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ORIGINAL ARTICLE

EUROSTRUCT

Sustainability assessment of bridge structures in the operation phase based on a digital twin

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Abstract

There are about 65,000 bridge structures in the infrastructure network of the Federal Republic of Germany. Due to the long operating phase of bridges, they have an influence on sustainability. To evaluate the sustainability of bridges in the operational phase, digital building models can serve as a consistent and structured database to increase the efficiency and transparency.

In this article, an innovative evaluation system for measuring and assessing the sustainability of a bridge structure in the operational phase based on a digital bridge twin is developed. First, the workflow is presented in a process model and the necessary requirements for the digital twin of the bridge structure are defined. In addition, the semi-automatic sustainability assessment system is described and the linkage via an interoperable interface to the digital twin is designed. The approach is tested and validated using a real demonstrator. The result of the paper shows an approach to use digital twins for a novel and semi-automatic sustainability assessment in the operation of bridge structures.

Keywords

Digital Twins, Sustainability Assessment, Bridge Structures, Operation and Maintenance, Building Information Modelling, Operational Phase

1 Introduction

International climate targets require resource conservation and a reduction in environmental impacts such as carbon dioxide (CO_2) emissions [1]. These targets significantly affect the construction sector, which is responsible for generating 35% of the European Union's waste, extracting 50% of raw materials, and producing at least 5,00 - 12,00% of national greenhouse gas emissions [2]. Further, Bridges are a fundamental element of the transportation infrastructure in Germany, providing essential support for the efficient movement of both passengers and freight. As a result, they play a vital role in bolstering the German economy. Though, out of approximately 40,000 bridges currently in existence on federal highways in Germany, a significant number need to be modernized and upgraded in order to meet the growing demands of traffic performance [3]. Considering a service life of 100 years, the deteriorating condition of numerous bridges in Germany underscores the need for innovative and sustainable maintenance strategies [4].

In the digital method of Building Information Modeling (BIM), digital building models are enriched with further geometric and semantic data. This promotes a consistent database over the entire life cycle and encourages collaboration among project participants. These BIM models can also be linked to other dynamic databases. This enables a real-time and automated exchange of data between the real building and the digital model, creating a digital twin. This helps to achieve the most accurate representation of the actual building [5, 6]. In this way, factors such as energy efficiency, environmental impact, cost, user satisfaction, technical and process quality can be taken into account and the performance of the building can be monitored throughout its life cycle. In the operational phase of bridge structures, a digital model also serves as a data basis for the entire life cycle of the infrastructure [7, 8]. To ensure that bridge structures, which are important for the economy and society [8, 9], can be sustainably managed and maintained in their long operating phase over several decades in the future, it is necessary to establish an optimized assessment system [10].

2 Classification in the status quo

The establishment of the digital working method BIM is being steadily integrated into infrastructure construction

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through the “Masterplan BIM Bundesfernstraßen” and subsequently from 2025 through the implementation of the digital twin [4]. In BIM, digital models of the building structure are provided with digital data for this purpose, so that an interdisciplinary collaboration of all parties involved can arise across all life cycle phases [11, 12]. BIM building and specialist models can be connected with each other in a digital twin as well as with heterogeneous further data, such as sensory and manual condition recordings, with the aim of the best possible representation of the real building [5]. In addition, a bidirectional and automated data exchange between the real building and its digital representation is generated [6].

The use of BIM models in operation focuses on their use for maintenance management [13, 14], such as building inspection [15, 16], monitoring [17, 18] and diagnostics [19, 20]. Initial approaches to implementing digital twins in the operation of bridge structures also exist [21–23]. To perform a semi-automatic sustainability assessment, the digital BIM model requires detailed geometric and semantic information. Geometric information refers to the visual representation of the shape and size of the structure, while semantic information describes the function and properties of the structure and its components [24]. This includes data on, for example, materials, manufacturer, or user information.

In general, the evaluation models published by the Federal Highway Research Institute (BASt) can be described as a criteria-based procedure divided into five sustainability aspects. The sustainability domains - ecological quality, economic quality, sociocultural quality, technical quality, and process quality - are considered. A uniform procedure is applied, which evaluates sustainability on the basis of an accumulated degree of fulfilment based on individual criteria [25]. Although approaches to assessing sustainability in infrastructure construction are available, these are neither standardized to a sufficient extent, nor established in application with BIM.

To integrate sustainability assessment into BIM, different strategies can be pursued. Mainly the life cycle assessment (LCA) integration strategies are available in BIM [26], for Digital Twins not yet. In [27] the initial situation regarding LCA integration strategies in Germany is described on the basis of a quantitative survey with 161 interviewed users. The study divides the respondents into 5 user profiles [28]:

1. Application of LCA with BIM
2. Application of LCA and BIM, but without BIM-integrated LCA.
3. Application of LCA without BIM
4. Application of BIM without LCA
5. No application of BIM or LCA

The number of respondents per user profile reveals that user profiles 1 and 2, those with the highest relevance to the present research topic, are covered by the fewest respondents. This is justified by challenges due to incomplete data, lack of standards, and low external demand [28]. Among other things, the unified BIM use cases have so far not considered sustainability considerations [28]. Furthermore, the unified BIM use cases for the application in the infrastructure sector have so far not taken sustainability into account [4, 29]. This gap is closed within the scope of the research paper and a generally applicable sustainability assessment system for bridge structures in the operational phase is developed and tested on a real demonstrator.

3 Methodology

After the presentation of related works, identified by a literature review, the development of the new assessment method is done in three consecutive parts - (i) concept development - criteria definition, (ii) concept - development of the assessment system, and (iii) validation on the real demonstrator. In the first part, the definition of the criteria for sustainability assessment based on digital twins is made. For this purpose, a hybrid approach is chosen. On the one hand, literature on the topic of sustainability assessment in construction and transport infrastructure is analyzed. On the other hand, guideline-based expert interviews will be conducted and evaluated. As a result, a catalogue of criteria for the consideration of sustainability for bridge structures is developed using digital twins. In the second part, the basic system for the semi-automated sustainability assessment is defined. Thereby, the geometric and semantic information requirements are defined considering the previously specified criteria. Furthermore, the general approach is presented in a process model. Subsequently, the newly developed method of sustainability assessment is validated as a proof-of-concept on a real demonstrator. At the end of the article, the results are critically reflected and discussed. In addition, limitations of the research approach and future research needs are presented.

4 Criteria Definition

The sustainability assessment of bridge structures requires the definition of dimensions to be considered as well as their subordinate, specific assessment criteria. Furthermore, the dimensions receive a superordinate weighting and the criteria a specific scoring scale for a quantified evaluation. The basis for the evaluation scheme is formed by existing literature, standards and technical regulations analyzed by literature research. This is supplemented and further optimized by acquired expert knowledge from a total of eight guideline-based interviews.

In total, 22 literature sources form the initial basis for the evaluation scheme. For example, DIN EN 17472 [30], a series of reports by the BASt [25, 31, 32] as well as the dissertation of Zinke [33] form the basis for the perspective of the sustainability assessment of engineering structures. The specifics for bridge structures in the operational phase are provided by DIN EN 1076 [34], the “Masterplan BIM Bundesfernstraßen” [4], the dissertation of Hartung [14] and research reports by the BASt [13, 35]. For further specification in the development process of the evaluation system, expert knowledge is included. A total of 8 experts were interviewed, their statements analyzed with the procedure of Mayring [36] and the aggregated conclusions considered in the definition of the dimensions and criteria. To cover all relevant areas for an optimal evaluation of the sustainability criteria, the experts with a fundamental knowledge in (i) Asset management of infrastructure construction, (ii) Sustainability assessment in infrastructure construction, (iii) Sustainability assessment using digital tools (BIM) and (iv) digital twins and monitoring in infrastructure construction are selected. The special feature of the newly developed evaluation system presented in the scientific article is the integration of the concept of a digital twin. This implies the promotion of a bidirectional data exchange between the physical asset and the digital representation [6, 21]. This is accompanied by the establishment of predictive maintenance as well as continuous condition monitoring and an always up-to-date sustainability assessment in real time.

After the data acquisition from existing literature and qualitative expert interviews, the definition of the actual evaluation system for bridges in the operational phase based on digital twins is carried out. The evaluation system has a total of five dimensions with a specific weighting factor and other subgroups - (a) Environment (22,50 %), (b) Economic (22,50 %), (c) Socio-Cultural (22,50 %), (d) Technical (22,50 %), (e) Processes (10 %). Each of the dimensions is further specified by additional assessment criteria (see Table 1). These weightings of the superordinate dimensions are based on [32].

Table 1 Specification of the assessment dimensions

Dimension No.	Name	Subgroups	Number of criteria	Examples of criteria
01	Environment	Impact on the global environment Resource Consumption Digital Twinning & Structure	26	Global warming potential Traffic disruption Land consumption Noise emissions CO_2-Emissions of the structure
02	Economic	Direct costs	2	Construction-related costs
		Indirect costs	6	Costs for citizens and the environment
03	Socio-Cultural	Health, comfort and user satisfaction	17	Involving the public Impact on the health of the surrounding population
		Functionality	5	Contribution to general road safety
04	Technical	Technical execution quality	18	Accessibility Traffic safety Durability
05	Process	Process quality of maintenance	10	Qualification of the project participants

The evaluation system includes quantitative and qualitative evaluation criteria. For all quantitative criteria, there is always a guideline factor for categorization into a scale. This factor is also subjected to scoring. For the qualitative criteria, the evaluation of an expert is required. At the end of the evaluation approach, all criteria are scored individually and accumulated per subgroups. An overall score is then calculated, considering all the individual dimension weightings. This is subsequently converted into a sustainability index. With this final score, the basic sustainability of the building is made understandable for all parties involved. When defining the criteria, attention is paid to consistency, comprehensibility, and usability. The rating system should be practicable and not too complex, yet all relevant parameters in terms of sustainability and operation of bridge structures are included.

5 Digital Twin based Assessment

The basic procedure of the sustainability rating is described below and is shown as a process model in Figure 1. This is based on existing sustainability assessments by [32] and [33]. It is extended by new criteria in the context of using a digital twin as a data basis. The assessment system considers four different levels of sustainability - (i) indicators, (ii) criteria, (iii) dimensions, and (vi) the final index, shown in Figure 2. Individual indicators were defined by the expert interviews and the literature research, significantly by DIN EN 17472 [30]. These are subordinate to sustainability criteria, which in turn belong to the five

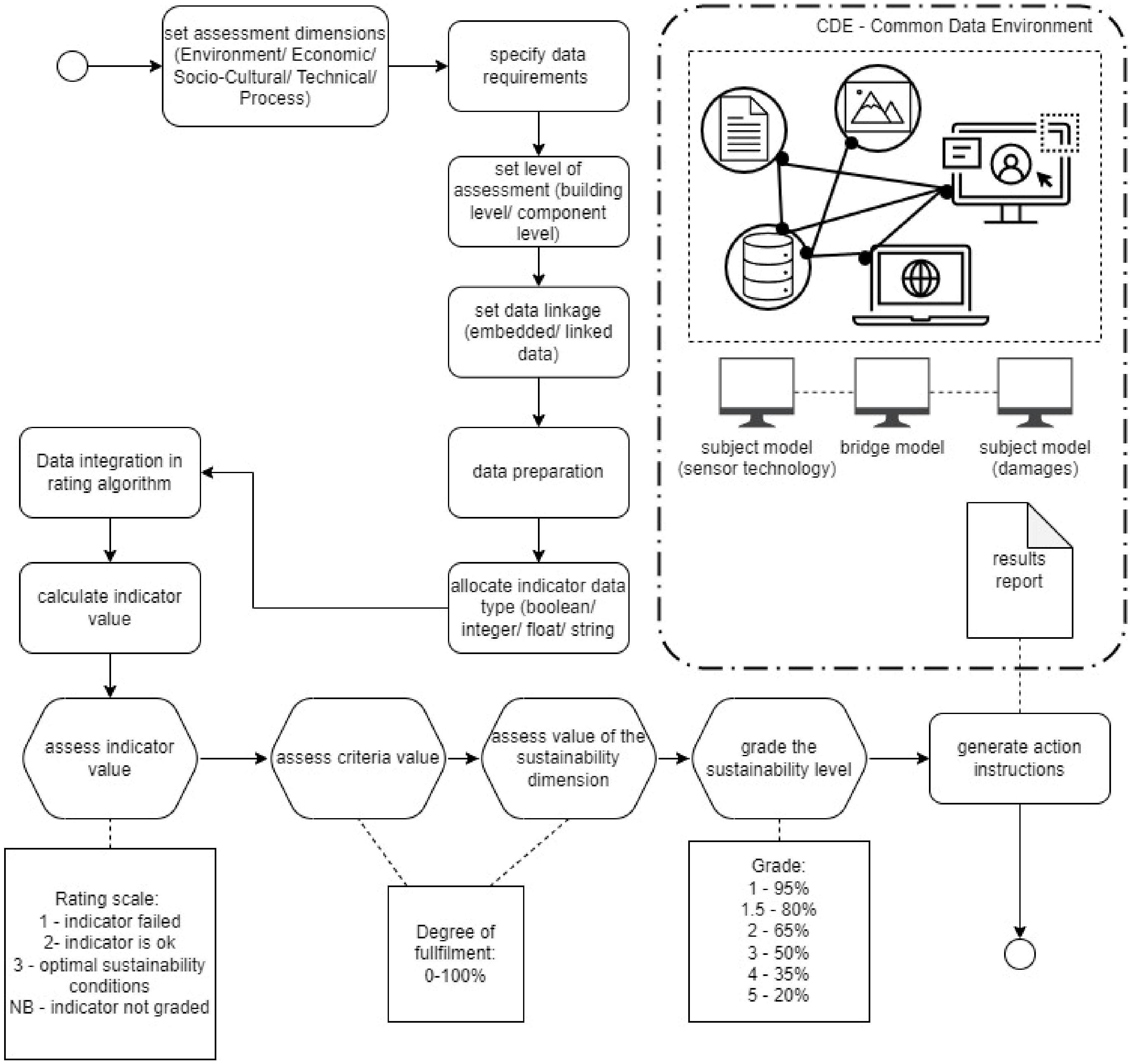

Figure 1 Process model of the sustainability assessment

sustainability dimensions. The process steps of the sustainability assessment based on a digital twin begin with the definition of the object to be examined. This is the sustainability dimension of the bridge structure under consideration. Subsequently, the required data basis for the partially automated assessment must be created, if not already done. In the first step, this includes the definition of the data requirements. A digital bridge model with semantic information as well as further machine-readable sustainability information from documents, databases and, if applicable, from the damage model and the sensor model is indispensable. The amount of data required depends on the depth of the assessment. Therefore, it must be defined whether the assessment is to be carried out at the building level or at the component level. For the qualitative implementation it requires the completeness, accuracy, and machine readability of the data. If the data does not meet the basic quality requirements, it requires processing. For further processing, the data types of the relevant indicator values - integer, float, boolean and string - are differentiated. For the sustainability evaluation, the indicator values are integrated into an evaluation algorithm in the following. Based on the indicator values, the scoring of the individual sustainability parameters is determined. These are dependent on predefined bridge classes with predefined reference values. This is based on a three-point scale, so that an indicator either fails, is okay, or meets optimal requirements. If an indicator cannot be scored, it is marked "not graded" and must be evaluated manually. In the next evaluation step, the indicator points are added up for each sustainability criterion and the degree of fulfilment (in %) is formed based on the maximum number of points. Likewise, the degree of fulfilment per sustainability dimension is calculated by looking at the respective criteria. The overall assessment results from the consideration of all previously selected sustainability dimensions. Between each evaluation step, the importance of individual indicators, criteria or sustainability dimensions can be emphasized over others by multiplying them by a weighting factor. In the final evaluation step, a sustainability rating for the building is generated based on the overall assessment result. The sustainability is then reflected in grade 1-5, with the grade representing the maximum. This then appears together with the results report as data output.

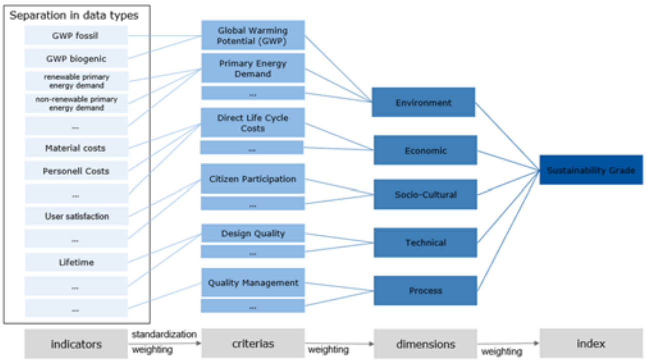

Figure 2 Hierarchical structure of the assessment system (based on [10])

6 Validation

To demonstrate the basic feasibility of the previously designed sustainability assessment system based on digital twins, testing and validation is carried out on a real demonstrator. For this purpose, an extract of the evaluation system including a total of 33 criteria is used. Since the digital twin of bridge structures is not yet widespread, a BIM model of a real structure is used as the data basis at first. In the proof-of-concept, a BIM model of a real bridge structure is used as the data basis, due to the not yet existing digital twin of the structure. The real data is provided by the "Landesbetriebe für Straßen Brücken und Gewässer (LSBG) Hamburg" as part of the validation process. The bridge structure used is the "Haynspark Bridge" in Hamburg (s. Fig. 3). This is also a pilot project as part of the "Stufenplan Digitales Planen, Bauen und Betreiben" [37] and the "Masterplan BIM Bundesfernstraßen" [4].

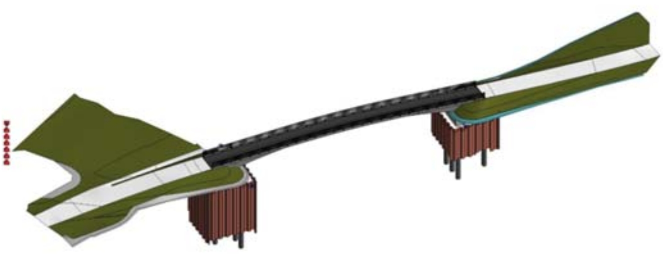

Figure 3 BIM-Model of the Haynspark Bridge (Provided by the LSBG Hamburg)

To represent a realistic scenario, attributes are integrated into the digital building model as well as stored and linked in an external database. The integration of the data sets is done in a model authoring software (Revit parameters). The linked, external data sets were stored in an Excel spreadsheet as part of the initial validation. To automate the data retrieval and the execution of the sustainability assessment, an interface is developed with a visual programming interface and separate Python scripts (see Fig. 4). In this case, the script runs through the process chain - (i) data retrieval, (ii) criteria evaluation, (iii) dimension weighting, and (iv) output of an aggregated sustainability index. It is developed with the programming tool Autodesk Dynamo (s. Fig.4). Subsequently, the script of the sustainability assessment was executed as a minimal example. Both the data points integrated in the model and the linked data points could be retrieved. In the following, the evaluation of the individual criteria as well as the accumulated sums within the evaluation dimension were weighted. Since the minimal example worked with an extract of the criteria, the algorithm could be executed for the subcriteria, but no overall sustainability assessment and indexing for the entire bridge structure could be performed.

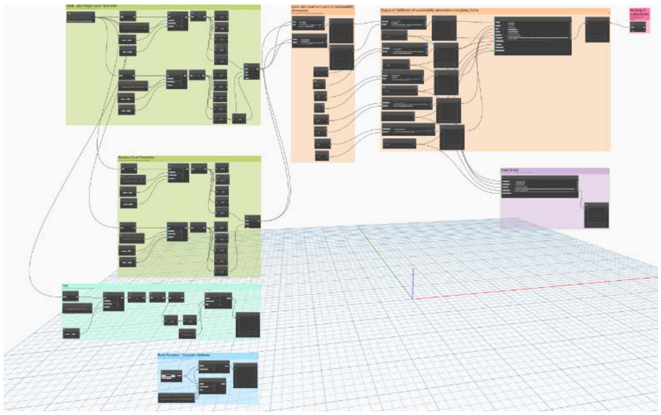

Figure 4 Example - Script of the visual programming interface

For the selected data set of 33 criteria, a compliance rate of 70.31 % was obtained. This results in a sustainability rating of 2 (good). During the execution of the programmed interface, it is to be emphasized that all integrated as well as linked parameters of the data types BOOLEAN and INTEGER could be queried and processed without problems. When executing the separate script for the string parameters, problem areas were identified during query and further processing. String data will first be converted to Boolean or integer data to facilitate automatic evaluation in the demonstrator in Dynamo. Otherwise, the programming effort increases considerably. Moreover, quantitative state indicators cannot be evaluated uniformly, particularly including the evaluation of the number of supports or sensor elements. Additionally, reliable reference values are generally lacking for evaluation, for example for each bridge class.

7 Discussion

The article presents the development and validation of a sustainability assessment of bridge structures in the operational phase based on digital twins. Due to the high importance of bridge structures for society and economy [7] and the long operating phase of several decades [14, 38], the creation as well as evaluation of constant positive sustainability is of significance. For this purpose, the use of a digital twin as a database and current representation of the physical object as a digital image is essential. Using the new approach, sustainability in the operation of bridge structures can be measured qualitatively in the future. On the other hand, the assessment system and the evaluated criteria serve as a basis for the definition of measures for the continuous optimization of sustainability. As a result, the impact of the bridge structure and associated maintenance measures on the surrounding environment and the people affected will be positively influenced. From the technical, procedural and economic perspective, the quality of the running processes is also increased, and the operation is made more economical. Furthermore, the use of the digital twin and more advanced algorithms will increase the level of automation and provide the basis for predictive maintenance management in the operational phase. Thus, the sustainability evaluation and further scenario analyses can be automated. Also, the research contribution helps to further establish digital methods in transport infrastructure and promotes the implementation of the goals set by [37] and [4] of the Federal Ministry of Digital and Transport Germany.

In addition to the presented feasibility and the associated added value, there are limitations to the research approach. A first limitation relates to the definition of the individual sustainability criteria, their generic dimensions, and existing weightings in the complete system. So far, the database is limited to existing literature and a total of eight selected experts. All criteria should therefore be subjected to a further round of verification with either a larger number of qualitative experts or a quantitative empirical study. Furthermore, the entire evaluation concept has so far been limited to the operating phase. While this phase represents the majority of the life cycle due to its duration of several decades, the planning, execution and dismantling phases should also be included in a future further development for a holistic life cycle assessment. Another limitation is the BIM model used in the validation and no complete digital twin. This can lead to inaccuracies in the consideration of dynamic data sets due to longer update periods. This problem will resolve itself in the coming years with the further establishment of digital twins in bridge construction [4]. In the validation of the systematics, only a set of selected criteria are currently considered as a minimum example in the article. For a future fully comprehensive validation, it is also necessary to integrate all evaluation criteria into the algorithm presented. Then the sustainability evaluation can be tested holistically and tested on several digital models.

Building on the previously discussed limitation, the future research activities in the area in question follow directly on from this. In the next step, further qualitative or quantitative research methods will be used to further verify the evaluation system and its possible optimization. At the same time, additional criteria related to the missing phases in the life cycle (planning, execution, deconstruction) can be defined and added to the criteria catalogue for evaluation. To guarantee an interoperable and partially automated process of the evaluation methods, it is also necessary to test them on large digital models or digital twins of bridge structures. Only after many tests with flawless performance the method can be described as suitable for practical use. Furthermore, the whole approach of the evaluation system can be transferred to other areas of infrastructure (e.g. locks, dams, tunnels, etc.). The entire approach can also serve as the basis for a future federal certification system for structures of the infrastructure system.

8 Conclusion

The scientific article presents the development of a sustainability assessment method for bridge structures in the operational phase based on a digital twin. The evaluation system is defined using existing literature and further expert knowledge. Subsequently, an approach for linking with a digital twin as well as an interoperable and partially automated process chain is developed, the procedure is described and presented in a system model. The concept is then tested and validated on a real demonstrator under consideration of selected criteria. Subsequently, the concept approach is discussed, limitations highlighted and future research activities identified.

The novel evaluation method in combination with a digital twin contributes to the improvement of sustainability in the operational phase of transport infrastructure structures. In addition, the level of digitalization and automation in the domain of infrastructure construction as well as in the whole construction industry will be increased. Furthermore, the holistic context of the European Union's Industry 5.0 approach supports the creation of functional human-technology systems [39].

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