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Interactive visualization of uncertain embodied GHG emissions for design decision support in early stages using open BIM

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ABSTRACT: To meet the European climate goals in the building sector, a holistic calculation and optimization of embodied greenhouse gas (GHG) emissions using the method of life cycle assessment (LCA) in early design stages are necessary. Hence, this paper presents a comprehensive and transparent design-decision-making approach for reducing embodied GHG emissions in early design stages by interactive, model-based visualizations of uncertain results. The proposed approach is based on a previously developed Natural Language Processing (NLP) based methodology of matching elements of a Building Information Model (BIM) to those of an LCA database. With the help of a prototypical implementation and a case study, the uncertainties of the derived LCA results are visualized using different levels of transparencies. This paper shows that open BIM models and the proposed 3D color coding support the hotspot analysis in combination with box plot diagrams for visualizing uncertain GWP results for decision-making in early design stages.

1 INTRODUCTION & MOTIVATION

In order to reach the international climate goals, the AEC sector with its impact of 40% of the global Greenhouse gas (GHG) has a significant impact (UN 2021). Currently, the embodied GHG emissions, meaning those from material extraction, manufacturing of construction products, etc., are responsible for up to 12% of the GHG emissions (EU Commission 2022a). Life cycle assessment (LCA) has been an established method to evaluate these embodied GHG emissions in the design phase of new buildings. Several national and international frameworks are currently including LCA in their assessments for comparing sustainability of building designs, for example LEVEL(s), which is also used for ensuring current EU Taxonomy classification system (EU Commission 2022b).

In a market survey with 161 participants from Germany, Schumacher et al. (2022) identified significant potential of using Building Information Models (BIM) for a loss-free data-exchange, as well for understandable and user-friendly communication of LCA results. This also means that in future, non-LCA-experts should be able to understand LCA results and make design decisions based on these results.

Nevertheless, most of the existing tools and methods in the field of BIM-based LCA focus either on closed BIM approaches, developed for architects, designers or BIM modellers, or require a high level of LCA expertise to conduct and interpret LCA results. Building owners or clients, who are usually making design decisions, often have not the required expertise in LCA and are increasingly using open BIM models. Therefore, in this paper we propose an interactive and comprehensive approach of visualizing uncertain embodied GHG emissions for design decision making by non-LCA-experts using open BIM models in early design stages.

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2 BACKGROUND & RELATED WORKS

Several related publications were investigated with regards to variant selection and visualization. Wiberg at al. (2019a) presented in their publication a chronology of the development of a visual, dynamic and integrated approach of LCA of building. Regarding the dynamic aspect, they identified several approaches of integration using Visual Programming Language, such as Dynamo and Revit or Rhino and Grasshopper. Furthermore, they classified other approaches of parametric approaches as well as dashboards using Revit models or district models, where generally only the models were shown, but not used to highlight or visualize results. As a next step, they propose a visualization approach using Virtual Reality for improved stakeholder participation (Wiberg et al. 2019b). For this, they used Revit models to color the models with the LCA results and used the VR to interact with the model, which was concluded as a "good platform for communicating and visualising complex data [...] not only for researchers but also for the general public" (Wiberg et al. 2019b).

The recent review of Hollberg et al. (2021) regarding visualizing LCA results describes current practice and presents a systematic overview of different strategies and potentials. The methodology using BIM models to visualize LCA has shown great potential for synergies (Röck et al. 2018a, b, Mousa et al. 2016). In these approaches, color coding was mainly used to visualize final LCA results in authoring tools. In another visual method for detailed analysis of LCA results by Kiss and Szalay (2019), this model-based color coding was used to highlight certain aspects of the results in combination with a sunburst diagram. For implementation, Kiss & Szalay used Rhino and Grasshopper.

Miyamoto et al. (2022) proposed an approach for integrating LCA and LCC results as a basis for design decision-making. Although they did not use BIM models, they discussed the growing importance of integrating a spreadsheet approach with BIM workflows, however focusing on architects and not other stakeholders. Hollberg et al. put target users in the focus of their user-centric LCA tool development for early planning stages (Hollberg et al. 2022). Different stakeholders such as architects, sustainability engineers and consultants as well as real-estate developers were involved in the process. However, only fixed results were visualized, and no active interaction with the model was envisioned. Also, uncertainties and different levels of development have not been considered. To visualize these aspects, Abualdenien & Borrmann (2020) present several approaches of visualizing geometric and semantic uncertainties of building elements in early design stages. As one main conclusion of several approaches, "the combination of color value and transparency for quantifying the reliability of the semantics resulted in relatively high intuitiveness and acceptance" (Abualdenien & Borrmann 2020).

Furthermore, Ströbele (2022) introduced an approach of fuzzy life cycle assessments (fLCA) considering vaguenesses by distribution curves instead of single results. Schneider-Marin et al. (2022) established an EarlyData knowledge database for deciding material choices in a design stage, where no detailed information about specific materials is available. In this methodology, the semantic uncertainty is also visualized by assessing "a vast number of possible material combinations at once" using boxplot diagrams that visualize the ranges of the Global Warming Potential (GWP) (Schneider-Marin et al. 2022).

Petrova et al. (2019) propose a methodology for decision support for sustainable design based on knowledge discovery in disparate building data. They are using different matching mechanisms between project data repositories and Common Data Environments (CDE), such as data mining, direct semantic queries and geometric feature matching. The direct semantic queries are based on different ontologies, such as Building Topology Ontology (BOT) (Rasmussen et al. 2017) or product specific ontologies.

In summary, the discussed publications show the relevance of using BIM models to visualize LCA results and describe first approaches. However, an integration in an open BIM workflow was not investigated and also the interactive exploration of the results was not presented. This documents the gap existing regarding an interactive, design-decision tool for non-LCA-experts based on open BIM methodology in early design stages. The main focus of this publication is how to visualize uncertainties of the rough model semantics and vague results in a comprehensive way.

3 INTERACTIVE VISUALIZATION OF UNCERTAIN LCA RESULTS USING BIM

3.1 *General workflow*

As shown in Figure 1, the general methodology consists of the LCA knowledge database and four main steps. Overall, the methodology bases on a LCA knowledge database (LKdb), which consists of conventional elements and all information for calculating a holistic LCA, such as layer-specific replacement rates, LCI datasets using Ökobaudat, missing End-of-Life scenarios, etc. Details about the LKdb can be found in (Forth et al. 2021, 2022).

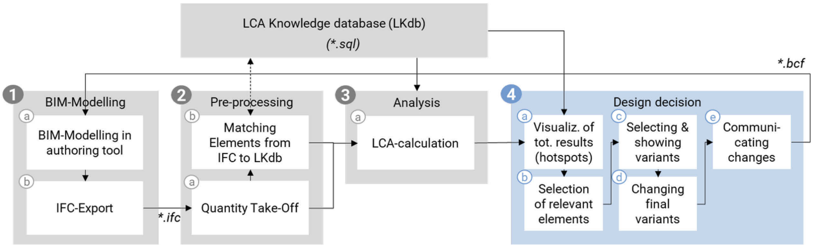

Figure 1. General workflow for visualizing uncertain embodied GHG emissions for design decision support in early design phases using open BIM.

The first step of the general method comprises the creation of the BIM model in an authoring software (step 1.a) and the subsequent IFC model export, which is performed by the BIM modeler (step 1.b). The next step consists of deriving the quantity take-off and element matching. The quantity take-off parses all geometric and semantic information of the IFC model for the calculation of the LCA, including base quantities, such as area, amount, layer thicknesses or length, as well as density, materials and the name of the element, its GUIDs and classification (step 2.a). The expressions of the materials and element are used in the next step for the matching of the IFC elements to the LKdb (step 2.b). This step has been previously introduced and validated (Forth et al. 2022, 2023). This matching is based on an existing NLP network, and compares cosine similarities of the element and material expressions in the IFC model and all elements and material categories and material options of the corresponding classification group in the LKdb. The most similar element of the LKdb is being matched to each IFC element.

After completing the element matching step, all missing information about LCA datasets, life spans or missing layers are filled by the datasets of the matched LKdb element. Afterwards, the results of the LCA are calculated taking into account the uncertainty of the element matching (step 3.a). Depending on the level of matching (see Section 3.3), a range of material options for each element's layer is taken into account and leads to a range of LCA results for each element and the whole building.

In this paper, the focus is on the concept for the final step of the general methodology, the design decision process (step 4.a-e).

3.2 *Design decision support concept*

The goal of the proposed workflow is to support non-LCA-experts in the decision making of construction-element and material-related variants. For supporting the decision maker in the early design stages, several hierarchical visualization goals are proposed, based on Hollberg et al. (2021). To identify hotspots for the design optimization, the 3D color code is recommended as an intuitive visualization type, which can be implemented using open BIM models (Figure 2). For comparing different design options, box plot diagrams are the only type which also include uncertainties in its visualization. Additionally, the selection boxes of each element variant or material option can be also color coded, normalised to benchmarks. As LCA benchmarks on element level are still missing according to the German classification systems used in this approach, the colors are normalised relatively to all potential design alternatives within one classification group. Once benchmarks will be available also on the third level of cost groups according to DIN 276, the colors can be normalised according to these benchmarks.

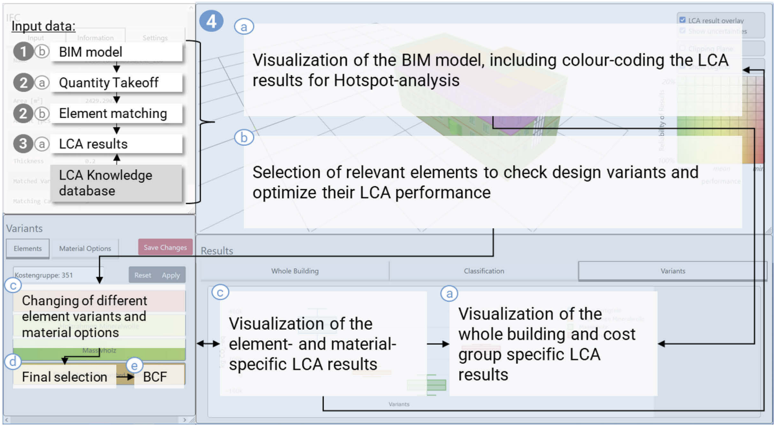

Figure 2. Concept of frontend visualization and interaction workflow for LCA-optimized design decision making.

This design decision process is based on the previous calculation and matching results including its uncertainties and is generally divided into five steps, as shown in Figure 2. First, the LCA results are visualized using a model viewer and conventional criterion-specific charts (4.a). When summing up the LCA results for each cost group and the whole building, Boxplot diagrams are suitable to visualize the ranges of possible results (bottom right). Furthermore, the element-specific results will be color coded on the BIM viewer to highlight the performance hotspots (top right). As a next step (4.b), the worst performing elements can be selected in the model viewer for design optimization (top left).

In the following step (4.c), variant results are visualized for the element selected in the model viewer, and different element variants of the same classification group can be selected (bottom left). Variants are derived on element and on material level according to the existing alternatives of each classification group in the LKdb. For every element in the BIM model, the LCA results of all design variants are previously calculated (step 3.a), independently of the matched element (bottom middle). In the last two steps, the final changes of variants are saved (4.d), and communicated back to the BIM modeler using the BIM Collaboration Format (BCF) as an open BIM standard (4.e).

3.3 *Visualization of matching-related uncertainties*

There are important features which are taken into account, based on the previous findings. On the one hand, the cosine similarity of the matching performance is an indicator for the desgree of similarity the matching is based on. On the other hand, there are different cases how the elements are matched from the IFC model to the LKdb, as described in the following list.

IFC elements are matched to:

1. default element of the classification group in the LKdb (worst case)
2. most similar element expression, as there are no materials available
3. most similar element expression, as the material matching performs worse
4. element with the most similar material category
5. element with the most similar material option

These different cases lead to different levels of reliability of the resulting LCA results. Therefore, this information needs to be considered when visualizing the semantic-related uncertainties.

As previously mentioned, Abualdenien et al. already concluded that the combination of color value and transparency of an element is highly intuitive and accepted for visualizing the reliability of semantics (Abualdenien & Borrmann 2020). Therefore, the transparency value for each element t_e is derived by the following equation:

$$t_e = \frac{\sum_{l=1}^{m} c_e * cos(\theta)_{e,l}}{m} \tag{1}$$

where l = layer number; m = maximum layer number; c_e= matching case of each element; and $cos(\theta)_{e,l}$ = cosine similarity of each element's layer (according to (Forth et al. 2022)).The values of the above mentioned five matching cases for each element c_e are distributed as followed: case 1 = 20%; case 2 = 40%; case 3 = 60%; case 4 = 80%; and case 5 = 100%.

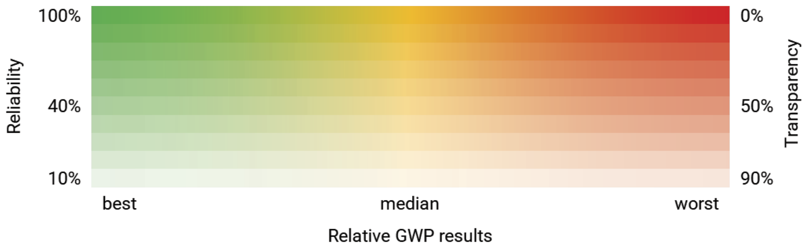

Figure 3. Color coding scheme for visualizing relative & uncertain GWP results.

To combine both information of semantic-related uncertainties and the relative performance of GWP results in the hot spot analysis, a color scheme matrix is established in Figure 3. On the *x*-axis, the relative GWP results according to the normalisation in each classification group is plotted. Generally, the legend of the relative colours ranges from green, representing the best performing variant, to red for the worst preforming variant.

On the *y*-axis, the transparency value for each element t_e is visualized derived by equation 1. For the selection boxes of the element variants and material options, the same color range is used using 0% as transparency.

For the visualisation of the pre-calculated GWP results (according to (Forth et al. 2022)) on whole building and classification group level, box plot benchmarks of a study of 50 buildings by the German Sustainable Building Council (DGNB) are used to compare the correlating box plot GWP results (Braune et al. 2021).

4 CASE STUDY & IMPLEMENTATION

4.1 *Case study project*

To validate the approach using a prototypical implementation, an IFC model of a real-world office building with 1950 m^2 is used as a case study. The matching results and the LCA results have been previously validated (Forth et al. 2023). As the project is located in Germany, the classification follows the standard of German cost groups according to DIN 276 (DIN276 2018). The German database Ökobaudat was used as the materials and elements are named in German language (BBSR 2021). For the element matching the best performing NLP network BERT is used, as previously evaluated in (Forth et al. 2022). The case study model consists of 307 individual elements, which are from 16 different object types. The total surface are of all elements sums up to ca. 5824 m^2.

4.2 *Prototypical implementation*

The prototypical implementation is based on conventional web development tools using HTML, JavaScript and CSS. The web-ifc-viewer library of IFC.JS (Gonzalez Viegas 2022) is used as model viewer, which is a state-of-the-art the open-source toolkit based on JavaScript library three.js for 3D scenes in web browsers (Mrdoob 2022). For the hotspot analysis, every element surface is colored according to its performance relative to the classification group and the mentioned color scheme of Section 3.3.

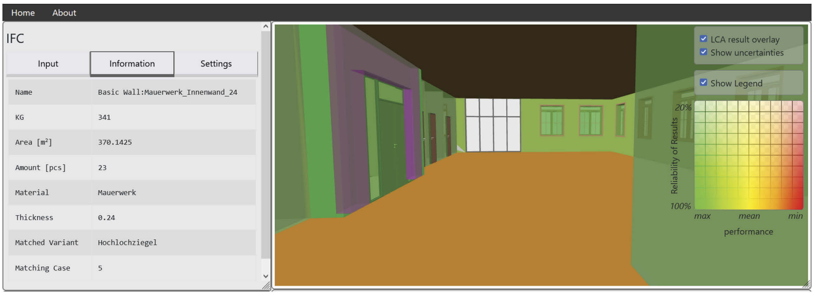

Figure 4. Prototypical implementation of the hot spot analysis using the case study (step 4.a-b).

Figure 4 illustrates the first part of the prototypical implementation using the case study. On the left side, all relevant quantities and semantical information of the selected element are shown (step 1-3), such as classification group (KG), element name, amount of elements of this object type, material name, layer thicknesses, the matched element variant and the matching case. On the right side, the 3D color coded hot spot analysis is applied on the uploaded IFC model using the color scheme and transparency values for showing the matching-related uncertainties (step 4.a). In the following step 4.b, one highlighted element with bad performance is selected to check design variants and optimize its GWP performance.

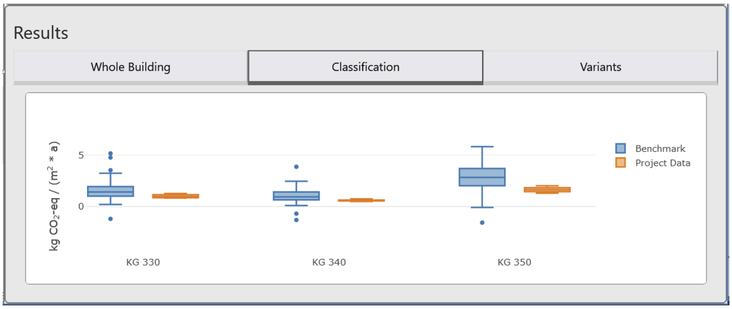

Figure 5. Prototypical implementation of the result on classification group level for comparing to benchmarks (step 4.a).

Figure 5 visualizes the GWP results in [kg CO2-eq./ (m2*a)] of each classification group compared to the DGNB benchmark results ranges (step 4.a). For comparing the GWP results to the DGNB benchmarks, the results are normalized using the net floor area and the reference study period of 50 years. As the DGNB benchmarks include 50 different case studies, the resulting range is wider than the ones of the case study. Nevertheless, a general performance trend of the designed model can be identified intuitively for non-LCA-experts.

In the next step 4.c according to the proposed visualization approach, different element variants (Figure 6) and material options (Figure 7) are visualized. On the left sides, the name of each element variant or material option is color-coded according to its normalized GWP range compared to the other selectable alternatives. On the right side of Figure 6, the box plot diagrams of all element variants are shown. As every material option is connected to one pre-calculated LCA result, it is visualized as a differently colored dot mapped on top the box plot diagram of the selected element variant (Figure 7).

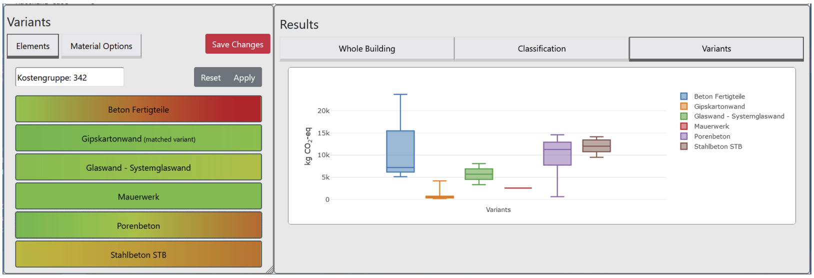

Figure 6. Prototypical implementation of the element variant comparison comparing variants of cost group 342 Non-load-bearing interior walls (step 4.c).

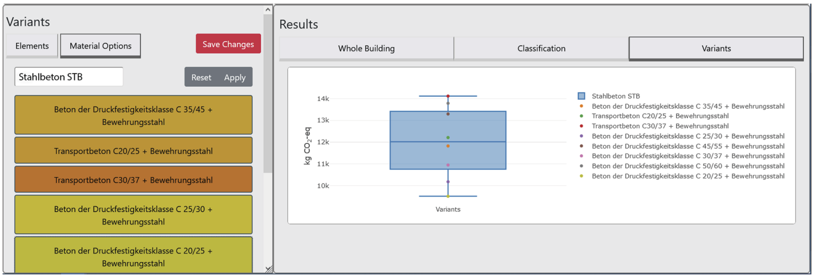

Figure 7. Prototypical implementation of the material option comparison of reinforced concrete (step 4.c).

5 CONCLUSIONS

This paper proposes a comprehensive and transparent approach for design decision making in early design stages in order to optimize embodied GHG emissions of new buildings. With the help of open BIM models and its 3D color coding for the hotspot analysis in combination with box plot diagrams for visualizing uncertain GWP results, an interactive process for non-LCA-experts is introduced.

Based on a previously validated method of NLP-based similarity assessment, this publication uses the results of the automatic element matching, where those elements of the IFC model are matched to the most similar ones in an LCA knowledge databases. The level of element matching and similarity analysis are taken into account for visualizing the uncertainty and reliability of the derived LCA results. Due to missing benchmarks on a level of elements and classification groups, the results are normalized based on the relative performance in each classification group and implemented for the 3D color coding as well as for the element variant and material option selection.

In the future, the proposed methodology will be evaluated by user testing and online surveys. Test users will be asked to assess different features in terms of intuitiveness, acceptance and applicability. The test users will be non-LCA-experts with different professional backgrounds.

To finalize the implementation of the proposed methodology, all relevant information of the Quantitiy Take-Off, Element Matching and LCA calculation will be stored and archived. Furthermore, the last step of the proposed methodology will be implemented using the BIM Collaboration Format (BCF) based on a server solution in order to communicate the feedback of the decision making back to the BIM modeller using authoring software. Thereby, an approach of archiving the design decision including the LCA results and further project information, such as the results of the element matching, needs to be considered.

The proposed methods is a first approach of supporting design decision making in early stages using BIM models and different visualizations, considering uncertainties of LCA results. In a next step, this prototype will be evaluated by non-LCA-experts from practice.

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