BIM integrated automation of whole building life cycle assessment using German LCA database ÖKOBAUDAT and Industry Foundation Classes

S Theißen¹, J Höper¹, R Wimmer², M Zibell³, A Meins-Becker³, S Rössig⁴, S Goitowski⁵, M Lambertz¹

¹TH Köln (University of Applied Sciences), Research Area Green Building, Cologne, Germany
²TMM Group, BIM, Böblingen, Germany
³University of Wuppertal, Chair of Construction Management & Economics, Wuppertal, Germany
⁴Federal Ministry of the Interior, Building and Community Division II 6: Construction and Environment, Berlin, Germany
⁵Federal Ministry of the Interior, Building and Community Division II 4: Building, GAEB, Bonn, Germany

sebastian.theissen@th-koeln.de

Abstract. The life cycle assessment (LCA) of buildings is an important evaluation method for the environmental quality of buildings and their impact on climate and environment. However, this method is time-consuming and cost intensive. Building Information Modeling (BIM) has a high potential to integrate LCA into day-to-day planning. This research project aims to form the basis for BIM (semi) automation of whole building LCA by enabling the integration of LCA data using the Industry Foundation Classes (IFC). The DIN EN 15804 compliant and open access ÖKOBAUDAT is used as the database for LCA data. As a result, a BIM-LCA framework is proposed that includes the development of an Information Delivery Manual (IDM) describing the LCA according to a German assessment system for sustainable buildings (BNB). Based on this, a Model View Definition (MVD) is developed, which defines the software subset of an IFC data model to meet the exchange requirements (ER) for a whole building LCA. Solution approaches for adapting LCA databases and IFC 4 are presented. Finally, a first prototypical implementation of these results for the (semi) automation of whole building LCA is developed. In summary, the proposed IDM and MVD enable identifying the information exchange required to perform an LCA within a BIM-based environment. They also provide the background knowledge to develop a BIM tool to perform an LCA based on the framework proposed. Thereby, this research project contributes to achieve higher environmental quality of buildings by combining sustainable and digital planning methods.

1. Introduction

The construction and operation of buildings is the largest emitter of CO₂ in the world, consumes a large amount of resources and generates 25% solid waste [1]. At the same time, the construction and building sector has the least potential for digitalization [2].
The holistic and cooperative working method BIM, offers a consistent exchange of information and data over the entire life cycle for the most diverse perspectives of stakeholders for planning, analysis, construction, operation and optimization.

The open BIM approach aims to enable the exchange of this information between software solutions from different manufacturers with the help of open, vendor-neutral data formats.

The environmental assessment of buildings is primarily recorded and evaluated by means of a whole building Life Cycle Assessment (LCA) within the framework of Green Building Certification Systems such as those from the German Sustainable Building Council (DGNB) or the Sustainable Building Assessment System (BNB). The basis for this is the verified data of the ÖKOBAUDAT LCA database, which is freely available from the Federal Ministry of the Interior, Building and Community (BMI).

The challenge of a whole building LCA lies in the data and information procurement from the many project participants. Up to now, a very high manual effort has been required for this. The process is also very unstructured, as the file formats as well as the scope, quality and timing can vary greatly and usually originate from 2D planning documents.

The BIM method and the IFC data format offer great potential to make the preparation of building LCAs much more efficient. By making the information required for the calculation theoretically uniform, more structured and more easily accessible, an almost fully automated building LCA would be possible, for example in accordance with the assessment system of BNB. An essential component of this would be the LCA data, which would have to be accessible within the digital building models.

In the context of this paper, a developed solution approach is described, which enables a simplified, partly automated building LCA in late project phases with the technical prerequisites of the ÖKOBAUDAT LCA database, the IFC data model and BIM modelling programs that have been possible so far.

2. State of the art
The BIM method requires a technological architecture that guarantees the success of the project in a targeted manner. To model a 3D model provided with data and information, so-called BIM modelling tools, BIM platforms or BIM authoring tools are required. When modeling digital building models, it has been common practice to work with specialized models that are superimposed at certain points in time for coordination purposes. In addition, so-called information management tools are used, which enable extended editing or referencing of the data in the model, including the generation of a link model using the Multi Model Container (MMC) method.

2.1. Multi Model Container Method
Multimodeling is a method to arbitrarily link different business models as a unit. Multimodels consist of heterogeneous domain models and explicit, external links between their elements [3]. The connection of the different models is managed and controlled by so-called link models. The topology, description and application of the multi-models allow the integration of independent resources of different formats, for instance, by linking a life cycle assessment database.

2.2. LCA database ÖKOBAUDAT
Freely accessible LCA data sets are available in Germany via the database ÖKOBAUDAT. The ÖKOBAUDAT platform is provided by BMI as a standardized database for environmental evaluations of buildings and is required as a data basis in the DGNB and BNB system. Since September 2013, ÖKOBAUDAT is the first life cycle assessment database that completely complies with the standard DIN EN 15804:2014 [4]. This means that values for 24 environmental impacts in 17 life cycle modules, structured from A1-A5, B1-B7, C1-C4 and D, can theoretically be provided per data set. However, as only the declaration of modules A1-A3 was previously mandatory under DIN EN 15804:2014, many of the data sets are not complete. The approximately 1200 data records of ÖKOBAUDAT are also conform to the International Reference Life Cycle Data System (ILCD) data format [5]. For the most part, generic
data sets are made available. Environmental Product Declarations (EPDs) from IBU. data are also available [6].

The ÖKOBAUDAT database is technically based on the software soda4LCA and is equipped with a standardized application programming interface (API) for data exchange. Via this interface, other applications and software tools can read data records from ÖKOBAUDAT or - with appropriate authorizations - import them directly into ÖKOBAUDAT [7]. For this purpose, the data records are identified by a unique identification number (UUID), which is version-dependent.

2.3. IFC data model
Since 1995, the buildingSMART organization has been developing the manufacturer-independent open source data format Industry Foundation Classes (IFC), which is now the only life cycle-compliant BIM data format that is also an international standard, DIN EN ISO 16739 [8]. This interoperable data format enables the exchange of all different disciplines on the basis of a digital BIM model.

IFC is extensible and neutral, making it a very suitable open format for the exchange of information between different software applications over the entire life cycle of a building [9]. With the help of this enhancement schema, information sources can be assigned to the objects or properties of the data model, which can be linked to each other. Thus, it is also suitable for the representation of complex ecological information. For example, with PSet_EnvironmentalImpactIndicators, possible environmental impacts can be mapped in relation to a functional unit according to the ISO 14040 [10] concept [11]. PSet_EnvironmentalImpactValues records the values of the environmental impact of an element. This means that the multiplication of the indicator value per unit by the respective quantity of the element [12].

2.4. Information Delivery Manual and Model View Definition
The buildingSMART organization developed the standardized method Information Delivery Manual (IDM) [13] for the uniform description of BIM processes based on Business Process Model and Notation Version 2.0 (BPMN 2.0) and the exchange requirements (ER) according to DIN EN ISO 29481 [13] or rather the exchange information requirements (EIR) according to DIN EN ISO 19650 [14]. The architecture of an IDM can include a process map (PM) and exchange requirements (ERs). For the PM, the stakeholders and their roles as well as the processes or tasks they perform are identified and described.

The PM is used to identify the interfaces of the individual roles. The interfaces require extensive coordination, since all stakeholder in their roles can control their tasks within the company (without interfaces with external partners) very well. Only when an interface with external partners is established, is there a loss of control and thus, an extensive need for coordination. This is described technologically in the first step with a model-related extension of the ER, in the form of an exchange information requirement model (ERM). This serves as the basis for the Model View Definition [15].

This defines and documents a partial view of a data model - e.g., an IFC specification. Certain sub-areas in the data model are delimited and minimum requirements, i.e., the ER, for export and import are also defined. Thus, an MVD allows the specialization of the data and information of the model for certain processes and usage phases, especially for their interfaces. This specification in turn allows the application of a targeted process and tries to avoid interpretation possibilities as far as possible. In the user interface of the IFC interfaces of BIM software, the supported MVDs should be offered to the user for selection [15].

2.5. LCA according to German Green Building Certification Systems BNB/DGNB
The German sustainability certification systems BNB/DGNB require the calculation of a whole building LCA and define further calculation requirements based on DIN EN 15978:2012 and DIN EN 15804:2014. According to the BNB requirements, the life cycle modules A1-A3, B4, B6 and C3-C4 as well as module D as an informative outcome must be calculated. ÖKOBAUDAT version 2016-I or newer is specified as the data basis.

Within the scope of a BNB certification, eight environmental impact categories in accordance with DIN EN 15804:2014, e.g., Global Warming Potential (GWP) and total use of non-renewable primary
energy resources (PEnrt) are considered. Also, data from the BNB-System [16] are used to determine the service life of the building or building structure (KG 300). Values for the service life for building services (KG 400) are taken from VDI 2067 [17].

3. Method

Within the scope of the research project "Life Cycle Assessment and BIM in Sustainable Construction" funded by BMI and the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR), the first fundamentals are being developed based on the open BIM standard of the IFC data model in order to adapt the officially recognized German database for LCA data ÖKOBAUDAT in the course of progressive digitization in the building industry [18].

Based on the mentioned research project and further work [19], this section presents a methodology that describes a solution approach for the integration and automated linking of ÖKOBAUDAT data in BIM models. In concrete terms, the MMC method and the API interface of ÖKOBAUDAT is used to implement the whole building LCA as a certification proof for the BNB system for late project phases.

3.1. Definition of BNB whole building LCA process in late project phases using the Information Delivery Manual

Firstly, in accordance with the IDM concept, a standardized process is defined in advance, which describes all information delivery or transfer points between the process participants with the necessary data and levels of detail over the entire life cycle of the building. True to the guiding principle: "Who needs which data and information from whom, when, for what, in which data format", the process of BNB whole building LCA is documented.

The processes and the associated information are entered into the "Aeneis" business process management platform [20]. The underlying database enables mapping and evaluating information flows in the context of BIM [21].

3.2. Definition of Exchange Requirements

In the further course of the project, the necessary ERs are identified. From a technical point of view, the ERs describe the information that is to be exchanged between two processes from different stakeholders at a certain point in time. The ER must be defined in such a way that a technical implementation in software systems of the exchange formats to be generated by these processes can take place [22]. Then, these defined ERs are "mapped" with the IFC data model. The mapping process of the ER with the IFC data model results in the location of the identified information for the BNB whole building LCA in the IFC structure in late project phases. The final list of ERs, the resultant ERMs and the PM of the IDM serves as a basis for the development of the MVD.

3.3. Development of Model View Definition

MVDs are generally used to allow a customized implementation of the BIM data model and thus, simplify the integration of such large formats. To allow an automated use of an MVD, buildingSMART has additionally developed the format "mvdXML" [23]. This format is a computer-interpretable definition of an MVD. It is formulated in addition to the actual documentation of the MVD in order to enable an automatable process for software development.

The ifcDoc tool, which is currently under development by buildingSMART, is used to create the MVD in order to ensure absolute conformity to the buildingSMART standards [24]. This should ensure a wide availability of the results.

3.4. Development of an approach for automating whole building LCA according to BNB in late project phases, with respect to the available technical opportunities

After the process is defined with the help of the IDM, necessary ERs and ERMs can be identified and an MVD developed. Then, a solution approach for the integration and automated linking of ÖKOBAUDAT data in BIM models will be worked out that considers the current technical possibilities. This
one is shown in Figure 1. In the first step, the unique material and product classification of the UUID is integrated or stored within the IFC data model as an external reference through a link to ÖKOBAUDAT. This has to be done manually in the modeling software. For this purpose, a user-defined Property Set called "Plca", which is not standardized in IFC, is used. This property is used to integrate the UUID and to specify the ÖKOBAUDAT version, since UUIDs are still version-dependent.

![Figure 1](image)

**Figure 1.** Solution approach for the integration and automated linking of ÖKOBAUDAT data in BIM models for a whole building LCA according to BNB in late project phases [18]

After the first step, the transfer of the materials incl. UUID as well as geometries via IFC 4 file, the second step is to enable a clear allocation of a building material or product to a suitable ÖKOBAUDAT data set. This is achieved by using a link model with the help of an information management tool. At this point it should be pointed out that the necessary information for a clear link on material level is usually only possible in "late project phases".

Within the third step, the stored UUID of the materials are compared with the ÖKOBAUDAT UUID via rule-based linking. If they match, the environmental impacts related to their reference unit of an ÖKOBAUDAT data set can be multiplied by the project-specific quantity for the quantity or mass of the component from the BIM model.

4. Case Study

The solution approach presented was tested and validated using a BIM model, which was modeled according to the VDI standard building [25]. The software Autodesk Revit and DESITE MD was used.

The modelling of the architecture was done with AutoDesk Revit. Ceapoint DESITE MD was used to create the link model from the various specialist models, to carry out the information management for the calculation of a whole building LCA and, with the help of the implemented programming interface, to write the scripts required for the automatic calculation of the LCA in JavaScript and HTML.

Within the model, which is shown in Figure 2, an exterior wall is selected. It consists of three layers. The exact structure is defined as follows: sand lime brick, expanded polystyrene (EPS) layer and bricks. As described in the method representation, the corresponding UUID of ÖKOBAUDAT data sets were assigned as parameters in a user-defined “Plca” within the modeling program, AutoDesk Revit. After all materials in the BIM model were assigned the corresponding UUIDs of ÖKOBAUDAT data sets, an IFC export was generated. This export was read in with DESITE MD. At first the ÖKOBAUDAT was implemented as a type database in form of a CSV file in DESITE MD.

In addition there is the advantage to extend the ÖKOBAUDAT data sets with an own database structure with service life of BNB and VDI 2067, to add life cycle modules according to BNB/DGNB and to provide essential data sets for composites (e.g., reinforced concrete, window structures). Beyond this approach, a direct communication to the API interface of ÖKOBAUDAT with DESITE MD is also possible.

With this basis the user can automatically read out the components with the corresponding ÖKOBAUDAT data sets by rule-based links of DESITE MD. Thus, an evaluation of each component, material layer or the whole building is possible in real time. In Figure 2, for example, embodied greenhouse
gas emissions and embodied energy are calculated as well as shown as GWP and PeEnrt by a click. While on the left a building element (wall) is selected, on the right just the layer of EPS is focused.

![Figure 2. Screenshot of an automated LCA calculation of a wall, shown as a complete building element and a layer [19]](image)

5. Results & Discussion

Specifically, the multi-model container method and the API interface of ÖKOBAUDAT were used to implement the whole building LCA as a certification proof for the BNB system for late project phases.

5.1. Value of IDM and MVD

Through the IDM, which describes the whole building LCA process in "late project phases" based on the BNB system with all information transfer points and interfaces, the tasks of the LCA expert were assigned to inputs and outputs (information to be processed and generated). These were assigned as inputs to the individual processes (for what) for the preparation of a whole building LCA as BNB certification proof (when).

For reasons of clarity, the processes were nested in several process levels [20]. In Figure 3, a part of the process of an LCA expert can be seen on the third level. The resulting ERs were also entered as background information. However, according to BPMN 2.0, these are not a visual part of the PM. A total of 146 ERs were defined and then mapped with the IFC data model to map the ERM. Although IFC proved to be a comprehensive data model capable of covering complex processes with high information requirements, many attributes, entities and properties are not supported by the BIM platforms on the market [26].

Within the present project, therefore, it was necessary to implement non-imageable content for the building LCA using user-defined properties, e.g., for the UUID. Based on this, an MVD was developed, whose documentation can be implemented by software developers for BIM modeling programs as a "control instrument". This checks whether all necessary information is contained in the correct format, etc. to implement a BNB whole building LCA.

The potential that an IDM and an MVD offer for the whole building LCA process lies especially in the fact that the necessary information can be checked for completeness and standardized structure as well as the required data formats for the calculation. This control mechanism can be developed with the help of several IDMs and MVDs for different project phases or different levels of development (LODs).
Thus, the procurement effort of information for a whole building LCA can be reduced considerably for the LCA expert. If it is possible to transfer such a solution approach for early project phases, when there is still a high level of imprecise information content regarding materiality, etc., the focus can increasingly be placed on environmental optimization instead of simply creating a whole building LCA as a certification proof.

5.2. Solution approach for automating whole building LCA calculation according to BNB

The application of the method on the basis of the case study has shown that with the previous technical possibilities, a partial automation of the integration, linking of ÖKOBAUDAT data and their calculation for a whole building LCA is possible. However, this is only conditionally practicable and requires many individual adjustments, e.g., in data management or programming. It was shown that in many respects, an adaptation is useful to facilitate integrating and linking of LCA data of ÖKOBAUDAT. For example, a pure integration of the UUID is not sufficient. From a technical point of view, it is also necessary to include the information about the version of ÖKOBAUDAT, because up to now these are not unique but version dependent.

The use of a separate database structure was also necessary to manually assign and add missing service lives and life cycle modules in advance. Therefore, it is recommended as a short-term measure to adjust the integration of service lives and the completion of not existing life cycle modules (End of Life processes) within ÖKOBAUDAT. As a result of EN 15804/A2:2018-04 [27], a comprehensive need for adaptation will soon be necessary anyway, since, a breakdown of, e.g., GWP will lead to new or more environmental indicators with partly new units.

The mapping process of building physical BIM objects in the model with the environmental data sets (via UUID) is another challenge that can only be solved with the expertise of an LCA expert. Other possibilities to remedy this manual linking, e.g., by integrating IDs in BIM objects [28] that could be included in the models via drag & drop during modeling, are still under development and are considered to be solutions that are available in the long term. In general, one of the major challenges in BIM integrated automation of whole building LCA is the mapping of the material designations of the individual layers from the BIM application to their respective equivalent LCA data sets [29]. However, referencing by unambiguous assignment is considered to be very useful in order not to additionally integrate the large amount of environmental data in complex BIM models, but only to link them [18]. Nevertheless, expertise is needed to correctly interpret supposedly simple comparisons [30]. Thus, this solution approach represents a first starting point and an approach to simplify whole building LCA and to implement them in BIM processes in the future. Compared to the conventional method of calculating life cycle assessments in construction planning, the effort required can be reduced significantly.

Figure 3. Part of a process map of a whole building LCA as BNB certificate proof, in detailed view [18]
6. Conclusion and outlook

The results of this project illustrate the current challenges in the integration of LCA data from ÖKO-BAUDAT. They show a solution approach how to implement the whole building LCA according to BNB based on digital building models and the IFC data model with the technical possibilities available so far. To this end, five connection options were examined within the framework of the technical requirements. The investigation of these has shown that the IFC 4 data model (Addendum 2), with its previous structure, is primarily suitable for integrating various LCA environmental indicators and their units. Conformity to DIN EN 15804 is, however, not given. The existing IFC structure does not do justice to the integration of complex processes in the sense of a whole building LCA or a future detailed granularity for storing whole building LCA results.

In addition, various proposals were discussed, such as the integration of service life or the addition of non-existent life cycle modules (end of life processes) in ÖKOBAUDAT data sets. Should ÖKO-BAUDAT data sets be prepared in such a way that theoretically fewer changes in the IFC data model or properties have to be adapted/created, this could simplify the implementation of a BNB whole building LCA based on the open-BIM approach.

In doing so, the authors see a great potential and high motivation to use the whole building LCA more in practice, since the effort for information procurement can be reduced with the use of digital building models. Although the approach presented is primarily suitable for the application case BNB whole building LCA in late project phases, the knowledge gained can also be used in the future for the application of whole building LCA in early project phases.

In order to make a further important step towards using the whole building LCA more for environmental optimization in early project phases, e.g., for the reduction of greenhouse gas emissions or resource consumption, further research is essential. In connection with this, approaches to solutions are needed that allow simple environmental assessments in early stages of planning, e.g., via the type of construction, to handle the low information content given for an LCA [31].

Furthermore, the development of LCA benchmarks with a higher granularity at the functional system or component level is a central component for such early environmental optimizations [32]. At this point, care must be taken to derive LCA benchmarks not only from static evaluation as a reference, but also to take their strategic orientation towards target values into account. Specifically, this requires that LCA benchmarks in a national and international context be aligned with scientific studies as well as national and international targets with regard to climate and other protected assets on the basis of the Sustainable Development Goals (SDGs) or Planetary Boundaries.

Moreover, LCA results are often too abstract and incomprehensible even for experts. As a result, the potential for environmental optimization through whole building LCA results is not being fully exploited to any extent in order to achieve the climate goals and a stronger contribution of the construction and building sector to the SDGs.

Communication and comprehensibility of whole building LCA results and LCA benchmarks will therefore be decisive, in addition to simplified technical implementation, in order to be able to use whole building LCA effectively for the overarching reduction of environmental impacts and resource consumption and must therefore be taken into account in the integration and application of BIM and the IFC exchange format. Furthermore, the LCA expert develop a practical whole building LCA workflow parallel to the other stakeholders in order to contribute to a climate-neutral building stock in the future?

Acknowledgement

This publication was published within the research project "Ökobilanzierung und BIM im Nachhaltigen Bauen" (SWD-F 10.08.17.7-18.29) of the Zukunft Bau program, funded by the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) within the Federal Office for Building and Regional Planning (BBR).
References

[1] United Nations Environment Programme (UNEP), *As buildings and construction sector grows, time running out to cut energy use and meet Paris climate goals*. [Online]. Available: https://www.unenvironment.org/news-and-stories/story/buildings-and-construction-sector-grows-time-running-out-cut-energy-use-and (accessed: Mar. 31 2018).

[2] Bundesministerium für Wirtschaft und Energie, Ed., “Rolle der Digitalisierung im Gebäudebereich: Eine Analyse von Potenzialen, Hemmnissen, Akteuren und Handlungsoptionen,” BMWi-Projekt-Nr.: 102/16-13, 2017. Accessed: Dec. 11 2019. [Online]. Available: https://www.bmwi.de/Redaktion/DE/Publikationen/Studyen/rolle-der-digitalisierung-im-gebäudebereich.pdf?__blob=publicationFile&v=8

[3] S. Fuchs, P. Katranuschkov, and Scherer RJ, *A framework for multi-model collaboration and visualisation*. [Online]. Available: https://www.researchgate.net/publication/202289508_A-framework_for_multi-model_collaboration_and_visualisation

[4] Nachhaltigkeit von Bauwerken – Umweltproduktdeklarationen: Grundregeln für die Produktkategorie Bauprodukte, DIN EN 15804, 2014.

[5] T. Brockmann, “Digitalization of building LCA and international activities – in the context of German assessment system for sustainable building,” *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 323, p. 12108, 2019, doi: 10.1088/1755-1315/323/1/012108.

[6] Institut Bauen und Umwelt e.V., *What is IBU.data?* [Online]. Available: https://ibu-epd.com/faq-items/ist-ibu-data/ (accessed: Dec. 18 2019).

[7] T. Brockmann, H. Figl, N. Kerz, O. Kusche, and S. Rössig, Eds., *ÖKOBAUDAT: Grundlage für die Gebäudeökobilanzierung*, 2017th ed. Bonn: Bundesinstitut für Bau-, Stadt- und Raumforschung im Bundesamt für Bauwesen und Raumordnung, 2017. [Online]. Available: http://edok01.tib.uni-hannover.de/edoks/e01fn17/895544776.pdf

[8] *Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries - Part 1: Data schema*, ISO 16739-1:2018-11, 2018.

[9] G. I. Giannakis, G.N. Lilis, G.D. Kontes, C. Valmaseda, and D. V. Rovas, *A methodology to automatically generate geometry inputs for Energy Performance Simulation from IFC BIM models*. [Online]. Available: http://www.ibpsa.org/proceedings/BS2015/p2363.pdf (accessed: Dec. 20 2019).

[10] Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen, DIN EN ISO 14040, 2009.

[11] buildingSMART International Limited, *Industry Foundation Classes: Version 4 - Addendum 2: Pset_EnvironmentalImpactIndicators*. [Online]. Available: https://standards.buildingsmart.org/IFC/RELEASE/IFC4/ADD2/HTML/link/pset_environmentalimpactindicators.htm (accessed: Nov. 5 2019).

[12] buildingSMART International Limited, *Industry Foundation Classes: Version 4 - Addendum 2: Pset_EnvironmentalImpactValues*. [Online]. Available: https://standards.buildingsmart.org/IFC/RELEASE/IFC4/ADD2/HTML/link/pset_environmentalimpactvalues.htm (accessed: Nov. 5 2019).

[13] Bauwerksinformationsmodelle - Handbuch der Informationslieferungen, DIN EN ISO 29481-1, 2018.

[14] *Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) - Information management using building information modelling - Part 1: Concepts and principles*, ISO 19650-1:2018, 2019.

[15] A. Borrmann, M. König, C. Koch, and J. Beetz, Eds., *Building Information Modeling: Technologische Grundlagen und industrielle Praxis*. Wiesbaden: Springer Vieweg, 2015. [Online]. Available: http://dx.doi.org/10.1007/978-3-658-05606-3

[16] Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR), *Nutzungsduern von Bauteilen*. [Online]. Available: http://www.nachhaltigesbauen.de/baustoff-und-gebauedaten/nutzungsduarn-von-bauteilen.html (accessed: Mar. 22 2018).
[17] Wirtschaftlichkeit gebäudetechnischer Anlagen - Grundlagen und Kostenberechnung, VDI 2067, 2012.

[18] M. Lambertz, R. Wimmer, S. Theißen, J. Höper, A. Meins-Becker, and M. Zibell, “Ökobilanzierung und BIM im Nachhaltigen Bauen: Endbericht,” Zukunft Bau (10.08.17-18.29), Technische Hochschule Köln (TH Köln); Bergisch Universität Wuppertal, Lehr- und Forschungsgebiet Baubetrieb und Bauwirtschaft; TMM Group, 2020. Accessed: Oct. 4 2019. [Online]. Available: https://www.bbsr.bund.de/BBSR/DE/FP/ZB/Auftragsforschung/2NachhaltigesBauenBauqualitaet/2019/oekobilanz-bim/01-start.html?nn=436654

[19] J. Höper, “Entwicklung einer Methode zur Automatisierung der Gebäudeökobilanz unter Einbindung der digitalen Planungsmethode Building Information Modeling (BIM),” Masterthesis, Institut für Technische Gebäudeausrüstung, Technische Hochschule Köln, Köln, 2020.

[20] M. Helmus, A. Meins-Becker, A. Kelm, M. Kaufhold, and N. Khorrami, Entwicklung einer idealtypischen Soll-Prozesskette zur Anwendung der BIM-Methode im Lebenszyklus von Bauwerken: Abschlussbericht. Stuttgart: Fraunhofer IRB Verlag, 2018.

[21] M. Helmus et al., “Building Information Modeling und Prozesse: Grundlagenbericht,” Lehr- und Forschungsgebiet Baubetrieb und Bauwirtschaft, Wuppertal, 2017. Accessed: Dec. 5 2019. [Online]. Available: http://www.biminstitut.de/files/biminstitut/media/01_Forschung/Downloads/BIM%20-%20Prozesse%20-%20Grundlagenbericht.pdf

[22] R. Santos, A. A. Costa, J. D. Silvestre, and L. Pyl, “Integration of LCA and LCC analysis within a BIM-based environment,” Automation in Construction, vol. 103, pp. 127–149, 2019, doi: 10.1016/j.autcon.2019.02.011.

[23] buildingSMART International Limited, mvdXML. [Online]. Available: https://technical.buildingsmart.org/standards/mvd/mvdxml/ (accessed: Dec. 20 2019).

[24] buildingSMART International Limited, IFCDoc. [Online]. Available: https://technical.buildingsmart.org/resources/ifcdoc/ (accessed: Dec. 20 2019).

[25] Facility Management - Building management in practice, VDI 6009, 2002.

[26] E. Petrova, I. Romanska, M. Stamnenov, K. Svidt, and R. L. Jensen, Development of an Information Delivery Manual for Early Stage BIM-based Energy Performance Assessment and Code Compliance as a Part of DGNB Pre-Certification. [Online]. Available: http://www.ibpsa.org/proceedings/BS2017/BS2017_556.pdf (accessed: Nov. 28 2019).

[27] Nachhaltigkeit von Bauwerken – Umweltproduktdeklarationen: Grundregeln für die Produktkategorie Bauprodukte - ENTWURF, DIN EN 15804/A2, 2018.

[28] L. Á. Antón and J. Diaz, “Integration of Life Cycle Assessment in a BIM Environment,” Proceedia Engineering, vol. 85, pp. 26–32, 2014, doi: 10.1016/j.proeng.2014.10.525.

[29] G. Reitschmidt, “Ökobilanzierung auf Basis von Building Information Modeling: Entwicklung eines Instruments zur automatisierten Ökobilanzierung der Herstellungsphase von Bauwerken unter Nutzung der Ökobau.dat und Building Information Modeling,” Masterthesis, Technische Hochschule Mittelhessen, Gießen, 2017.

[30] D. Schlenkirch, “Entwicklung einer Methodik zur Abschätzung des kumulierten Energieaufwands (KEA) mittels Building Information Modeling (BIM) in frühen Planungsphasen,” Masterthesis, Technische Universität München, Ingenieurfakultät Bau Geo Umwelt, München, 2017.

[31] Bundesministerium für Wirtschaft und Technologie (BMWi), BIM2LCA4IP. Verbundvorhaben 01175535/1: EnOB. [Online]. Available: https://www.enargus.de/pub/bscw.cgi/?op=enargus.eps2&q=%2201175535/1%22 (accessed: Dec. 3 2019).

[32] E. Meex, A. Hollberg, E. Knapen, L. Hildebrand, and G. Verbeek, “Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design,” Building and Environment, vol. 133, pp. 228–236, 2018, doi: 10.1016/j.buildenv.2018.02.016.