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APPROACH FOR SEMANTIC ENRICHMENT AND VALIDATION OF DIGITAL BRIDGE MODELS IN SUSTAINABILITY ASSESSMENT

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Abstract

This paper addresses the challenge of efficiently integrating and validating sustainability data within digital bridge models for accurate sustainability assessments. As bridge infrastructure faces growing demands for maintenance and modernization, alongside the increasing importance of climate protection measures and increased traffic load, it is essential to assess the sustainability of structures in a transparent, comprehensive and solid way. For a holistic sustainability assessment, a great deal of information from various sources is needed, which currently shows gaps and quality deficiencies. Building Information Modeling (BIM) presents significant potential for evaluating the sustainability of bridges across their entire lifecycle.

For this reason, this paper develops a methodological approach focused on the semantic enrichment of BIM models, enabling the automatic integration of relevant sustainability data and ensuring the accuracy and completeness of these models. It takes into account the specific requirements for modeling bridges within the sustainability context and addresses practical challenges in the technical implementation of this approach. Therefore, existing workflows and research approaches are analyzed by a literature review beforehand. The analysis also investigates the integration of external data and systems that can provide supplementary sustainability-specific information, with the design of the link being of equal importance. The proposed method is then applied to a practical case study to validate its efficiency and applicability. Finally, some recommendations for future development work in this field are provided.

The results demonstrate that partial automation of sustainability data integration into digital bridge models ensures data quality while reducing the effort involved in data collection and validation. As a conclusion, for enhanced sustainability evaluations and optimization of bridge lifecycles during the design phase, more effort should be made in data management in the infrastructure sector to fill the data gaps. This requires obligatory regulations, more digital data and technical recommendations.

Keywords: Building Information Modeling, Data Quality, Digital Bridge Models, Semantic Enrichment, Sustainability Assessment.

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1. Introduction

1.1. The Problem in Sustainability Assessment of Bridges

Bridges are not merely structural elements enabling the crossing of physical obstacles; they are critical components of societal infrastructure with significant economic, political, and social implications [1]. The recent and ongoing closure of the Rahmede viaduct exemplifies the severe consequences such failures can have on mobility, businesses, social participation, and the environment [2]. In Germany, around 40,000 bridges are in service, yet approximately 42% of municipal bridges are in substandard condition [3]. Consequently, there is an urgent need for large-scale rehabilitation, with 8,000 highway bridge structures requiring modernization. To address this, the German government has set the ambitious target of completing 400 bridge renovations per year [4]. Simultaneously, the construction sector must align with climate goals, as it is responsible for nearly 37% of global CO_2 emissions [5]. Despite its economic importance, the sector remains one of the least digitalized in Germany [6]. Achieving both sustainability and digital transformation in infrastructure construction requires integrated approaches, such as the use of BIM, which is strategically promoted in national infrastructure plans [7].

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Sustainability Assessment emerges as a key tool for evaluating sustainability across the entire lifespan of a structure, though significant challenges remain in its digital implementation [8].

1.2. Research questions and limitations

The paper’s objective is to answer the following 3 research questions:

1. What are the requirements for the enrichment and attribute checking of BIM models in the course of the sustainability of bridge structures?
2. What can a methodical procedure for semantic enrichment and attribute checking of a digital BIM bridge model look like based on these requirements?
3. What obstacles exist in the software implementation of this methodical approach?

The primary aim is to demonstrate a suitable workflow for creating the database for the sustainability assessment, by checking the information enrichment and developing an attribute validation method, rather than the specific calculation of sustainability indicators. The suitability and the numerous evaluation options of the selected indicators are not considered. A pre-existing digital bridge model is used, assuming that all information is fixed, excluding the study of time-dependent changes in information quality or quantity. The research is based on selected software and a bridge model in the IFC data format, without considering other formats or systems. Additionally, no differentiation is made between different user groups; the method is assumed to be used generally.

2. Status Quo

2.1. Sustainability Assessment of infrastructure construction

The German Federal Ministry for Economic Cooperation and Development (BMZ) defines sustainable development as a process that meets the needs of the present without compromising the ability of future generations to meet their own needs [9]. This understanding is further developed in the widely accepted three-pillar model of sustainability, which includes the ecological, economic, and social dimensions [10].

In the context of civil engineering, e.g., the European standard DIN EN 17472 provides a calculation framework for sustainability assessments, outlining general requirements, a list of indicators, and procedures for conducting life cycle assessments (LCA) of infrastructure projects [11].

In practice, sustainability assessments often focus only on the production phase of construction (A1-A3). A literature review by Obrecht et al. showed that 72% of studies in the construction sector concentrate on life cycle phases A1–A3 [12]. Effective use of sustainability assessments requires structured data exchange and clear definitions of interfaces, data sets, and detail levels throughout a bridge's lifecycle. According to Röder and Finkbeiner, ecological impact indicators are the most frequently used in construction [13]. This is why LCA is predominantly addressed in the literature, whereas fields like social sustainability assessments are often characterized by a limited (digital) data availability and technical implementation.

In Germany, the Federal Highway Research Institute (BASt) has developed assessment frameworks for infrastructure. The report [14] enables certification of both new construction and rehabilitation. The system is based on the three-pillar model, expanded by technical and process quality dimensions. Technical and process quality include aspects such as maintainability and planning quality. It has a weighting system structured into five main qualities, further divided into criteria groups and specific indicators. These are assessed through calculations, such as for primary energy demand, or via checklists, such as for comfort. The resulting scores are aggregated into an overall rating. Over time, the system has been revised. Some indicators were removed due to limited practical applicability or an unfavorable balance between effort and benefit [14, 15]. The technical implementation of a holistic sustainability assessment of bridges, based on the three-pillar model or the BASt assessment framework is not sufficiently investigated so far.

2.2. Digital methods

Digital models, including bridge models, are typically created as 3D representations in authoring software – commonly referred to as native BIM software – and are enriched with additional project-specific information. For the execution of LCA processes, specialized software tools such as standalone LCA platforms or LCA plugins are used. An LCA software is defined as a tool that facilitates the performance of environmental impact assessments by leveraging various data sources, typically through embedded databases. These tools compile the necessary data from both external sources and the information extracted from the digital building model [16].

Plugins, in contrast, are software extensions that enhance existing platforms such as BIM authoring tools, enabling direct processing and visualization of LCA data within the native project environment. These plugins also rely on external databases to retrieve relevant sustainability-related information [16].

Additional technical approaches for implementing LCA include the use of generic LCA tools such as GaBi or SimaPro, as well as spreadsheet-based applications like Ökobilanz Bau or eTool. However, generic LCA tools often only allow the representation of basic interdependencies, limiting their use in more complex modeling scenarios [17].

To address integration challenges, Wastiels and Decuypere proposed five strategic approaches for combining LCA and BIM, which have been referenced and expanded upon in subsequent research. These five practical workflows are summarized in Figure 1.

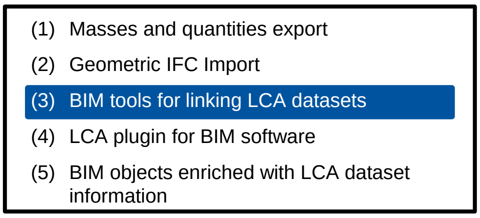

Figure 1: Workflows according to Wastiels and Decuypere [16], own illustration.

According to [16], the integration process consists of six key phases: Modeling the digital BIM structure (1), extracting input quantities from the model (2), generating or retrieving LCA datasets (3), linking LCA datasets with BIM model elements (4), calculating environmental impacts based on the combined data (5), and analyzing and visualizing results for interpretation and decision-making (6). This paper concentrates on phase (4).

A survey of 200 practitioners on the implementation of digital sustainability assessments showed that Workflow 1 is used most frequently, followed by Workflows 2 and 4. Workflow 3, which received the lowest usage score (8.1), is therefore the focus of a more detailed investigation into its technical implementation. [18]

3. Scientific approach

3.1. Methodology

The methodology follows the research process for applied sciences [19]. Based on the status quo, relevant procedures, a new application context, and evaluation criteria are derived. These form the basis for assessing successful implementation within the new application context. Finally, practical recommendations for action are developed.

The literature review is partly systematic, partly based on a snowball principle. First, the focus is on the concept of sustainability and its assessment in the context of bridge structures, prevailing digital methods in this field, and the basic approach to semantically enriching a data source. These aspects are then considered together as a foundation for digital sustainability assessment of bridges. Finally, key practical challenges are briefly outlined before introducing a concrete solution approach.

To answer the first research question, the following requirement criteria were developed and explicitly defined, based on the literature review, to ensure high quality in data management of BIM-based sustainability assessments:

1. Existence of a rule-based attribute validation instance: Check data quality and consistency

2. Automated data mapping, exchange: Automated information enrichment, loss-free, successful access, bidirectional and dynamic data flow via standardized and open data exchange formats
3. Flexible extension of sustainability indicators: Flexibility definable system boundaries and investigation framework
4. User-friendly application without expertise: Consistent, intuitive usability
5. Open interfaces for data integration: Ensure interoperability of software tools and integration of external data bases

These criteria serve as a target image in the subsequent development of the procedure, but also as a benchmark to ensure implementation in line with requirements and are therefore taken up again in the context of validation.

3.2. Research framework

Based on the third workflow approach of Wastiels and Decuypere [16], the corresponding software instances were adopted, see figure 3.

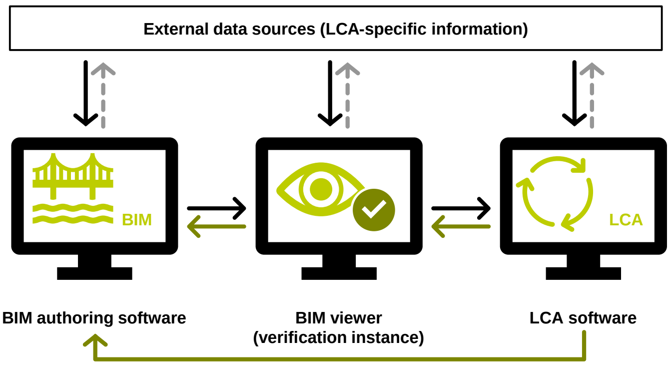

Figure 2: Concept of the method, based on Wastiels and Decuypere [16], own illustration.

The BIM-capable authoring software represents the first instance, where the enrichment of the digital bridge model takes place. A BIM viewer serves as an intermediary validation instance, enabling rule-based queries that can be dynamically adapted to the specific conditions of the project. Acting as a link between the digital model and the LCA software, it is intended to ensure a seamless and error-free workflow. The LCA software forms another essential instance within this setup. It should allow for the inclusion of additional sustainability-specific data - either loosely linked or unrelated to the BIM model - to enable a holistic sustainability assessment. Following Wastiel's and Decuypere's workflow, the term "LCA software" is used for the sustainability assessment environment. Nonetheless, a holistic approach must also include other dimensions of sustainability.

Similar to the BIM viewer, the assessment scope within the LCA software should be adaptable. This includes the ability to expand the sustainability framework with project-specific, customized indicators. The sustainability criteria examined – global warming potential, noise emissions, and barrier-free design – were selected partly due to their indispensability, and partly due to insufficient consideration. The following section focuses primarily on the findings concerning noise emissions, as the LCA, like global warming potential, is already sufficiently investigated, according to the literature review.

4. Investigation for semantic enrichment and validation

4.1. Procedure

First, a new methodical procedure is developed to enrich the BIM model in the one hand and to validate the sufficient enrichment on the other hand, shown in figure 4. The procedure is based on the exemplary chosen authoring software Autodesk Revit, the BIM viewer and verification instance Solibri and the LCA Software One Click LCA. Second, according to the research framework and the developed methodical procedure, the indicator "noise protection" is investigated, see the required information, the checking methods in Solibri and the implementation requirements shown in table 1.

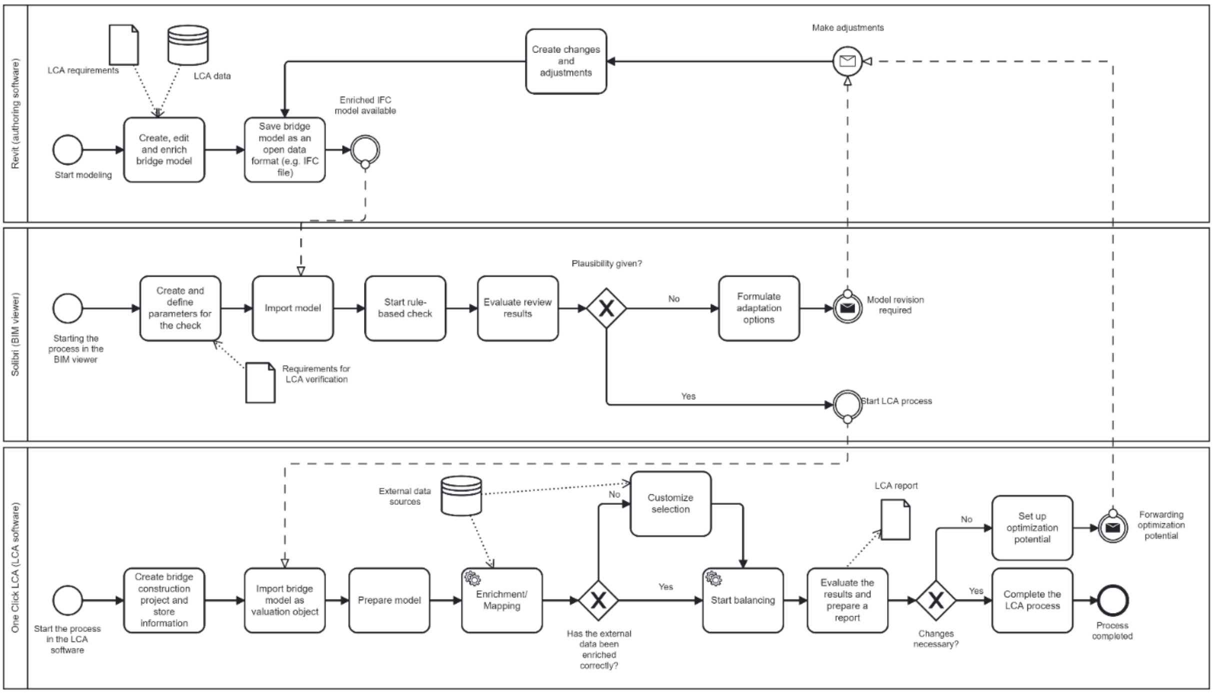

Figure 3: Methodical procedure for semantic enrichment and attribute checking, excerpt, own illustration.

Table 1: Implementation approach of the sustainability indicator „Noise protection", own illustration.

Noise protection	Required information	Implementation in Solibri	Implementation Requirements
Sub-indicator A: **Minimum requirements,** **minimum distances**	1. Are noise protection measures available (in the BIM model)? [No] 2A. Are the minimum distances between the traffic route and built-up areas observed?	Check 1. [Yes]: Abort. [No]: →Check 2A: [Yes]: Positive influence [No]: Negative influence	Re 1.: Extension of the entities of the elements of the BIM model by the attribute "noise protection element" Re 2A.: Integration of the bridge into an urban planning environment by enriching a geographical system
Sub-indicator B: **Minimum requirements for sound limit values**	1. Are noise protection measures available (in the BIM model)? [Yes] 2B. Do the noise protection measures comply with the noise limits?	Check 1. [No]: Abort [Yes]: →Check 2B: [Yes]: Positive influence [No]: Negative influence	Re 1.: Extension of the entities of the elements of the BIM model by the attribute "noise protection element" Re 2B.: Integration of the bridge into a specialized model in which the sound value at the location of the bridge is reflected

In general, the workflow for the indicator implementation and information validation depends on the information basis. Assuming, that the noise indicator consists of the sub-indicators A and B, then the following questions may occur: 1, 2A and 2B, which can be integrated in the verification instance as a question rule. The first question queries the existence of protection measures. Therefore, information concerning a "noise protection element" should be enriched in the BIM model (authoring software) beforehand. Only if the information is available and the question is answered by "Yes" can further questions be added.

With integration of the bridge into an urban planning environment by enriching a geographical system, question 2A can address the minimum distances between traffic route and built-up areas, or the existence of the distance investigation itself. Comparable to this, question 2B can query if the noise protection measures comply with the noise limits, but only if further information is added by linking a specialized model with the sound value at the location of the bridge.

4.2. Discussion of the findings

An attribute can be enriched using any authoring software. The scope of such manual attribution differs depending on the chosen software. For example, Autodesk Revit enables the simultaneous creation of this attribute in all existing elements in the model by setting a new basic property. In this study, however, the attribution was implemented using the BIMvision software with the supplementary IFC Edit plugin. The enrichment was carried out manually on each structural element of the bridge. For more extensive BIM models, the choice of software would certainly be important due to the effort involved, but in view of the limited enrichment effort in the case study, this aspect is negligible with regard to the investigations aimed at. This attribute should indicate whether the respective element is a noise protection element or not. The required enrichment is based on the naming standards of the BIM.Hamburg object catalogue [20]. The property set Pset_Objektinformation with the associated noise protection element property, which can assume the Boolean values "TRUE" or "FALSE", was successfully created and checked for all elements of the BIM model.

An enrichment through the LCA software or the BIM viewer Solibri was not possible for the indicator noise emission. Also, the LCA software One Click LCA does not offer any further enrichment beyond the ecological indicators, which they provide in their database. While the LCA software did not provide the needed information basis, also the sustainability assessment itself had to be outsourced and could be simulated with the BIM viewer and verification instance Solibri.

Solibri does not support the integration of external data systems. Models of the urban environment or noise maps cannot be directly integrated into the analysis, so that the questions 2A and 2B remain relevant for further research. The rule "noise protection element" for answering the question 1 was created using the Ruleset Manager within the Solibri BIM viewer. The rule for the attribute check is based on the rule template "ifcFireRating" – fire resistance class (support tag SOL/203/2.5), which is already included in Solibri. Rules can be changed by adjusting the stored settings. The structure of the rule to be implemented is defined by selecting a corresponding rule template. This rule template must correspond to the basic query logic. For example, when querying the relationship between two or more components, a different rule structure would have to be selected than when querying a single attribute or complying with certain design rules.

In general, many manual steps are necessary, meaning that the requirement to automate data mapping is not achieved. In contrast, a future expansion of the above-mentioned query rules into a rule catalogue promises a high potential for reuse and automation in the future.

5. Conclusion and further research

In this Paper a methodological approach focused on the semantic enrichment of BIM models, enabling the automatic integration of relevant sustainability data and ensuring the accuracy and completeness of these models is developed. Prior to this, existing workflows and research approaches are analyzed by a literature review. Based on a selected workflow according to Wastiels and Decuypere, the corresponding software instances were adopted.

The findings show that sustainability indicators, in the form of information that can be integrated into the BIM model, must be considered separately from BIM-independent information. The information check in the form of query rules can be implemented in several possible ways, whereby some sustainability indicators can even be evaluated as query rules in addition to the pure information quality evaluation. Furthermore, the chosen software showed clear limitations and expansion options for the future.

Further research can investigate the enrichment and query rules with other commercially available software solutions. Additional indicators, besides the noise emissions, global warming potential and barrier-free design, should be investigated. Finally, the full functionality of the query should be ensured, and other query types can be examined for the same question. In regard to the 5 identified requirements for consistent data management and automated data flows in the sustainability assessment of infrastructure, standardization and subsequent mandatory use of standards is recommended to reduce the need for manual adjustments.

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References

[1] B. Domer and R. Bernardello, “Interoperability. An introduction to IFC and buildingSmart standards, integrating infrastructure modeling,” Lausanne, Switzerland: EPFL Press, 2023. The referenced item does not yet have a DOI number.
[2] IHK, Ed., “Umfrage zu den Folgen der Sperrung der Talbrücke Rahmede,” 2025. [Online]. https://www.ihk.de/koeln/hauptnavigation/mobilitaet/umfrage-talbruecke-rahmede-5463178#:~:text=Die%20direkten%20Folgen%20sind%20erheblich,schlechter%20zu%20erreichen%20als%20bisher. The referenced item does not yet have a DOI number.
[3] C. Endt, M. Rohwetter, S. Rudolph, and Z. Zacharakis, “Im Land der bröselnden Brücken,” 2024. [Online]. https://www.zeit.de/mobilitaet/2024-09/brueckensanierung-dresden-carolabruecke-reparatur. The referenced item does not yet have a DOI number.
[4] BMDV, “FAQ zur Brückenmodernisierung,” 2023. [Online]. https://bmdv.bund.de/SharedDocs/DE/Artikel/K/brueckenmodernisierung-faq.html. The referenced item does not yet have a DOI number.
[5] UNEP “2023 Global Status Report for Buildings and Construction: Beyond foundations - Mainstreaming sustainable solutions to cut emissions from the buildings sector,” 2024, doi: 10.59117/20.500.11822/45095.
[6] Statista, Ed., “Bruttowertschöpfung des Baugewerbes im Vergleich zur gesamtwirtschaftlichen Bruttowertschöpfung* in Deutschland in den Jahren 2010 bis 2023 (in Milliarden Euro),” 2025. [Online]. https://de.statista.com/statistik/daten/studie/252400/umfrage/bruttowertschoepfung-des-baugewerbes-in-deutschland/. The referenced item does not yet have a DOI number.
[7] BMVI, “Masterplan BIM Bundesfernstraßen. Digitalisierung des Planens, Bauens, Erhaltens und Betreibens im Bundesfernstraßenbau mit der Methode Building Information Modeling (BIM),” 2021. [Online]. https://bmdv.bund.de/SharedDocs/DE/Anlage/StB/bim-rd-masterplan-bundesfernstrassen.pdf?__blob=publicationFile. The referenced item does not yet have a DOI number.
[8] N. Bartels, J. Höper, S. Theißen, and R. Wimmer, “Anwendung der BIM-Methode im nachhaltigen Bauen. Status quo von Einsatzmöglichkeiten in der Praxis.” Wiesbaden, Germany: Springer Fachmedien Wiesbaden, 2022, doi: 10.1007/978-3-658-36502-8.
[9] BMZ, “Nachhaltigkeit (nachhaltige Entwicklung),” 2024. [Online]. Available: https://www.bmz.de/de/service/lexikon/nachhaltigkeit-nachhaltige-entwicklung-14700#:~:text=Nachhaltigkeit%20oder%20nachhaltige%20Entwicklung%20bedeutet,zuk%C3%BCnftiger%20Generationen%20nicht%20eingeschr%C3%A4nkt%20werden. The referenced item does not yet have a DOI number.
[10] A. Valentin and J. H. Spangenberg, “A guide to community sustainability indicators,” Environmental Impact Assessment Review, vol. 20, no. 3, pp. 381–392, 2000, doi: 10.1016/s0195-9255(00)00049-4.
[11] “DIN EN 17472:2022-09, Nachhaltigkeit von Bauwerken_- Nachhaltigkeitsbewertung von Ingenieurbauwerken_- Rechenverfahren; Deutsche Fassung EN_17472:2022”, doi: 10.31030/3269232.
[12] T. Potrč Obrecht, M. Röck, E. Hoxha, and A. Passer, “BIM and LCA Integration: A Systematic Literature Review,” Sustainability, vol. 12, no. 14, p. 5534, Jul. 2020, doi: 10.3390/su12145534.
[13] A. Röder and M. Finkbeiner, “Was jeder im Bauwesen über Ökobilanzen wissen sollte,” in Nachhaltigkeit, Ressourceneffizienz und Klimaschutz. Konstruktive Lösungen für das Planen und Bauen: Aktueller Stand der Technik, B. Hauke, C. Lemaitre, and A. Röder, Eds. Berlin, Germany: Ernst & Sohn, 2021, pp. 136 ff. The referenced item does not yet have a DOI number.
[14] T. Mielecke, V. Kistner, C.-A. Graubner, A. Knauf, O. Fischer, and G. Schmidt-Thrö, Eds., Entwicklung einheitlicher Bewertungskriterien für Infrastrukturbauwerke im Hinblick auf Nachhaltigkeit. Berichte der Bundesanstalt für Straßenwesen, Brücken- und Ingenieurbau, B 125, 2016. The referenced item does not yet have a DOI number.
[15] Hess et al., “Nachhaltigkeitsbewertung von Streckenzügen der Straßeninfrastruktur – Sustainability assessment of road infrastructure routes,” Berichte der Bundesanstalt für Straßenwesen, Verkehrstechnik, V 361, 2022. The referenced item does not yet have a DOI number.
[16] L. Wastiels and R. Decuypere, “Identification and comparison of LCA-BIM integration strategies,” IOP Conference Series: Earth and Environmental Science, vol. 323, no. 1, p. 012101, 2019, doi: 10.1088/1755-1315/323/1/012101.
[17] A. Hollberg and J. Ruth, “LCA in architectural design—a parametric approach,” The International Journal of Life Cycle Assessment, vol. 21, no. 7, pp. 943–960, 2016, doi: 10.1007/s11367-016-1065-1.
[18] R. Schumacher et al., “Analysis of current practice and future potentials of LCA in a BIM-based design process in Germany,” E3S Web of Conferences, vol. 349, p. 10004, 2022, doi: 10.1051/e3sconf/202234910004.
[19] H. Ulrich, T. Dyllick, and G. Probst, “Management,” Bern, Switzerland: P. Haupt, 1984.
[20] BIM.Hamburg, Ed., “Objektkatalog Ingenieurbau. Version V005,” Hamburg, Germany, 2023. [Online]. https://bim.hamburg.de/resource/blob/612238/68cff0ed5ff7d983a7e477e4198fe40c/d-ingenieurbau-v005-data.pdf. The referenced item does not yet have a DOI number.
[21] Bundesministerium für Digitales und Verkehr, “Entwicklung eines intelligenten Nachhaltigkeitsrechners von Infrastrukturprojekten auf Basis digitaler, georeferenzierter BIM-Modelle – SusInfra,” 2023. [Online]. https://bmdv.bund.de/SharedDocs/DE/Artikel/DG/mfund-projekte/SusInfra.html. The referenced item does not yet have a DOI number.
[22] Bundesministerium für Digitales und Verkehr, “Teilautomatisierte Erstellung objektbasierter Bestandsmodelle mittels Multi-Daten-Fusion – mdfBIM+.” [Online]. https://bmdv.bund.de/SharedDocs/DE/Artikel/DG/mfund-projekte/mdfbim-plus.html. The referenced item does not yet have a DOI number.