



## **Concept for combining LCA and hazardous building material assessment for decision support using BIM**

Downloaded from: <https://research.chalmers.se>, 2022-11-19 13:35 UTC

Citation for the original published paper (version of record):

Theißen, S., Höper, J., Lambertz, M. et al (2022). Concept for combining LCA and hazardous building material assessment for decision support using BIM. IOP Conference Series: Earth and Environmental Science, 1078(1).  
<http://dx.doi.org/10.1088/1755-1315/1078/1/012101>

N.B. When citing this work, cite the original published paper.

PAPER • OPEN ACCESS

## Concept for combining LCA and hazardous building material assessment for decision support using BIM

To cite this article: S Theißen *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1078** 012101

View the [article online](#) for updates and enhancements.

You may also like

- [Coronary CT angiography \(cCTA\): automated registration of coronary arterial trees from multiple phases](#)  
Lubomir Hadjiiski, Chuan Zhou, Heang-Ping Chan *et al.*
- [Can life-cycle assessment produce reliable policy guidelines in the building sector?](#)  
Antti Säynäjoki, Jukka Heinonen, Seppo Junnila *et al.*
- [Life cycle assessment and life cycle cost analysis for geotechnical engineering: review and research gaps](#)  
I Samuelsson, S Larsson and J Spross



The Electrochemical Society  
Advancing solid state & electrochemical science & technology

243rd ECS Meeting with SOFC-XVIII

**More than 50 symposia are available!**

Present your research and accelerate science

Boston, MA • May 28 – June 2, 2023

[Learn more and submit!](#)

# Concept for combining LCA and hazardous building material assessment for decision support using BIM

S Theißen<sup>1</sup>\*, J Höper<sup>1</sup>, M Lambertz<sup>1</sup>, A Hollberg<sup>2</sup>, H König<sup>3</sup> and P Hollberg<sup>4</sup>

<sup>1</sup> TH Köln (University of Applied Sciences), Cologne, Germany

<sup>2</sup> Chalmers University of Technology, Gothenburg, Sweden

<sup>3</sup> Ascona GmbH, Munich, Germany

<sup>4</sup> CAALA GmbH, Munich, Germany

\* sebastian.theissen@th-koeln.de

**Abstract.** The construction and building sector is responsible for a large part of the world's resource and energy consumption and is considered the largest global emitter of greenhouse gas (GHG) emissions. Hazardous and toxic substances in building materials affect indoor air quality as well as the environment and thus have a high impact on human health, as we spend around 90 percent of our lives in buildings. Life cycle assessment (LCA) and hazardous building material requirements of green building certification systems allow to reduce the environmental and health impacts of building products and materials. However, they are usually very complex and time-consuming to perform and require expert knowledge to use the results for decision support. Digital approaches to support the simplified application of these methods and intuitive visualization of results are becoming increasingly important. Especially Building Information Modeling (BIM) offers a high potential for this purpose, as the integration and linking of geometric and semantic information in 3D-models for LCA and hazardous building material assessment can be done much more efficiently and intuitively. Within the scope of this work, the following three objectives were pursued (1) development of a method for combining LCA and hazardous building material assessment, (2) simplification of the results by converting them into comprehensible indicators for decision support, and (3) implementation of the method in a BIM-based digital assistant for intuitive visualization and communication. The preliminary results show a concept for combined use of LCA and hazardous building material assessment in Germany with differentiation in six use cases. A prototypical implementation as BIM-integrated digital assistant was developed for one of these use cases. For the first time, this prototype provides understandable feedback in real time of LCA and hazardous building material requirements. This research project contributes to the awareness in the context of embodied impacts and low emitting materials in buildings and advances the current digitalization potentials.

**Keywords:** open BIM, IFC, LCA, hazardous building materials

## 1. Introduction

The construction and building sector is responsible for a large part of the worldwide consumption of resources and energy and is considered the largest global emitter of greenhouse gas emissions (GHG) [1]. Since construction and demolition waste accounts for approx. 50% of the waste generated in Germany, its hazardous and toxic-free recycling and reuse is of great importance for the environment [2].



The risk and pollutant content of installed materials in buildings also affects indoor air quality (IAQ) and thus has an impact on human health, since we spend about 90% of our lifetime in buildings [3].

Many assessment methods already exist to capture the various environmental impacts related to construction. However, some of these are highly complex and very time-consuming to perform. Therefore, digital assessment and optimization methods are becoming increasingly important for simplified, sustainable and health-oriented building design. So far, however, the potential for digitizing the construction and building sector is still largely untapped compared to other sectors [4].

Studies show that the use of Life Cycle Assessment (LCA) for buildings to evaluate the environmental impact in early design phases with the help of Building Information Modeling (BIM) can reduce GHG emissions by about 30% on average over the life cycle. It is of high importance that the results are correctly interpreted and understood [5]. A basic understanding is therefore essential to effectively apply methods for environmental optimization and avoidance of hazardous materials and to use them for holistic decision-making in a planning process with all responsible stakeholders.

So far, however, their application is mostly addressed only in voluntary sustainability certification systems for buildings, such as the system of the German Sustainable Building Council (DGNB) or the Sustainable Building Assessment System (BNB). These require conducting LCA as well as fulfilling specific thresholds of various hazardous and toxic substances in building materials [6].

Up to now, these assessment methods have been carried out by experts and they were usually conducted separately from each other or were not considered concurrently. The greatest challenge, however, is the communication of the results to non-experts. The results are usually unfamiliar to the planning team and the client. These stakeholders need support for interpretation of the results. Simplified communication that enables early practical application or decision-making through intuitive visualization options in the same place, e.g., in BIM models, is currently very limited [7]. The potential of digital assessment and optimization methods for sustainable buildings is thus only being used to a limited extent.

Therefore, the research question of this work is described as: how can results of LCA and hazardous building material assessment be combined using BIM models to support informed decision making?

To answer this, the following three objectives are pursued:

- Development of a method for the combination of LCA and hazardous building material assessment
- Simplification of the results by summarizing and converting them into comprehensible indicators for decision support
- Integration of the method and indicators in a BIM-based digital assistant for better visualization and application with practice partners.

## 2. State of Art

### 2.1. Standardization of Life Cycle Assessment

LCA is a method used to evaluate the potential environmental impact of a product or process over its entire life cycle. EN 15978 and EN 15804 are the basic standards for LCA in the construction industry. Up to now, the results of LCA have been mostly presented in the form of 2D-based formats, e.g. extensive tables or bar charts with many individual results [7]. Hazardous building material assessment cannot be performed with the help of a LCA for buildings. Therefore, separate hazardous building material assessments are necessary.

### 2.2. Hazardous and toxic building materials in legal requirements and assessment according to DGNB system

The Regulation of the Council on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) has a candidate list of substances, in which 223 substances have been included so far. It lists the substances of very high concern that meet the criteria of Article 57 of the REACH Regulation (Regulation (EC) No 1907/2006). The examination of hazardous and toxic substances often requires

more chemical knowledge than planners and sustainability consultants possess [8]. In addition, the lists contain many chemicals that are not used in the construction industry. Therefore, certification systems for sustainable buildings try to remedy the situation.

Within the DGNB system, criteria ENV 1.2, material requirements and documentation, which is described by a criteria matrix with currently 48 requirements in each of four quality levels (QS 1-4) for material groups, are defined. In addition, a further quality level (QS0) is planned, which will represent an exclusion criterion [6]. The higher the quality level, the higher the requirements to be verified. Currently, for example, groups of substances (as products or as components of formulations) such as substances of very high concern (see SVHC according to REACH (1907/2006/EC)) or VOC emissions as well as formaldehyde are considered.

The DGNB does not set its own requirements, but refers to existing standards, such as the REACH regulation or the German ecolabel Blue Angel. For example, for products made of plastics (PVC), the proportion of SVHC according to REACH in plastic products must be less than 0.1 percent within the framework of QS4.

### 2.3. *Relationship between LCA and hazardous building material assessment in DGNB*

The hazardous building material assessment and its documentation according to DGNB requires a very similar input information as detailed whole-building LCA. This is described by a detailed breakdown of the materials used, their classification and the quantity in the building.

The hazardous building material assessment must also be based on product specific information, and this can only be specified by the contractors who install the building products. Therefore, in the planning phases prior to contracting, only the exclusion of certain hazardous substances in building materials can be formulated as an additional technical preliminary remark for the invitation to tender.

Furthermore, additional data regarding the scope of the assessment of hazardous substances in building products need to be collected. For example, primers, undercoats, or permanent elastic joints are typically not part of the LCA of a building.

If this necessary information is collected, standardized product specific data sets on the possible hazardous substances in building materials or environmental effects as well as other building ecology information from external public databases, e.g., ÖKOBAUDAT and WECOBIS, can be linked. Thus, the building model, which is used for the LCA, can be extended accordingly with regard to the limitation of hazardous substances in building materials.

However, while 2D-based processes have been used in practice up to now, and easy data access for LCA and ingredient reports in order to screen for harmful substances is associated with a high manual effort, assessments are time-consuming and cost-intensive [9, 10]. Currently, there is usually no combined consideration of the two criteria in practice. One reason for this is that there is little or no specific software available for this purpose, and LCA software for buildings does not yet offer a function for supporting building product assessment about harmful substances using BIM models.

### 2.4. *BIM and Industry Foundation Classes*

The BIM methodology is understood as the integration, linking and enrichment of all relevant building data in a virtual data model throughout the entire life cycle. In this way, BIM also offers the possibility of implementing the information procurement and calculation process for LCA of buildings and the localization and quantification of hazardous building material assessment in a structured and consistent manner, in order to exploit the potential for automation [11] and the added value of the 3D representations for the communication of sustainability indicators [7].

While the complex and time-consuming process of calculating LCA, excluding the hazardous building material assessment, is currently being automated in various research projects with the help of the BIM method [12], there is still a lack of a fundamental understanding of LCA results for sustainability evaluation. Furthermore, to the authors' best knowledge and literature review there is no research which combines hazardous building material assessment and BIM.

In order to exchange different models, data exchange formats are necessary. The basic data model for the open BIM method is the open data exchange format Industry Foundation Classes (IFC), which is standardized in ISO 16739 [13]. IFC describes a hierarchically structured and object-oriented data format, whereby attributes can be inherited by subordinate layers. Simplified, the IFC data format can be interpreted like the PDF format. If different formats (e.g., Microsoft Word and Apple Pages) are used to create text files in a project, these texts can be exchanged and read using the PDF format.

### 2.5. Communication and visualization of LCA results and hazardous building materials using BIM

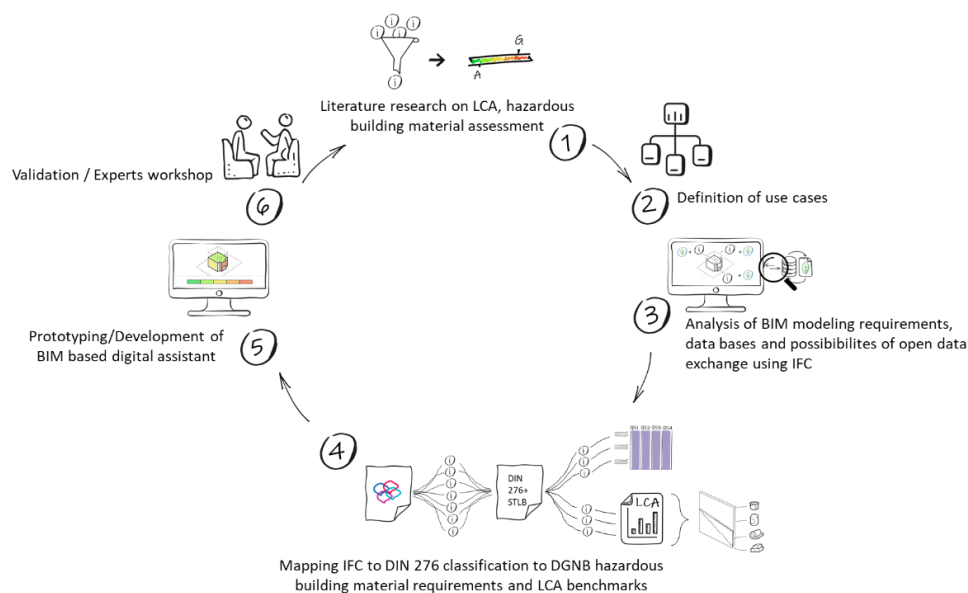
The DGNB system mentions the topic of communication of building LCA results in a guideline from 2018 and provides a toolbox that is intended to provide incentives [14] to communicate the results of the building LCA in an understandable way.

Using the ecological scarcity method, various indicators were weighted and summarized as "environmental impact points" in Switzerland in 2013 [15]. So far, application and integration specific to the building sector with reference to LCA for buildings has only taken place within the framework of the Swiss LCA database KBOB. However, this is not EN 15804 compliant and will therefore not be considered further here.

In the area of hazardous building materials, the DGNB also created a simpler evaluation and communication using quality levels (QS). However, further visualization options are not available. In general, no work could be identified that communicates and visualizes hazardous building material assessment in the context of BIM and/or in combination with LCA for buildings.

## 3. Method

The method can be divided into six steps. In step 1, the basics of LCA for buildings as well as hazardous building material assessment are analyzed. This includes the identification of suitable indicators and assessment options with regard to the day-to-day planning practice to develop simplified decision-making. Among others, the indicators global warming potential (GWP) and total use of non-renewable primary energy resource (PENRT), VOC content and formaldehyde will be considered. The aim of the first step is to identify and combine suitable indicators and to 'translate' the units of these indicators into comprehensible quantities and presentation/visualization formats.



**Figure 1.** Schematic diagram and description of the method, divided into six work steps

In step 2, use cases of LCA for buildings as well as hazardous building material assessment are analyzed and defined throughout the planning and project phases. The different objectives and information requirements for the implementation of the methods are considered. This serves to better identify the combination of the two topics and to connect them in the BIM process.

Step 3 is dedicated to the analysis of the extent to which the current possibilities of BIM software systems and IFC data format are suitable for automatically addressing components and materials and linking them with ecological information from external databases like ÖKOBAUDAT and WECOBIS. With this basis, it will be further investigated which requirements and quality of modeling must be fulfilled in order to be able to dynamically calculate and communicate the indicators from step 1.

In step 4, mapping of the IFC schema with DIN 276, as well as a DIN 276 mapping with the DGNB requirements from ENV 1.2 and the German standard performance book (STLB) is done. Here, DIN 276 is used because it is the common German classification system. It consists of three levels to classify costs in relation to a building, e.g. KG 300 building structure, KG 330 external walls, KG 331 loadbearing external walls. This basis is also used to be able to assign LCA benchmarks of the DGNB and other literature sources, which are referenced on DIN 276, for variant comparisons [16, 17].

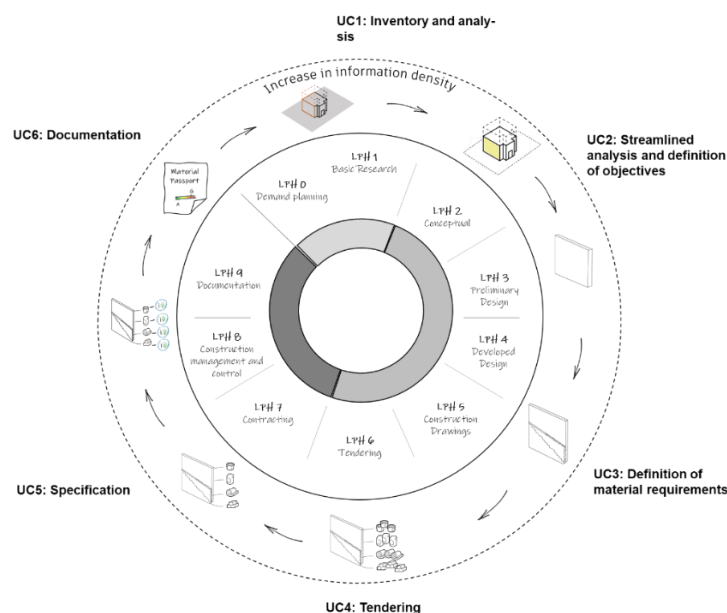
In step 5, the findings are used to develop and implement new visualization options within a BIM environment to make the indicators identified in step 1 visually available in such a way that user-friendly representations and an intuitive understanding can be achieved. Based on exemplary wall assemblies, which are linked with data of ÖKOBAUDAT, the prototype of the digital assistant is explained. This is initially done with the help of an information management tool for BIM models, e.g., DESITE BIM.

In addition to the permanent exchange with practitioners via the partners, an expert workshop will take place in step 6 in further progress to critically validate the preliminary results with practitioners and to discuss their potential as an aid for decision-making.

## 4. Results

### 4.1. Concept for combining LCA and hazardous building material assessment and definition of use cases

The combination of LCA and hazardous building material assessment depends on the information density during the design and planning process.



**Figure 2.** Schematic representation for the combination of LCA and hazardous building material assessment, divided into use cases.

This means that along the different phases, there are different possibilities for combining the two topics, which are referred to below as use cases. To define these more clearly, a scheme along the HOAI project phases is created that shows the different use cases including the individual application possibilities/benefits of the LCA and hazardous building material assessment. Table 2 describes the use cases in detail.

**Table 1.** Description of the application possibilities and benefits of LCA and hazardous building material assessment along project phases as well as needed modeling requirements in the BIM process.

Use case	HOAI Phase	LCA for buildings	Hazardous building material assessment
1) Inventory and analysis	LPH 0-1	At the beginning of the demand planning, rough estimates of the masses and quantities of the shell, e.g., concrete, can be determined with the help of the LCA if an existing building is available, in order to show avoidable GHG emissions through the use of new concrete.	In the area of hazardous building material assessment, a contamination report can be used to investigate where and how much contamination is present in a building stock when it is present and preserved. This makes it possible to estimate conversion and disposal costs, which serve as an important basis for decision-making.
2) Streamlined analysis and definition of objectives	LPH 2	LCA benchmarks at building level [CO <sub>2</sub> -Eqv/m <sup>2</sup> /a] can be used to set targets, for example, to determine the maximum GHG emissions through a GHG budget.	In early phases, requirements can be defined, for example, by using QS according to DGNB. A selection of building products and materials that is as free of harmful substances as possible is defined by QS4.
3) Definition of material requirements	LPH 3-5	In preliminary and design planning, LCA can be used, for example, for variant comparisons of geometry, construction types, technical building services concepts, or even individual comparisons of components and materials, such as exterior walls. Furthermore, LCA benchmarks can be used to examine the environmental impact of different variants at the component level.	Once the layer structure and the materials to be used are known, the requirements for BIM objects can already be roughly assigned by means of semantic descriptions and anchored for the further course of the planning process up to tendering and awarding.



4) Tendering	LPH 6	The status of the execution planning provides a basis for a detailed LCA with concrete information on generic materials, etc. The results of the LCA can be used for the design of the building. While structural decisions have already been made, the application of LCA here usually still offers optimization potential, for example, when comparing materials in the selection of insulation or flooring.	In the context of hazardous building material assessment, an automatic integration of the stored requirements in the BIM model into the tender can take place. For example, the trade-specific service specifications with the corresponding material requirements of the selected QS4 can be automatically created with text blocks.
5) Specification	LPH 7-8	After the tendering and during the contracting phase, generic material data can be replaced by product-specific data (EPDs), since it is now known which manufacturer's product will be installed.	As soon as the manufacturers' products that the contractors intend to use or install during the construction phase become known, preliminary and site tests of the product properties with the material requirements already specified must be carried out. Various verifications of the construction products are required to confirm compliance with the requirements.
6) Documentation	LPH 9	With the completion of the building, there is ideally an as-built documentation of the materials used as well as their quantities and masses. Ideally, this is ensured by a BIM model or a digital building material passport. The information that can be extracted from this can then be used as evidence for an as-built whole-building LCA or a material-ecological component catalog as part of sustainability certification and reporting, e.g., in accordance with DGNB or the EU taxonomy requirements. At the end of the life cycle of the building, the building material passport proves to be a detailed source of documentation of the materials used, which is very useful for accessing information on material-related emissions or harmful substances during renovation, including the preservation of existing buildings, or deconstruction.	

#### 4.2. Implementation workflow of use case 3) within BIM

As part of the preliminary results, a first application and implementation of use case 3, the digital assistant is programmed as a user form in DESITE BIM, based on an algorithm by Höper [18], which can decompose IFC files into the DIN 276 cost group structure and conduct real time LCAs.

The prototype of the digital assistant consists of three parts. An input mask for the specification of hazardous building material requirements, a result output that combines calculated LCA results and hazardous building material requirements in a table and an integrated BIM viewer from DESITE BIM (see Figure 3). Within the first part, filtering by the user can be done by using checkboxes and dropdown menus. For example, whether the hazardous building material requirements according to DGNB, BNB or according to the EU Taxonomy screen criteria should be selected as a basis. Further filtering can be narrowed down via the DGNB/BNB quality levels, DIN 276 cost groups, selection of the construction trade according to STLB-Bau (e.g., "painting and varnishing work - coatings"). Furthermore, it is possible to filter by certain harmful substances or chemicals, e.g., VOC and formaldehyde, as well as by component or material category, e.g., only wood materials or metals.

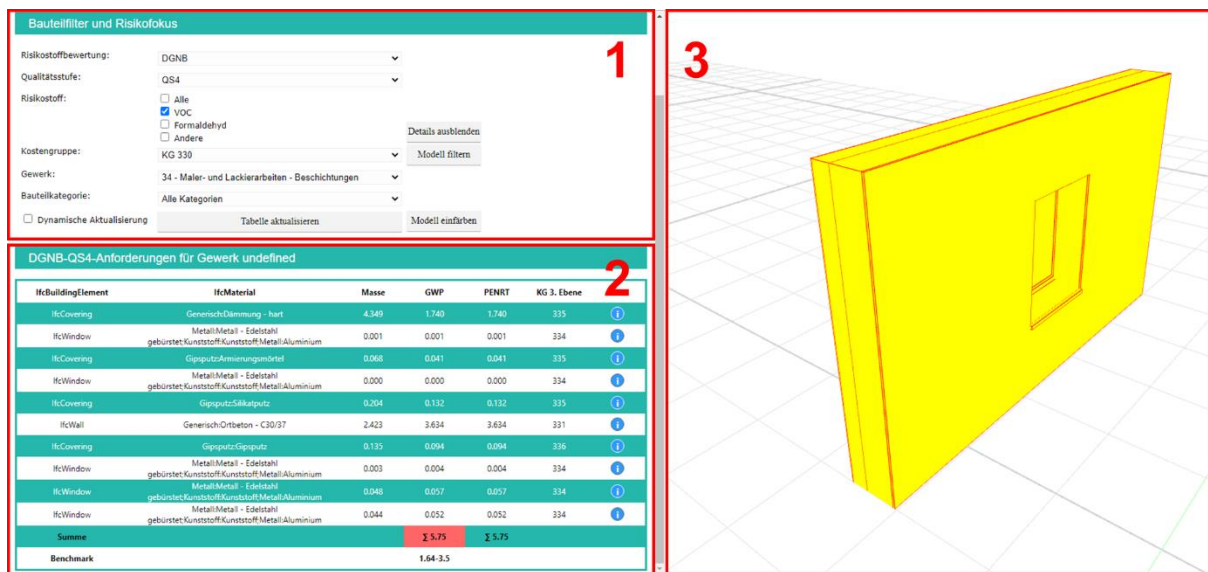


Figure 3. Screenshot of the digital assistant in BIM, applied for use case 3 showing hazardous building material potential, focusing VOC, within a wall assembly

In the second part, the result table is presented, where IfcBuildingtype and IfcMaterial are displayed as information read from the IFC file. The results are always classified in the output according to the DIN 276 cost group of the 2nd level - in this example according to KG 330 exterior walls. If multiple or/and different building components are selected, several tables are displayed one after the other, which are visible by scrolling down, see Figure 4.

The corresponding mass, quantity, volume of the BIM objects is also read from the IFC file. For parallel conducting the LCA, the Universally Unique Identifier (UUID) of the material or product from the LCA database, in this case ÖKOBAUDAT, is also required. Thus, based on the specific mass, quantity, volume as well as the link to the corresponding LCA data set, the GWP and PENRT, also known as embodied carbon and embodied energy, can be calculated in real time.

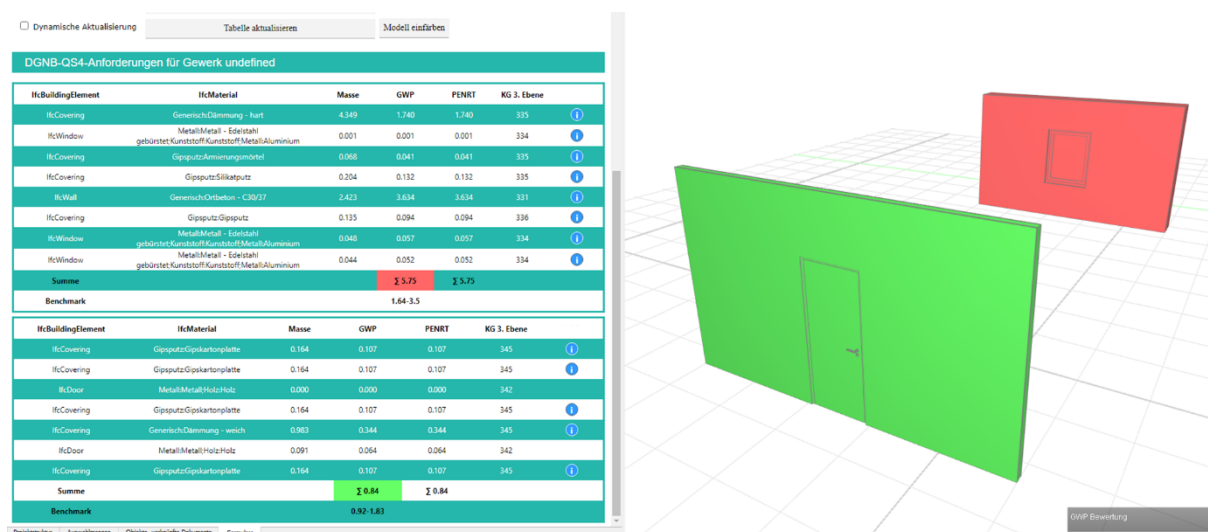


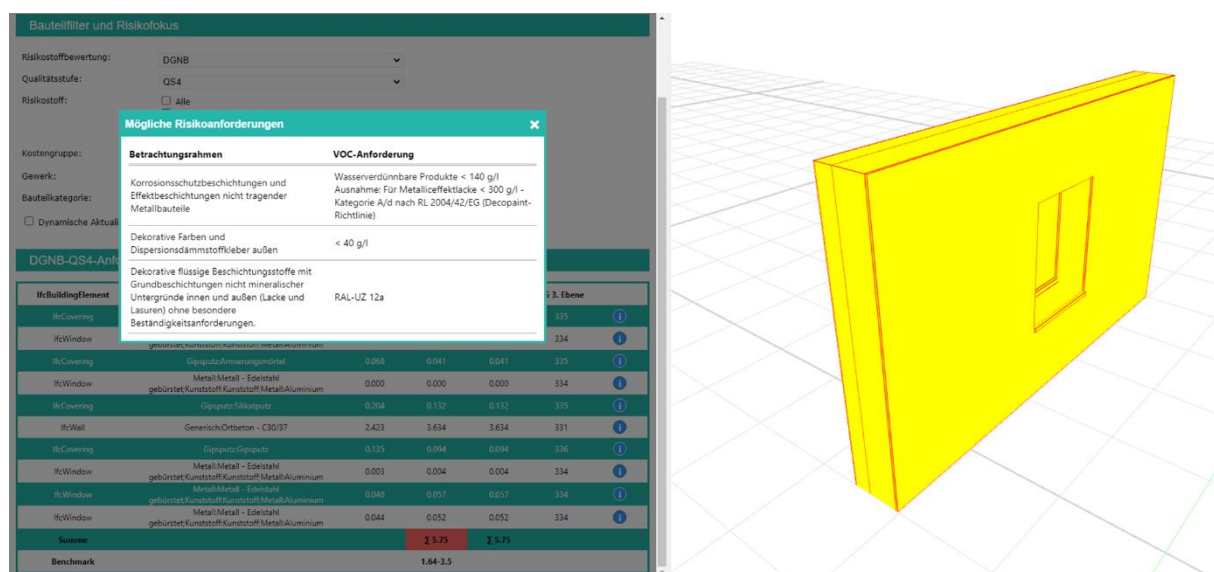
Figure 4. Screenshot of the digital assistant in BIM, applied for use case 3 showing comparisons to DGNB LCA Benchmarks as color-coded wall assemblies

This is possible as DESITE BIM offers to integrate and adapt database structures, as the ÖKO-BAUDAT, allowing to read all information of the data sets, once a link has been created using matched UUIDs. Alternatively, an application programming interface (API) interface could be used, as many LCA databases offer an API.

In addition, the sum of GWP and PENRT per level 2 of DIN 276 cost group is presented in the results table. This sum is compared with an LCA benchmark, e.g. from a DGNB study [17], evaluated and color-coded accordingly. This color coding can be transferred to the model for visualization to show if thresholds are met, highlighted as red or green, see Figure 4.

The level 3 of DIN 276 cost groups shown are determined using information of the IFC file, for example, "IfcType", "IfcPredefinedType", "LoadBearing" or "IsExternal". In this way, a concrete assignment can be made. This in turn is used together with the set specifications from the input area of the hazardous building material requirements to display the note "requirements exists" as a blue info symbol. This means that if lines contain a blue info symbol, requirements exist according to the chosen filter settings, classified using the DIN 276 cost group. A click on the respective info symbol opens the detailed view, as shown in Figure 5. Here, the specific requirements of a window according to DGNB QS4 can be shown as detailed information.

In the third part, different BIM objects of the model can be selected manually via the viewer function of DESITE BIM, e.g., an exterior wall. If such a manual selection is made, the set filters are applied on the basis of the selected BIM objects, the LCA is performed again, and the table result output is updated dynamically.



**Figure 5.** Screenshot of the digital assistant in BIM, applied for use case 3 showing detailed DGNB ENV 1.2 QS4 requirements as a pop-up window, within a wall assembly

## 5. Discussion

With regard to the objectives of the paper, a concept is developed that shows the interrelated application possibilities of LCA for buildings and hazardous building material assessment. As part of the preliminary results for use case 3, a solution in the form of a workflow and a digital assistant is developed, which provides information at an early stage about which components or layers have requirements with regard to hazardous building material assessment.

A summary of LCA results and hazardous building material assessment as one score did not prove to be useful, as a merging of these as well as a combined result display is problematic. To relate the calculated values of the different LCA indicators to the many different requirements of hazardous building material assessment would not be scientifically correct.

The advantage of the prototype is that an LCA can be performed based on an IFC file and at the same time hazardous building material requirements can be considered according to different standards in a BIM software environment. The filtering and automatic display of hazardous building material requirements per component and material is particularly helpful for reducing the workload compared to conventional work processes.

The validation by presenting the preliminary results within an expert workshop to 14 German experts of LCA and harmful substances showed that the consideration of hazardous building material requirements in addition to the LCA results, which are visually displayed in a BIM environment, proved to be a valuable supplementary function, especially in early phases, which previous LCA software did not provide. In addition to saving time and effort, this also minimizes the complexity for the LCA experts when considering hazardous building material requirements in parallel, e.g., for certification processes. Against the background of further new requirements, such as the EU taxonomy criteria or the German label Qualitätssiegel Nachhaltiges Gebäude (QNG), which follows the BNB requirements, this can mean a useful simplification for LCA experts and DGNB auditors.

A disadvantage is that certain layers, which are mostly affected by hazardous building material requirements, such as paints and varnishes, are not modeled or geometrically represented in the model. Further solutions are needed to describe these layers semantically by means of logical additions using algorithms and predefined data sets, so that they can be considered for assessments. The prototype is not able to do this, yet.

## 6. Conclusion and outlook

Reducing hazardous substances in building materials by defining requirements are of high importance for sustainable construction but prove to be complex and are therefore often considered very isolated as a special discipline. This work contributes to the parallel consideration of hazardous building material assessment during early BIM based LCA. Likewise, an implementation in BIM should offer more intuitive visualization possibilities and uncover hidden connections. The first approaches to a solution have been identified, but they will have to be validated in the future. To this end, new results will be presented and discussed again within a second online expert workshop. Therefore, further approaches for use case 4 "Tendering" will be developed, in aiming to select a DGNB QS in the digital assistant and to automatically integrate the requirements for the relevant components/building product level in the BIM model. Another approach is to be developed for use case 6 "Documentation" and verification of installed building products, in which integration into BIM-based building material passports is to be established via product codes using GTN/ETAN codes. The aim is to create a more automated verification document that has the potential to replace time-consuming verification processes, such as the creation of the material-ecological component catalog in accordance with DGNB.

## Acknowledgments

This research is part of the research project "Intuitive communication and visualization of whole-building LCA and hazardous building materials for decision support in the digital planning process (BIM)" funded by the German Federal Environmental Foundation (DBU, Deutsche Bundesstiftung Umwelt), number 36041/01.

## References

- [1] Global Alliance for Buildings and Construction. 2020 Global Status Report for Buildings and Construction: Towards a zero-emissions, efficient and resilient buildings and construction sector; 2020.
- [2] Ilvonen O, Dürkop J, Horn W, Englert N, Plehn W, Bolland T, et al. Umwelt- und gesundheitsverträgliche Bauprodukte: Ratgeber für Architekten, Bauherren und Planer; 2015.
- [3] Bundesumweltministerium. Verbesserung der Luftqualität in Innenräumen: Ausgewählte Handlungsschwerpunkte aus Sicht BMU; 2005.

- [4] Friedrich R, Le Merle, M. and Koster, A. Measuring Industry Digitization. Leaders and Laggards in the Digital Economy; 2011.
- [5] Hollberg A, Ebert M, Schütz S, Cicek B, Gump R, Ruth J. Application of a parametric LCA tool in students' design projects. In: SBE16 Hamburg: International Conference on Sustainable Built Environment ; strategies - stakeholders - success factors ; 7th-11th March 2016 ; conference proceedings. Hamburg: ZEBAU; 2016. p. 72–81.
- [6] German Sustainable Building Council (DGNB). DGNB System: New Construction, Buildings Criteria Set; 2021.
- [7] Hollberg A, Kiss B, Röck M, Soust-Verdaguer B, Wiberg AH, Lasvaux S, et al. Review of visualising LCA results in the design process of buildings. *Building and Environment*. 2021;190:107530. doi:10.1016/j.buildenv.2020.107530.
- [8] Lewis M. Screening for hazardous chemical content in certified buildings: a comparison of Nordic certification systems. *IOP Conf. Ser.: Earth Environ. Sci.* 2020;588:32064. doi:10.1088/1755-1315/588/3/032064.
- [9] Lewis M. Incompatible trends - Hazardous Chemical Usage in Building Products Poses Challenges for Functional Circular Construction. *IOP Conf. Ser.: Earth Environ. Sci.* 2019;225:12046. doi:10.1088/1755-1315/225/1/012046.
- [10] Gantner J, Both P von, Rexroth K, Ebertshäuser S, Horn R, Jorgji O, et al. Ökobilanz - Integration in den Entwurfsprozess. *Bauphysik*. 2018;40:286–97. doi:10.1002/bapi.201800016.
- [11] Gade P, Svidt K, Jensen RL. Analysis of DGNB-DK criteria for BIM-based Model Checking automatization: Department of Civil Engineering, Aalborg University; 2016/09/16.
- [12] Potrč Obrecht T, Röck M, Hoxha E, Passer A. BIM and LCA Integration: A Systematic Literature Review. *Sustainability*. 2020;12:5534. doi:10.3390/su12145534.
- [13][13]. German Institute for Standardization (DIN). Industry Foundation Classes (IFC) für den Datenaustausch in der Bauindustrie und im Anlagenmanagement 2017: Beuth Verlag GmbH.
- [14] Braune A, Ruiz CD. Leitfaden zum Einsatz der Ökobilanzierung (LCA).
- [15] Bundesamt für Umwelt. Ökofaktoren Schweiz 2013 gemäss der Methode der ökologischen Knappheit. Schweiz; 2013.
- [16] Schneider-Marin P, Dotzler C, Röger C. Design2Eco: Lebenszyklusbetrachtung im Planungsprozess von Büro- und Verwaltungsgebäuden : Entscheidungsgrundlagen und Optimierungsmöglichkeiten für frühe Planungsphasen; 2019.
- [17] Deutsche Gesellschaft für Nachhaltiges Bauen – DGNB. Benchmarks für die Treibhausgasemissionen der Gebäudekonstruktion: Ergebnisse einer Studie mit 50 Gebäuden; 2021.
- [18] Höper J. Entwicklung einer Methode zur automatisierten ökologischen Analyse der TGA in frühen Projektphasen unter Einbindung einer Wissensdatenbank mithilfe von open-BIM. Wuppertal; 2022.