bundesministerium für Digitales und Verkehr, Hannover, 2022. [Online]. Available: https://www.tib.eu/de/suchen/id/TIBKAT:1835088058

[11] Bundesministerium für Digitales und Verkehr, “Stufenplan Digitales Planen und Bauen: Einführung moderner, IT-gestützter Prozesse und Technologien bei Planung, Bau und Betrieb von Bauwerken,” Berlin, Dec. 2015. [Online]. Available: https://bmdv.bund.de/SharedDocs/DE/Publikationen/DG/stufenplan-digitales-bauen.pdf?__blob=publicationFile

[12] A. Meister, F. Scholz, and S. Baneman, “Masterplan BIM Bundesfernstraßen: Digitalisierung des Planens, Bauens, Erhaltens und Betreibens im Bundesfernstraßenbau mit der Methode Building Information Modeling (BIM),” Berlin, Sep. 2021. [Online]. Available: https://bmdv.bund.de/SharedDocs/DE/Artikel/StB/masterplan-bim-bundesfernstrassen.html

[13] M. Breitenberger, J. Kreutz, and T. Braml, “Effizientes BIM für die Planung von Infrastrukturmaßnahmen,” *Beton- und Stahlbetonbau*, vol. 113, no. 1, pp. 68–76, 2018, doi: 10.1002/best.201700059.

[14] M. Hochmuth, T. Nguyen, and M. Häußler, “Innovative und moderne Planungsmethoden im Brückenbau,” *Bautechnik*, vol. 97, no. 2, pp. 100–106, 2020, doi: 10.1002/bate.202000001.

[15] Verein deutscher Ingenieure e.V., *VDI 2552 Blatt 2:2022-08: Building Information Modeling - Begriffe*. Berlin: Beuth Verlag, 2022. [Online]. Available: https://www.beuth.de/de/technische-regel/vdi-2552-blatt-2/354476617

[16] M. Deubel, J. Wolber, and S. Hagsheno, “Identifikation, Analyse und Kategorisierung von BIM-Anwendungsfällen/Identification, analysis and categorization of BIM use cases,” *Bauingenieur*, vol. 93, 07-08, pp. 295–303, 2018, doi: 10.37544/0005-6650-2018-07-08-61.

[17] M. Deubel, “Untersuchungen zur Wirtschaftlichkeit von Building Information Modeling (BIM) in der Planungs- und Realisierungsphase von Bauprojekten,” 2021.

[18] R. Schönbach, K. Klemt-Albert, E. Aßmus, and M. Bergmann, “Entwicklung des Masterplan BIM für Bundesbauten/Development of the BIM master plan for Federal Buildings,” *Bauingenieur*, vol. 96, no. 05, pp. 173–181, 2021, doi: 10.37544/0005-6650-2021-05-57.

[19] A. Borrmann *et al.,* “Steckbriefe der wichtigsten BIM-Anwendungsfälle,” Berlin, 2019. Accessed: May 6 2023. [Online]. Available: https://bim4infra.de/wp-content/uploads/2019/07/BIM4INFRA2020_AP4_Teil6.pdf

[20] A. Meister *et al.,* “Masterplan BIM Bundesfernstraßen: Rahmendokument: Steckbriefe der Anwendungsfälle – Version 1.0,” Berlin, 2021. Accessed: May 6 2023. [Online]. Available: https://bmdv.bund.de/SharedDocs/DE/Anlage/StB/bim-rd-anwendungsfaelle.pdf?__blob=publicationFile

[21] Deutsche Einheit Fernstraßenplanungs und -bau GmbH (DEGES), “BIM-Anwendungsfälle,” Deutsche Einheit Fernstraßenplanungs und -bau GmbH (DEGES), 2022. Accessed: May 6 2023. [Online]. Available: https://www.deges.de/building-information-modeling-bim/

[22] M. Seitner, R. Probst, A. Borrmann, and S. Vilgerthofer, “Building Information Modeling (BIM) im Brückenbau,” Bundesanstalt für Straßenwesen, Bremen, 2022. Accessed: May 6 2023. [Online]. Available: https://www.bast.de/DE/Publikationen/Berichte/unterreihe-b/2022-2021/b-182.html

[23] BIM Deutschland, “Standard-Anwendungsfälle: Mustersteckbriefe, Nomenklatur und harmonisierte Liste der Anwendungsfälle,” Bundesministerium für Digitales und Verkehr, 2022. Accessed: May 6 2023. [Online]. Available: https://www.bimdeutschland.de/fileadmin/media/Downloads/Anwendungsfaelle_-_AWF/20220216_BIM_D_AP22_AWF_V2.0.pdf

[24] P. Mayring and T. Fenzl, “Qualitative Inhaltsanalyse,” in *Handbuch Methoden der empirischen Sozialforschung*, N. Baur and J. Blasius, Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2019, pp.

633–648.
[25] A. Bogner, B. Littig, and W. Menz, *Interviews mit Experten: Eine praxisorientierte Einführung*. Wiesbaden: Springer VS, 2014.
[26] H. A. Mieg and M. Näf, *Experteninterviews in den Umwelt- und Planungswissenschaften: Eine Einführung und Anleitung*. Lengerich, Berlin, Bremen, Vierheim: Pabst Science Publ, 2006.
[27] C. Helfferich, “Leitfaden- und Experteninterviews,” in *Handbuch Methoden der empirischen Sozialforschung*, N. Baur and J. Blasius, Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2019, pp. 669–686.
[28] M. Meuser and U. Nagel, “Das Experteninterview — konzeptionelle Grundlagen und me-thodische Anlage,” in *Lehrbuch, Methoden der vergleichenden Politik- und Sozialwissenschaft: Neue Entwicklungen und Anwendungen*, S. Pickel, G. Pickel, H.-J. Lauth, and D. Jahn, Eds., 1st ed., Wiesbaden: VS Verlag für Sozialwissenschaften, 2009, pp. 465–479.
[29] T. Straßer and B. Axmann, “Analyse und Bewertung von KI-Anwendungen in der Logistik,” 2021.
[30] *HOAI 2013-Textausgabe/HOAI 2013-Text Edition*. Wiesbaden: Springer Fachmedien Wiesbaden, 2019.
[31] Bundesministerium für Digitales und Verkehr, “Richtlinien für die strategische Planung von Erhaltungsmaßnahmen an Ingenieurbauwerken (RPE-ING),” 2020. Accessed: May 6 2023. [Online]. Available: https://www.bast.de/DE/Publikationen/Regelwerke/Ingenieurbau/Erhaltung/RPE-ING.pdf?__blob=publicationFile&v=2
[32] *DIN EN 17412-1:2021-06, Bauwerksinformationsmodellierung_- Informationsbedarfstiefe_- Teil_1: Konzepte und Grundsätze; Deutsche Fassung EN_17412-1:2020*, Berlin.