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BIM4EarlyLCA: An interactive visualization approach for early design support based on uncertain LCA results using open BIM

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ABSTRACT

To meet the European climate goals in the building sector, a holistic optimization of embodied greenhouse gas (GHG) emissions using the method of life cycle assessments (LCA) are necessary. The early design stages have high impact on the final performance of the buildings and are characterized by high uncertainty due to the lack of information and not yet taken decisions. Furthermore, most current LCA approaches based on Building Information Models (BIM) require high expertise and experience in both BIM and LCA and do not follow an intuitive visualization approach for other stakeholders and non-experts. This paper presents a novel design-decision-making approach for reducing embodied GHG emissions by interactive, model-based visualizations of uncertain LCA results. The proposed workflow is based on open BIM data formats, such as Industry Foundation Classes (IFC) and BIM Collaboration Format (BCF), and is developed for decision support for non-LCA experts in the early design stages. With the help of a user study, the prototypical implementation is tested by 103 participants with different levels of experience in BIM and LCA based on a case study. We evaluate the proposed approach regarding the support of open BIM data formats, different LCA visualization strategies, and the intuitiveness of different approaches to visualizing uncertain LCA results. The user study results show a broad acceptance and need for open BIM data formats and model-based LCA visualization but less for visualizing uncertainties, which needs further research. In conclusion, this interactive, model-based visualization approach using color coding supports non-LCA experts in the design decision-making process in early design stages.

1. Introduction

The AEC industry, which contributes to 40% of the world's greenhouse gas (GHG) emissions, needs to make significant changes to contribute adequately to achieving the global climate goals (United Nations Environment Programme, 2022). Recent studies have shown the increasing importance of embodied environmental impacts (Röck et al., 2020).

Life-cycle assessments (LCA) of the whole building are being used as an established method to evaluate these environmental impacts during the design phase of buildings taking the operational and embodied emissions of buildings into account. Different environmental impact indicators, such as Global Warming Potential (GWP), are assessed, estimating the emitted GHG emissions. This LCA method ensures current national and international regulatory frameworks, for example, LEVEL (s), used to verify EU Taxonomy classification and report ESG conformity (European Commission, 2021).

Schumacher et al. pointed out that Building Information Modeling (BIM) has significant potential for a lossless data exchange, as well as for understandable and user-friendly communication of LCA results (Schumacher et al., 2022). Recent BIM-based approaches partially automate the LCA calculation process and reduce the assessment effort using different strategies (Wastiels and Decuypere, 2019). For automatic semantic enrichment, Sacks et al. highlighted a ”combined, optimal use of topological rule inferencing and machine learning” as a foundational research challenge (Sacks et al., 2020). Fonseca et al. identified BIM-based ”data retrieval and representation based on the needs of nonexperts” (Fonseca Arenas and Shafique, 2023) as a current research gap in the field of BIM-LCA integration.

However, most of the current approaches in the field of BIM-based LCA are either using closed BIM workflows or require a high level of LCA expertise to conduct and interpret the calculated LCA results. Building owners, clients, or project developers, who usually make overall decisions, often do not have the required expertise in LCA and

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are increasingly using open BIM models. Today's decision-making of construction and material choices in industry practice hardly considers environmental impacts. Furthermore, there is high uncertainty in early design phases, arising from the lack of precise information. Current BIM-based LCA approaches do not communicate or visualize these fuzzy results to decision-makers, yet. Most of them are only based on crisp values, and don't use BIM models for visualizing the results. This gap of visualization of environmental impacts in BIM models, including uncertainties of early design stages for non-experts, has not been filled yet (Tam et al., 2022).

The main aim of this publication is to close this gap by proposing a conceptual workflow for interactively visualizing LCA results for design-decision support in early design stages using open BIM models. Different interactive visual strategies, such as model-based color-coding or box-plot diagrams, are supposed to help non-LCA experts to intuitively understand the environmental impact of different design variants and select the preferred option.

In summary, we aim to answer the following three research questions:

1. How can open BIM data formats support the design decision-making process for environmental impacts?
2. Which LCA visualization strategies support non-LCA-experts in the decision-making of elements and material variants in early design stages?
3. How can uncertainties of LCA results in early design stages be intuitively visualized?

To answer them, we first propose a workflow for visualizing LCA results for design decision support based on open BIM Standards, such as Industry Foundation Classes (IFC) and BIM Collaboration Format (BCF). Second, we test different LCA visualization strategies for decision-making and uncertainty visualization by a prototypical implementation. Finally, we test them with a user study to evaluate how they perform for different participants, differentiating, for example, by their LCA experience.

This publication is structured as follows: Section 2 provides an overview of the state-of-the-art of BIM-based LCA for decision-making, feedback communication using open BIM data formats, visualization of LCA results, and uncertainties. Section 3 presents the general research method and an approach for an interactive visualization and design decision support of LCA using open BIM. The proposed workflow is then explained in Section 4.1 and evaluated using a prototypical implementation described in Section 4.2 and a user study using a real-world project as a case study provided in Section 5. Finally, Section 6 provides the overall conclusions and recommendations for future research.

2. Background and related works

This section describes multiple fundamental topics about BIM-based LCA calculation, model-based feedback communication, visualization strategies of LCA results, as well as visualization of uncertainties of LCA results, providing the necessary background for the following sections.

2.1. BIM-based LCA for decision-making in early design stages

The field of LCA using BIM models has been increasing over the last few years. To allow for maximum flexibility in the choice of software employed for the various tasks, it is necessary to use open BIM data formats to enable lossless interoperability between different software tools over the whole design and planning phase of a project, including the early design stages (Borrmann et al., 2018). Industry Foundation Classes (IFC) is an open BIM data format for exchanging semantics-rich geometric building information models. It is developed and maintained by buildingSMART (buildingSMART Technical, 2023a).

Rezaei et al. proposed a BIM-based workflow for LCA calculation using closed BIM and Revit for early and detailed building design stages (Rezaei et al., 2019). They used a Monte Carlo simulation to allocate the uncertainty of materials in the early design stages. Schneider-Marin et al. focus in their approach on uncertainty analysis of LCA using BIM in early design stages (Schneider-Marin et al., 2020). In order to reduce the vagueness and increase the result precision, they use sensitivity analysis as guidance for design teams. However, they did not include material uncertainties in the early design stages. Kamari et al. introduce a BIM-based LCA tool for early design stages (Kamari et al., 2022). Their study showed that critical hotspots can be identified at a low level of detail at an early design stage. However, they did not implement an element-based LCA where the material with the highest contribution can be identified.

Palumbo et al. propose in their study the use of Environmental Product Declarations (EPD) in early design stages for LCA based on BIM models (Palumbo et al., 2020). In their limitation section, they state a lack of harmonized and homogenous formats of EPD schemes and only focus on specific material groups, mainly of the main structure, but excluding the building envelope. Llatas et al. extend their proposed approach to life cycle sustainability analysis (LCSA) to also integrate social life-cycle assessment (sLCA) and use IFC4 schema in early design stages (Llatas et al., 2022). They used Autodesk Dynamo to calculate and visualize the LCSA results. They enriched the IFC properties and attributes using IfcPropertySet. Soust-Verdaguer et al. propose a similar approach of LCSA introducing and validating an "element method" from early to late design stages (Soust-Verdaguer et al., 2022). Although their approach uses element-specific property sets for GWP, costs, and labor effort, their process is performed manually but can be automated with an Application Programming Interface (API).

2.2. Feedback communication

As most approaches are based on closed BIM workflows, not all project stakeholders, such as clients or project developers, are involved in the decision-making process. Conversely, those methods, which are based on open BIM workflow, face the challenge of communicating the decision back to the BIM modeler and into the authoring tool.

One established communication method using open BIM workflows includes the BIM collaboration Format (BCF) (buildingSMART Technical, 2023b). Generally, BCFs help in a BIM-based collaboration project by communicating and solving issues, such as clashes, and work similarly to a ticketing service. BCF is an XML-based file format zipped with other relevant data, such as images. It consists of an issue name with a short text, a viewpoint including a screenshot of the BIM model, a GUID of the selected elements, descriptions, a history of the issue, the recipient of the message (group, person, or craft), a status of information, as well as annotations. The topic details can be directly linked to the BIM model by storing particular viewpoints and the unique identifiers of the related elements (Borrmann et al., 2021). At the time of writing, more than 70 software products implement the XML-based BCF exchange, while almost 30 software products use additionally the server-based BCF API (buildingSMART Technical, 2022).

Horn et al. propose in their method the integration of IFCXML for a bi-directional BIM-LCA integration (Horn et al., 2020). To this end, they enrich the BIM model with raw LCA results, structured by LCA phases and materials, and are linked to the reference data set. Their approach requires a complex setup, which is not applicable in broad, yet.

Zahedi & Petzold introduce a minimized communication protocol specifically for the early design stages (Zahedi and Petzold, 2019). Meng et al. implemented a web-based communication platform for discussing early design stages variants (Meng et al., 2020). Different functions from a defined workflow were implemented using different data formats, such as JSON, IFC, or CSV.

2.3. Visualization of LCA results

Wiberg et al. document the progression of a visual, dynamic, and integrated approach to building LCA in their publication (Wiberg et al., 2019a). They identify various methods of integration utilizing Visual Programming Languages, such as Dynamo and Revit or Rhino and Grasshopper, to address dynamic aspects. Additionally, they categorize other parametric approaches and dashboard implementations that employ Revit models or district models, typically displaying the models without utilizing them to highlight or visualize results. In their subsequent proposal, they put forward a visualization method employing Virtual Reality (VR) to enhance stakeholder engagement (Wiberg et al., 2019b). In this approach, Revit models are employed to apply color coding based on LCA results, and VR is utilized to interact with the model. This is deemed a “good platform for communicating and visualizing complex data […] not only for researchers but also for the general public” (Wiberg et al., 2019b).

Utilizing BIM models to visualize LCA results has demonstrated significant potential (Mousa et al., 2016; Tsikos and Negendahl, 2017; Röck et al., 2018a, 2018b; Naneva, 2022). These approaches primarily employ color coding in authoring tools to represent the final LCA results visually. Kiss and Szalay apply a different visual technique for a detailed analysis of LCA results, utilizing model-based color coding in conjunction with a sunburst diagram to emphasize specific aspects of the results (Kiss and Szalay, 2019). For their implementation, Kiss and Szalay utilize Rhino and Grasshopper.

Miyamoto et al. present a method that suggests incorporating LCA and LCC findings to serve as a foundation for making design decisions (Miyamoto et al., 2022). Despite not utilizing BIM models, they discuss the increasing significance of integrating a spreadsheet approach with BIM workflows, albeit solely focusing on architects.

Hollberg et al. emphasize the importance of considering target users in developing their user-centric LCA tool, specifically for early planning stages (Hollberg et al., 2022). The process involved various stakeholders such as architects, sustainability engineers, consultants, and real-estate developers. However, the visualization of results is limited to fixed outcomes, and there was no provision for active interaction with the model. Nevertheless, we partially use this method for tool development using a case study and a user test, iteratively improving it with stakeholders’ feedback.

In their review regarding the visualization of LCA results, Hollberg et al. provide an assessment of current practices and present a comprehensive overview of various strategies and potentials (Hollberg et al., 2021). The overview clusters different visualization strategies for LCA results according to its LCA goals and amount of information. We use this overview for the selection and development of different visualization strategies.

2.4. Visualization of uncertainties

The consideration of uncertainties in BIM models across varying levels of development has been overlooked for a long time. To address these aspects, Abualdenien and Borrmann (2020) propose multiple methods for visualizing geometric and semantic uncertainties of building elements during early design phases. Among the various approaches, they find that combining color value and transparency to quantify the reliability of semantics resulted in a relatively high level of intuitiveness and acceptance (Abualdenien et al., 2020).

Marsh et al. reviewed uncertainties of LCA for the built environment and the different sources of uncertainties (Marsh et al., 2023). Besides uncertainties due to the Goal & Scope, the Life Cycle Inventory, and the Life Cycle Impact Assessment, they list the data quality assessment, human error, and practitioner knowledge/experience, as well as the comparability of carbon data sources and tools, data availability, unknown material specification at early stages, and time requirement for assessments as barriers.

In addition, Ströbele introduces a fuzzy life cycle assessment (fLCA) approach that accounts for vagueness through distribution curves instead of singular outcomes (Ströbele, 2022). Schneider-Marin et al. establish the EarlyData knowledge database for making material choices during the design stage when detailed information about specific materials is unavailable (Schneider-Marin et al., 2022). This method visualizes semantic uncertainty by assessing a wide range of potential material combinations simultaneously using box plot diagrams to represent the Global Warming Potential (GWP) ranges.

Petrova et al. propose a decision-support framework for sustainable design based on knowledge discovery from diverse building data. They employ various matching mechanisms between project data repositories and Common Data Environments (CDE), including data mining, direct semantic queries, and geometric feature matching (Petrova et al., 2019). The direct semantic queries rely on different ontologies, such as the Building Topology Ontology (BOT) or product-specific ontologies.

In summary, the discussed publications highlight the significance of using BIM models to visualize LCA results and present initial approaches. However, the investigation of integration within an open BIM workflow and the presentation of interactive result exploration are lacking. This reveals a gap in terms of an interactive design decision tool for non-LCA experts based on the open BIM method during early design stages.

3. Method

The approach consists of the following key features:

- Design decision support concept based on IFC models and embodied emission performance
- Feedback communication using BCF for LCA
- Visualization of uncertain LCA results using different strategies

After introducing the method and general workflow, we briefly explain the steps for prototypical implementation before introducing the user study and its case study, set up, and the participants.

3.1. Research method and workflow

This paper aims to develop an approach for an interactive visualization approach for design decision support of embodied GHG emissions using open BIM in early design stages. Therefore, we propose a workflow and evaluate it through a prototypical implementation and a user study. Global Warming Potential (GWP) is used as the only environmental impact category.

We follow the research method of design science research (DSR) according to Pfeffers et al. (Peffers et al., 2012). Doing so, the developed approach represents the artifact supposed to answer the formulated research questions. We prototypically implement this workflow using a case study to evaluate it. The prototype hereby aims to demonstrate the utility and suitability of the artifact while the case study is applied to a real-world situation. Finally, we set up an experiment and a user study for evaluating experts versus non-experts regarding the BIM and LCA experience.

Fig. 1 depicts how the research method is applied to answer these questions by conceiving a workflow (see Section 4.1), providing a prototypical implementation, and performing a user study. The latter is performed to evaluate the prototypical implementation using a case study involving 103 participants. It will be introduced in detail in Section 3.4.1 and 4.2.

The semantic healing process introduced in (Forth et al., 2023a) for the IFC-based LCA calculation process is implemented to answer the first research question related to open BIM data formats. Furthermore, a model viewer for IFC models is implemented and tested, and the BCF server follows open BIM standards of buildingSMART International. Finally, the questionnaire of the user study evidences and supports the

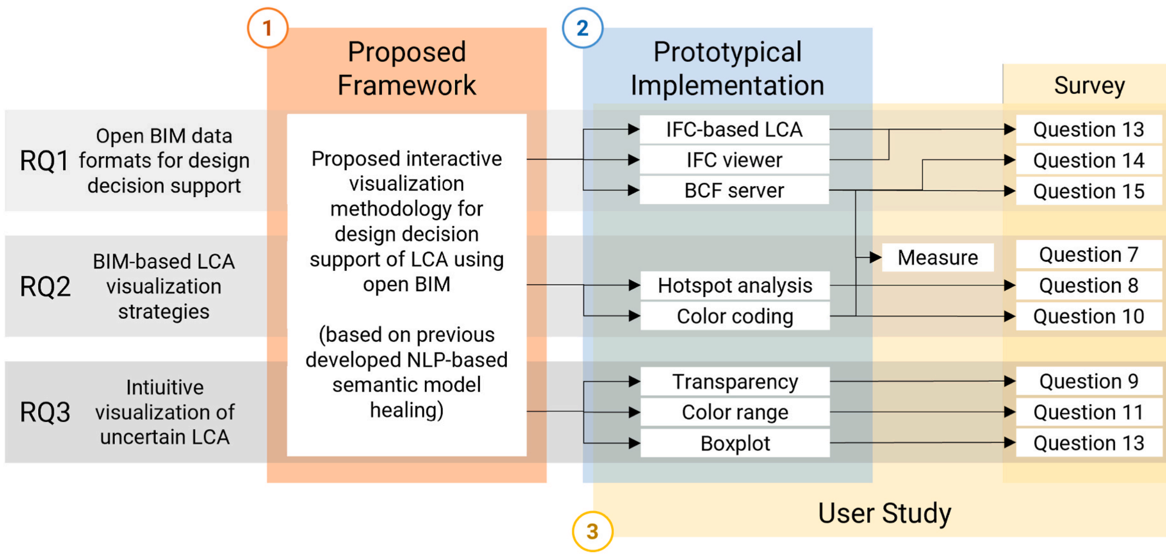

Fig. 1. Research method and general workflow for answering the three main research questions (RQ1-RQ3) by (1) proposing a workflow, (2) prototypical implementation, and (3) user study.

position of the importance of the open BIM workflows and BCF as a standardized communication format.

For the second research question regarding different visualization strategies, we implement three strategies: a model-based color-coding for hotspot analysis, the color-coding of element and material-specific variants, and box plot diagrams of different design variants. Besides measuring the performance of different participants according to GWP reduction and needed time, we evaluate their feedback on these different visualization strategies using questionnaires in the user study.

The third research question is about three different visualization strategies of uncertainties, for which their intuitiveness is evaluated using a questionnaire. The three approaches include using transparency in the model viewer according to the findings of (Abualdenien et al., 2020), gradient color ranges for the different variants and box plot diagrams.

3.2. General workflow for design decision support of LCA using open BIM

The overall structure of the general workflow, illustrated in Fig. 2, comprises four main steps and relies on the LCA knowledge database (LKdb). The LKdb includes the most typical elements based on domain knowledge and comprehensive information required for a holistic LCA, including layer-specific replacement rates, LCI datasets based on Ökobaudat, and any necessary End-of-Life scenarios. Further details regarding the LKdb can be found in (Forth et al., 2023a). The operational part B6 is excluded from the LCA calculation. In terms of the LCA system boundaries, it encompasses the life cycle phases of production (A1-A3), replacement (B4), as well as End-of-Life (C3, C4), and benefits and loads beyond the system boundary (D). More details of the calculation process of the LCA result ranges were previously described in (Forth et al., 2023a).

In the initial stage of the proposed workflow, the BIM model is created using any capable authoring software (step 1.a), followed by the export of the IFC model (step 1.b). The subsequent step involves extracting the quantity take-off and conducting element matching. The quantity take-off entails parsing all geometric and semantic information from the IFC model for LCA calculations. This includes fundamental quantities such as area, amount, layer thicknesses, or length, as well as density, materials, element names, GUIDs, and classifications (step 2.a). The expressions of materials and elements are utilized in the following step to match the IFC elements with the LCA knowledge database (LKdb) (step 2.b), which has been previously introduced and validated (Forth et al., 2022a, 2023a). This matching process relies on Natural Language Processing (NLP) employing a Large Language Model (LLM) to determine cosine similarities between the expressions of elements and materials in the IFC model with those in the LKdb. The most similar LKdb element is assigned to each IFC element. Previously, we identified Google's LLM BERT (Devlin et al.) as the most suitable for this task (Forth et al., 2023a).

Upon completing the element matching step, any missing information regarding LCA datasets, life spans, or absent layers is populated with the datasets of the matched LKdb element. Subsequently, the LCA

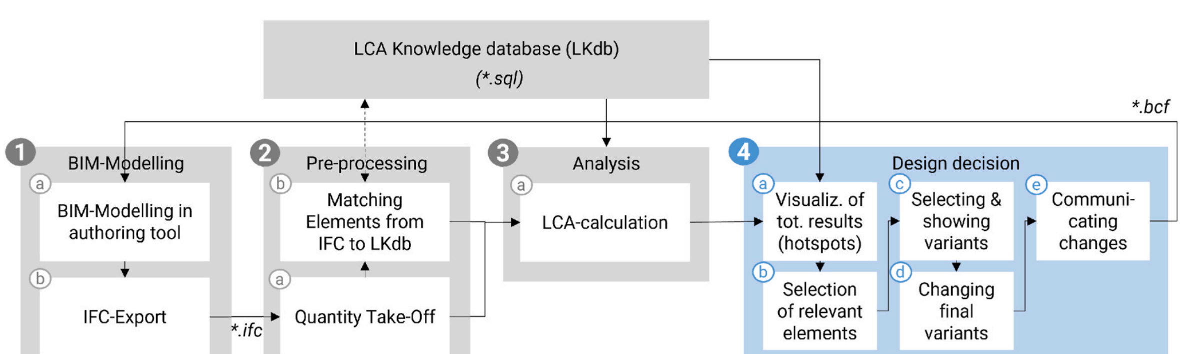

Fig. 2. General workflow for visualizing uncertain embodied GHG emissions for design decision support in early design phases using open BIM.

results are computed, accounting for the uncertainty associated with the element matching (step 3.a). Depending on the level of matching (refer to Section 3.3), a range of material options for each layer of an element is considered, leading to a range of LCA results for both individual components and the entire building.

This publication focuses on the final step of the general process, specifically the design decision process (step 4.a-e). All steps are briefly described to provide an overview. The design decision-making process can be invoked after all LCA information is calculated and assembled. In the first step, 4.a, the results are visualized in the BIM model for hotspot analysis. The median values of the element-specific LCA result range are used to color-code the element in the IFC model in relation to its potential design variants. Next, those elements are selected, which still show optimization potential and can be easily detected using color coding (step 4.b). When one element variant is selected, all potential element variants based on the same classification group and IFC type from the LKdb are shown and highlighted (step 4.c). After all design choices have been made, the final variant has been changed (step 4.d), and the changes are communicated back to the authoring tool (step 4.e). To this end, an extended schema of BCF issues is automatically created and uploaded to the BCF server, as described in more detail in Section 4.2.3.

3.3. Prototypical implementation

As the first part (steps 1–3) have been already previously presented (Forth et al., 2023a), we focus here on the implementation of the proposed decision-making approach. After defining the different steps in the design decision support concept and different visualization strategies, we implement the proposed workflow based on HTML, JavaScript, and CSS and host it on a web server. We run the previous LCA results for the case study, store all relevant information as a JSON file, and upload it with the IFC model into the web tool. The JSON file contains the following information from the previously calculated steps 1–3 from the general approach in Section 3.2:

- IFC model exported either as IFC2x3 or IFC4 from authoring software in step 1.b
- Quantity takeoff including element-specific information on its object type name, IFC type (e.g., IfcWall, IfcWindow), classification group, total surface area in square meters, number of all elements of the same object type and its IDs, layer-specific materials and their thicknesses from step 1.a
- Results of element matching including the level of matching (see cases in Section 4.1.3), most similar matched element, and if existing material options
- LCA results including the total GWP, the results for each layer, and the quantiles of its result distribution in [kg CO2-eq.]
- Potential element variants based on the same classification group and IFC type from LKdb including for each element variant the element name, its layer-specific, total GWP results, and the quantiles of its result distribution in [kg CO2-eq.]

To integrate the design decisions into the current BCF version, there are two options, either as BIM snippets, which are usually partial IFC files or by extending the BCF schema. We consider the second option, as for now, we only use this communication to send and store all created topics of the user study's design changes on a BCF server. After the first implementation round, we iterate and improve the tool with the first test candidates. Next, we host the prototypical design decision tool on a website, integrating it with an introductory video and the survey of the user study.

3.4. User study

The user study evaluates the prototypical implementation by setting up an experiment for testing the prototype by participants who fill out a survey. In the following section, we first briefly introduce the chosen case study, explain the overall setup of the user study, and lastly, the participants and survey.

3.4.1. Case study project

We validate the proposed workflow and prototypical implementation by applying it to a case study. To this end, an IFC model of an office building measuring 1950 m^2 is used. The matching results and LCA outcomes have undergone previous validation (Forth et al., 2023a). Given that the project is situated in Germany, the classification adheres to the German cost groups as per DIN 276 standard (DIN 276). The Ökobaudat database, which contains materials and elements named in German, is utilized for this purpose (BBSR, 2021). The NLP network BERT is employed for element matching, as previously assessed in (Forth et al., 2022a). The case study model encompasses 307 individual elements originating from 16 distinct object types. The cumulative surface area of all elements amounts to approximately 5824 m^2.

The LCA Knowledge database (LKdb) was introduced in detail in (Forth et al., 2022a, 2023a). When setting up the datasets for this case study, we considered 137 of the most conventional construction elements across all classification groups. These elements mainly consist of different element layers, which add up to 223 different element layers. In total, there are 127 different material categories, which add up to 343 different classification-specific material categories. The material options are directly connected to Ökobaudat (BBSR, 2021), which we manually enriched to 1000 different classification-specific material options according to its potentially related element layers.

3.4.2. Set up of user study

To run the user study using the prototypical implementation, we set up a website server which hosts the user study itself and a BCF server storing the BCF issues and viewpoints. The user study itself is divided into three parts:

1. Introduction: following an explanation video (ca. 5 min)
2. Experiment: testing the prototype with the help of a case study by changing at least three different elements and/or material choices (ca. 3–5 min)
3. Survey: filling out the final questionnaire (ca. 4 min)

The user study aims to investigate an interactive decision-making process for element and material variants with regard to embodied emissions using the open BIM method in early design phases. Different stakeholders from the building and planning sector with and without experience with BIM and/or LCA have been surveyed.

The questionnaire considers the current Human-Computer-Interaction (HCI) standards following the guidelines of Lazar et al. (2017). The overview of all survey questions can be found in the Appendix B.2.

3.4.3. Participants

The participants have been directly notified about the survey with the link to the website via e-mails, chat groups, and LinkedIn posts of the authors' networks. Furthermore, we contacted participants from executive education programs in BIM, expert groups about "BIM and sustainability" of buildingSMART Germany and the German Sustainable Building Council (DGNB), and research contacts from the IEA EBC Annex 72 project. Additionally, the survey link has been shared via LinkedIn and presented at different scientific and industry conferences, for example, the working group sustainability of BIM Allianz e.V., the buildingSMART Germany User's Day, and the International Symposium on Life-Cycle Civil Engineering in Milan, Italy. The website with the survey was public so that every interested person could participate. There has been no selection or filtering process.

In total, 103 participants took part in the user study and the survey.

Most of the participants (81%) are from Germany, while the rest of the participants work in other European countries, such as Switzerland (4), Denmark (4), Austria (3), Spain (2), and Czech Republic (2). One participant each originated from Belgium, Italy, Netherlands, Poland, Sweden, and Turkey. Most of the participants work in research (27%), as planners (26%), such as architects, structural engineers, HVAC engineers, or similar, and as sustainability experts, buildings physicists, or energy consultants (25%). The rest is working as project developers and clients (15%), while only a few have a professional background in BIM Management (5%) and IT or software (2%).

In Figs. 3 and 4, the distribution of the user study participants and their profession is shown along with their BIM experience (Fig. 3) and LCA experience (Fig. 4). While the BIM experience is distributed almost equally amongst all professions, the LCA experience of sustainability experts is significantly higher than in other professions. Furthermore, project developers and clients seem to have the least LCA experience.

Figure B.22 in the Appendix shows a high correlation between those participants who have good experience with LCA to BIM-LCA experience (in total 58%) and vice-versa of those who only have little experience having no prior BIM-LCA-experience (in total 42%). This means most LCA-experienced participants already used BIM, while there is no correlation between BIM experience and BIM-based LCA experience.

4. Proposed workflow and implementation

In this Section, we first briefly introduce the proposed workflow, focusing on the design decision support concept and the selection of different visualization strategies of LCA and uncertainties. Afterward, we describe the prototypical implementation of the model viewer for hotspot analysis, the variant selection and visualization, and the feedback communication using an extended BCF schema.

4.1. Proposed workflow

The motivation of the proposed workflow is to assist stakeholders without expertise in LCA and/or BIM in making decisions related to construction-element and material-related variants in the early design stages. First, we describe the more detailed developed design decision support concept in Section 4.1.1. Based on this concept, we discuss and introduce different visualization strategies for LCA results in Section 4.1.2. Finally, we further develop these strategies incorporating uncertainty visualization in Section 4.1.3.

4.1.1. Design decision support concept

The design decision process is generally divided into five steps, as depicted in Fig. 5.

First (A), the IFC models must be loaded into the interactive decision-making platform. Based on this model and the previously proposed LCA Knowledge database (LKdb), the LCA results are calculated based on the IFC-based quantity takeoff and the NLP-based element matching according to (Forth et al., 2023a). All this information is preprocessed and precalculated.

Next, the LCA results are presented using a model viewer and the BIM-based 3D color coding, which will be described in more detail in Section 4.1.3. According to the project LCA results, the worst-performing elements can easily be highlighted using the color-coded model as a hotspot analysis (B.i). The color of each model's element is calculated according to the LCA results of the NLP-matched element variant of the previous process and normalized according to all other element variants of the same classification group and IFC type. In the future, once benchmarks become available at the level of classification groups, e.g., according to DIN 276, the colors can be normalized based on these benchmarks. In the next step (B.ii), the user selects those elements in the model interactively to check design variants on element and material levels and thereby optimize the overall and element-specific LCA performance.

Once one element is selected, the element-specific input information and all relevant element variants of the same classification group and IFC type are shown according to the LKdb. In step, C.i, the element variants and their LCA results are depicted using heat maps with gradient color ranges. According to the compared variants in the heatmap, those selected element variants are also shown as box plot diagrams in C.ii.

If one element variant suits the user, the design decision process continues on a material level (D). All layer-specific material options of this selected element are compared using heat maps (D.i). As those elements can consist of multiple layers, all possible combinations of layer-specific material options are displayed. According to the previous design-decision level, the selected material options of the heat maps are also plotted on top of the selected element's box plot diagram, showing the specific LCA results of each material combination (D.ii).

In the next step, E.i, when the element variant and material option are decided and changed, the user can start over by selecting the next element in the model viewer, iterating the process C.i-D.ii until satisfaction. Finally, after all design decisions are submitted (E.ii). These changes are communicated back to the authoring tool and BIM modeler using the BIM Collaboration Format (BCF). Therefore, BCF issues and viewpoints are created for each design change according to the workflow's step 4.e.

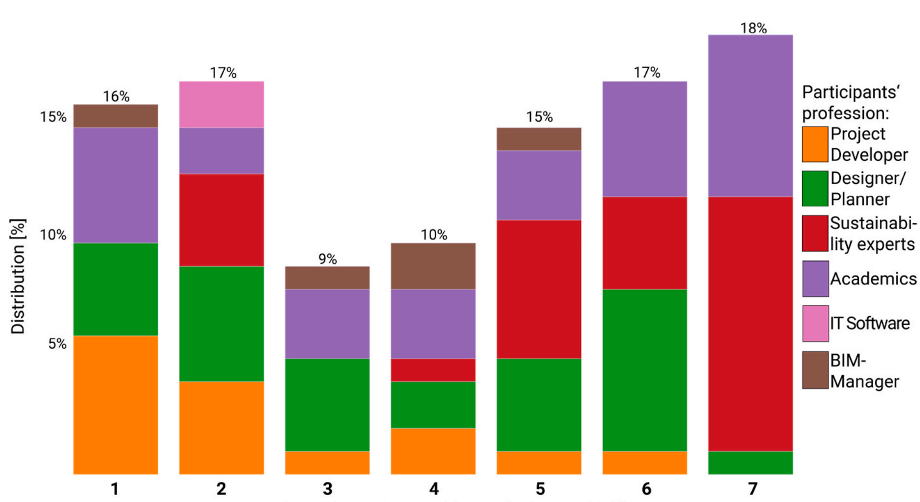

Fig. 3. Profession of the user study participants in relation to their LCA experience.

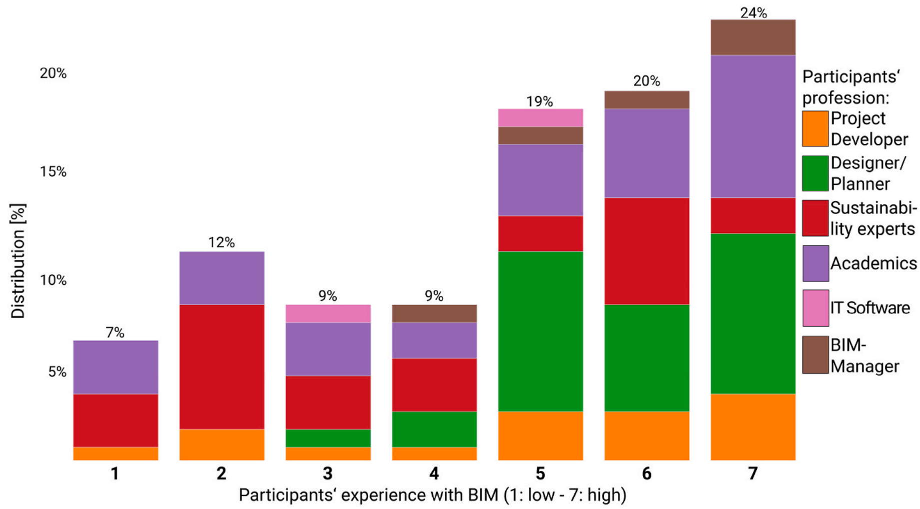

Fig. 4. Profession of the user study participants in relation to their BIM experience.

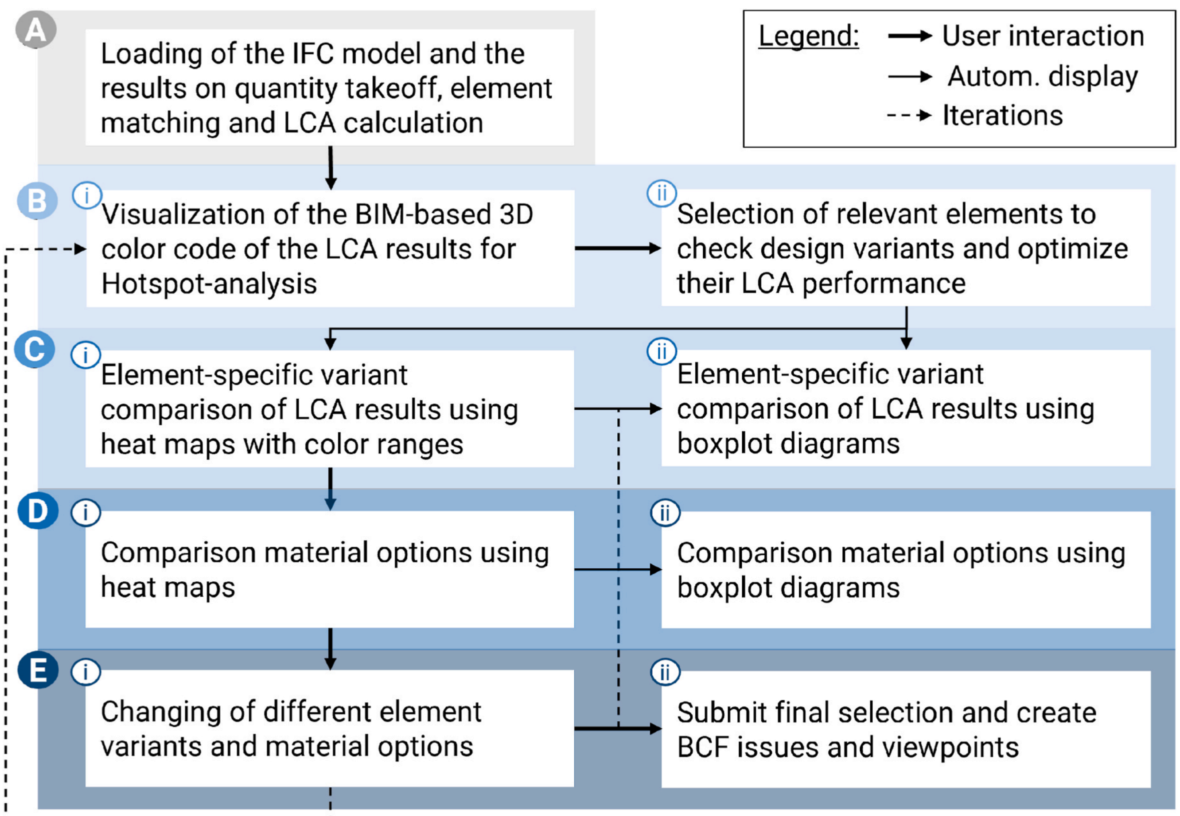

Fig. 5. Concept of design decision-making based on LCA results using BIM models and different visualization strategies.

4.1.2. *Visualization strategies for LCA results*

To support decision-makers during the early stages of design, a set of hierarchical visualization objectives, based on the work of (Hollberg et al., 2021), is proposed. To identify hotspot elements that require design optimization, the recommended visualization type is the 3D color code, which can be implemented using open BIM models (see Fig. 5).

The previously described goals include identifying hotspots, comparing design options, and visualizing uncertainties. The overview of our selection of visualization strategies for LCA results is shown in the upper part of Fig. 6. On the bottom part, the adaptation of these visualization strategies incorporating uncertainties is shown, which will be described in more detail in Section 4.1.3.

To communicate the LCA results intuitively for non-LCA-experts, we use BIM models, including color coding for visualization, which is also suitable for identifying hotspots. We propose heat maps to compare different design options and identify element variant hotspots simultaneously. As the third LCA visualization strategy, we choose the conventional approach of bar charts. However, when incorporating uncertainty information, we change them to box plot diagrams, which were already used in the previous study regarding this workflow (Forth et al., 2023a). Therefore, we are proposing to test the following three LCA hotspot and uncertainty visualization strategies:

I. Model-based 3D color code

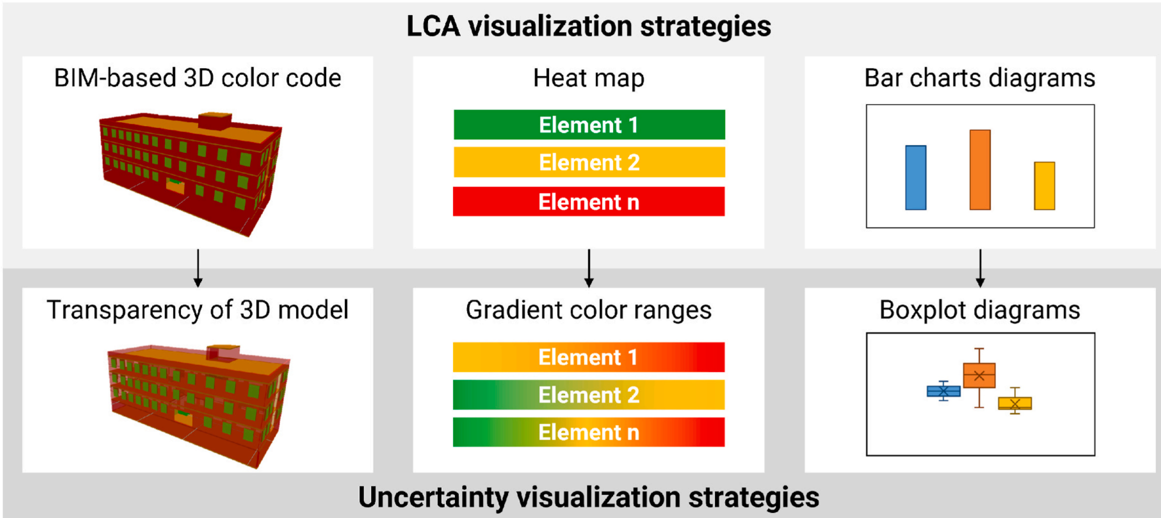

Fig. 6. Visualization strategies of visualizing LCA hotspots as well as uncertainty.

II. Heat maps
III. Box plot diagrams

4.1.3. Visualization strategies of semantic uncertainties

Marsh et al. mentioned several sources of uncertainty in building LCAs (Marsh et al., 2023). Our proposed workflow considers the time requirements for LCA and human error and practitioner knowledge by calculating the results automatically based on a LCA Knowledge database. Therefore, our approach mainly focuses on the unknown material specifications in the early stages as a source of uncertainty.

The previous study (Forth et al., 2023a) has identified significant aspects considered in the analysis. First, the cosine similarity of the matching performance indicates the degree of resemblance upon which the matching is founded. Second, various scenarios exist regarding how the elements are matched from the IFC model to the LKdb, as outlined in the following enumeration.

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

The varying scenarios give rise to distinct levels of reliability in the obtained LCA results. Consequently, accounting for this information is imperative when visualizing semantic-related uncertainties.

As mentioned, Abualdenien et al. have previously concluded that combining color value and transparency in an element provides a highly intuitive and accepted means of visualizing semantic reliability (Abualdenien et al., 2020). Therefore, the transparency value for each element t_e is determined using 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., 2023a)). The values of the above-mentioned five matching cases for each element c_e are distributed as follows: case 1 = 20%; case 2 = 40%; case 3 = 60%; case 4 = 80%; and case 5 = 100%.

To incorporate both, the information regarding semantic-related uncertainties and the relative performance of GWP results, in the hot spot analysis, a color scheme matrix is introduced considering the gradient color range and transparency in Fig. 7. The x-axis of the matrix represents the relative GWP results obtained through normalization within each classification group. The legend associated with the relative colors spans from green, representing the best-performing variant, to red, indicating the worst-performing variant. This gradient color range has been widely established and used in other research projects (Mousa et al., 2016; Tsikos and Negendahl, 2017; Röck et al., 2018a; Kiss and Szalay, 2019; Naneva, 2022).

On the y-axis, the transparency value corresponding to each element t_e is visualized, as determined by Equation (1). Regarding the selection boxes of element variants and material options, the same gradient color range is employed, with 0%

As described in Section 2.4, the form of box plot diagrams is the most used form of visualizing uncertain LCA results. Furthermore, in a previous study, we also proposed to visualize the comparing the total and classification group-specific results to box plot benchmarks (Forth et al., 2023b). These benchmarks are based on a study of 50 buildings by the German Sustainable Building Council (DGNB) and are used to compare the correlating box plot GWP results (Braune et al.). Nevertheless, in this paper, we left this feature out, as the calculation procedure and data of these benchmarks are not transparently available, and there is still a lack

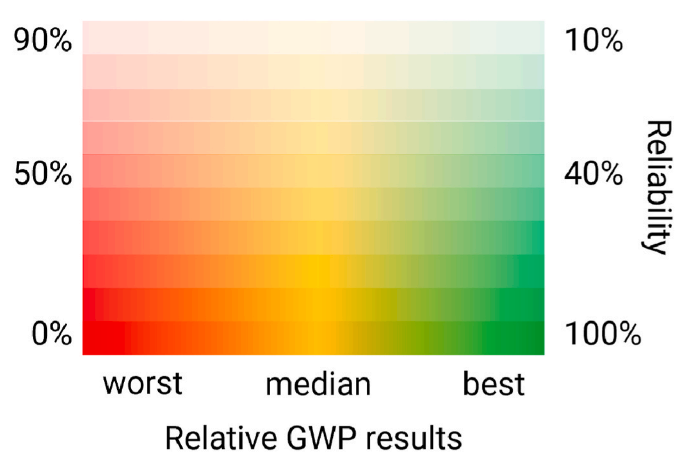

Fig. 7. Color coding scheme for visualizing relative & uncertain GWP results. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

of representative benchmarks, especially in Germany, as described in more detail in (Forth et al., 2022b).

4.2. Prototypical implementation

In this Subsection, we describe the prototypical implementation, first focusing on the model viewer for hotspot analysis, followed by the element variants and material options, the variant selection and visualization part, and concluding with describing the feedback communication using BCF. Fig. 8 shows a screenshot of the interface of the prototypical implementation.

4.2.1. Model viewer for hotspot analysis

The prototypical implementation is based on established web development tools using HTML, JavaScript, and CSS. The web-ifc-viewer library of IFC.JS (González Viegas, 2022) is used for implementing the model viewing feature, which is a state-of-the-art 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 4.1.3. Depending on which variant is selected, the coloring is applied interactively and iteratively updated based on Node.js.

On the top left side of Fig. 8, all relevant quantities and semantical information of the selected element are shown, 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 for step B.i. In the following step, B.ii, one highlighted element with insufficient performance is selected to check design variants and optimize its GWP performance.

4.2.2. Element variant and material option visualization

In the next step, C.i, different element variants, and material options are visualized according to the proposed visualization strategies II and III. On the bottom left side of Fig. 8, the name of each element variant is colored according to the range of its normalized results. The normalization considers the maximum and minimum GWP results for each classification group and its LKdb-based element variants. Visualization strategy III using box plot diagrams is used on the bottom right. The results are shown on the right if the user selects multiple element variants on the left side. In case the selected element variant is sufficient, the user needs to manually apply the selection, which automatically updates the colors in the model viewer, creates a screenshot and viewpoints, and uploads all relevant BCF issues to the BCF server.

The material option tab can be selected if one selected element is detailed further. All relevant layers and material options for this element variant are color-coded according to its normalized GWP performance of the classification group, as previously described for the element-specific gradient color ranges. As every material option is connected to one precalculated LCA result, it is visualized as a differently colored dot mapped on top of the element-specific box plot diagram of the selected element variant as shown in Figure A.18 in Appendix A.1.

4.2.3. Feedback communication using BCF API

As described in Section 2.2, BIM collaboration format (BCF) is a data format for communicating and solving issues in an open BIM workflow. In Section 3.3, we discussed not using BIM snippets but extending the current BCF format, consisting of a BCF topic and its related viewpoint, including a camera perspective and a snapshot.

As shown in Fig. 9, the BCF extension "lcaSelection" consists of the selected object type as Identifier, the selected element variant, the selected material option, the time passed between selecting the object type in the model viewer and the finally applied selection, a counter storing in which order the issue has been created, the IFC Type, all IFC IDs and finally the overall ID.

For implementing the feedback communication of the selected element and material variants, we use the BCF API by buildingSMART International (GitHub, 2023). For the server hosting, we use MongoDB (MongoDB, 2023).

After selecting the chosen element variant or material option, the button "Apply" temporarily holds all relevant information, according to the extended BCF schema in Fig. 9. In the same step, the viewpoint of the model viewer is created, including the camera perspective and a snapshot. The snapshot is stored as binary code, so it can be transferred back to images, as shown in Appendix B.3. Finally, by clicking the button

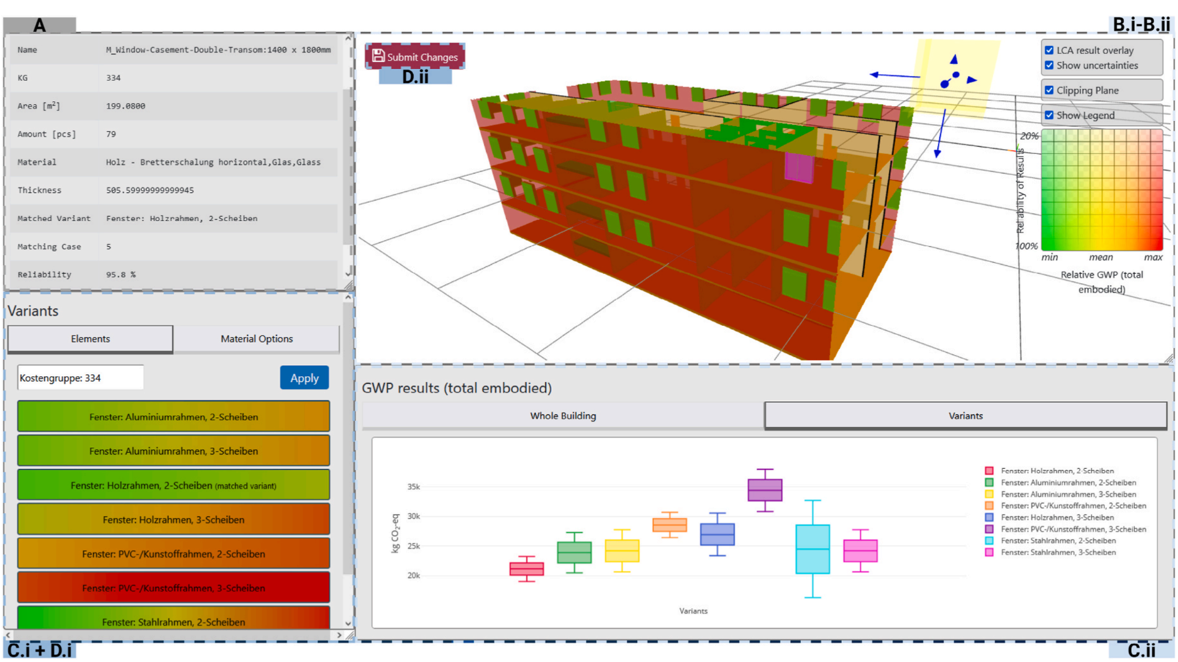

Fig. 8. Prototypical implementation of the interface according to the proposed workflow from Section 3.2.

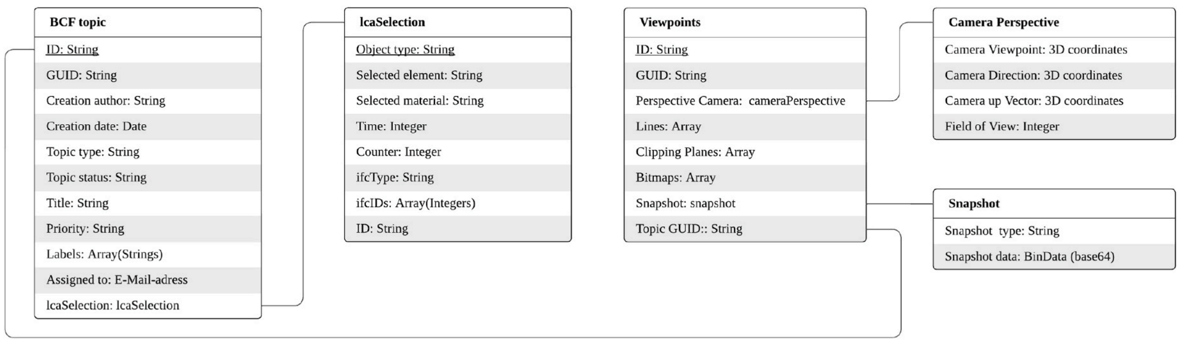

Fig. 9. BCF topic and viewpoint schema and extension for LCA-related element and material selection.

"Submit changes", all previously applied topics are pushed to the BCF server and are stored according to the extended schema.

5. Evaluation of the user study results

In this Section, we first evaluate the overall approach by quantitatively analyzing the general feedback of the participant and the measured data of their decision-making process. Next, we analyze their feedback on the topics of the three research questions in more detail about the open BIM data formats, the LCA visualization strategies, and the uncertainty visualization by analyzing the outcomes of the user study and qualitatively evaluating it according to the research questions. Finally, the limitations of the approach, implementation, and user study are discussed.

5.1. Quantitative evaluation of the overall approach

First, we analyze the general participants' feedback on the question of how difficult (score 1) or easy (score 7) the participants rate the whole design-decision process. Afterward, we analyze the measured results on the decision-making process focusing on the GWP optimization results and the timing of their decisions.

The overall average score of 5.12 out of a maximum of 7 score points, which means the majority find the overall procedure relatively easy. Fig. 10 shows the results in relation to their LCA experience, represented by the color of their LCA-experience score (1–7). Generally, a majority of 69% found the proposed workflow and the prototype of the whole design decision process rather easy, with almost a quarter scoring it as "very easy" (23%). Furthermore, no significant correlation is determinable between the participants' overall feedback and their LCA experience. Almost equally, LCA experts and non-LCA experts were rating all scores about the overall process feedback.

Fig. 11 and Fig. 12 show the measurement results of the participants' decision-making process in each two subfigures to analyze the difference between experts and non-experts. Generally, Subfigure 11 (a) only indicates a minor difference in relation to the participants' LCA experience, comparing the relative optimization of the final GWP results compared to the initial one. On average, those with the lowest LCA experience have slightly worse GWP optimization performances (ca. 70%) compared to those with high LCA expertise (ca. 80%). Nevertheless, the lower quartile of the box plot diagram of the lowest LCA experienced participants (around −10%), and the whiskers show less variance for the performance of the participant with high LCA experience.

Subfigure 11 (b) shows the average timesteps of each participant's decision-making in relation to their LCA experience, which is, on average, between 15 and 30 s. The box plot diagram shows no significant difference in the average time steps across all LCA experiences. This indicates the intuitiveness and overall acceptance of all participants independent of their previous expertise in LCA.

A more significant difference between experts and non-experts can be identified when considering the BIM-LCA experience, as shown in Subfigure 12 (a). While participants with no previous BIM-LCA knowledge have a lower median (ca. 65%) and lower quartile (ca. 10%) compared to the performance of the participants with previous BIM-LCA experience, which a median higher than 80% and the lower quartile around 60%.

When focusing on Subfigure 12 (b), no significant difference between those participants with prior BIM-LCA experience and those without can be detected. The average of both groups is around 18 s, while the upper quartile of the experienced participant is slightly higher.

Putting the described results in context with the correlation between

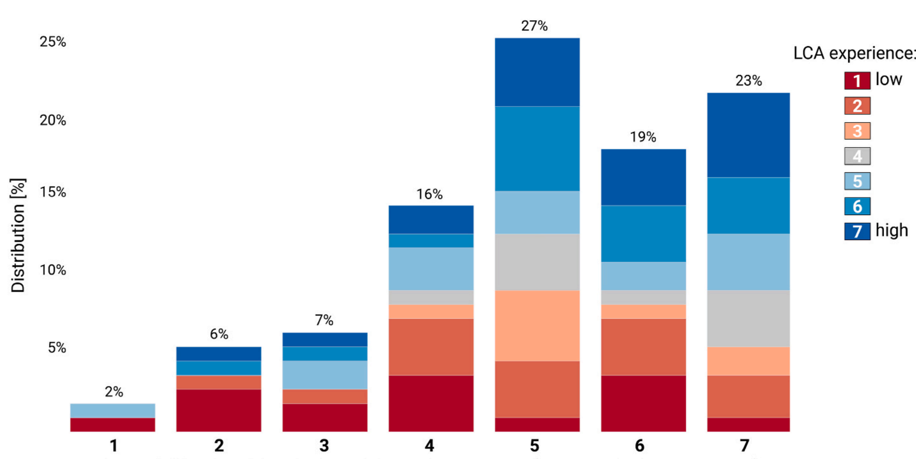

Fig. 10. Overall feedback on the difficulty of the whole decision-making process in relation to the participants' LCA experience.

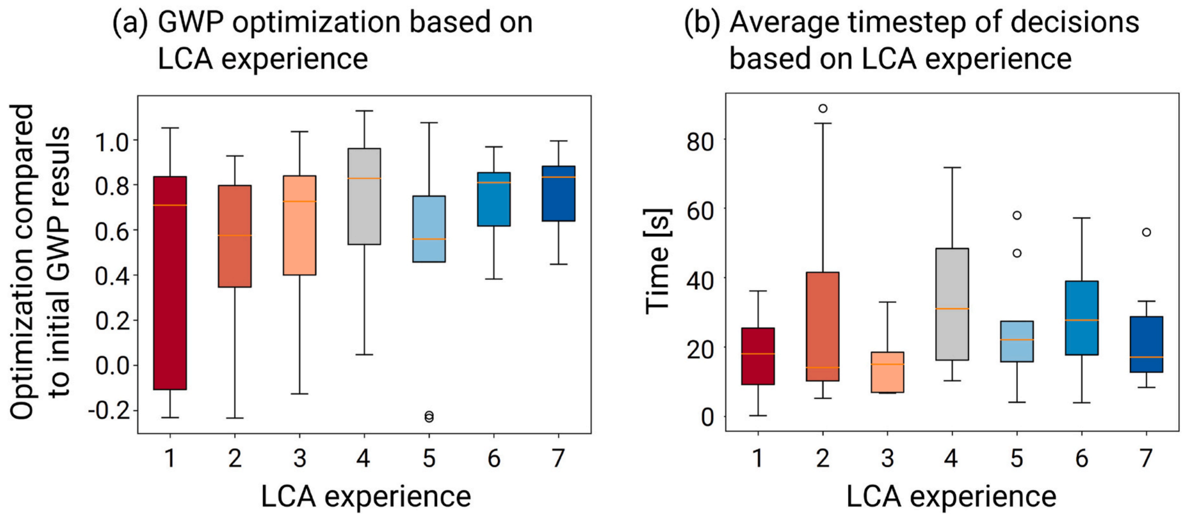

Fig. 11. Measurement of resulting GWP optimization (a) and timestep (b) of participants' decision-making in dependency with LCA experience.

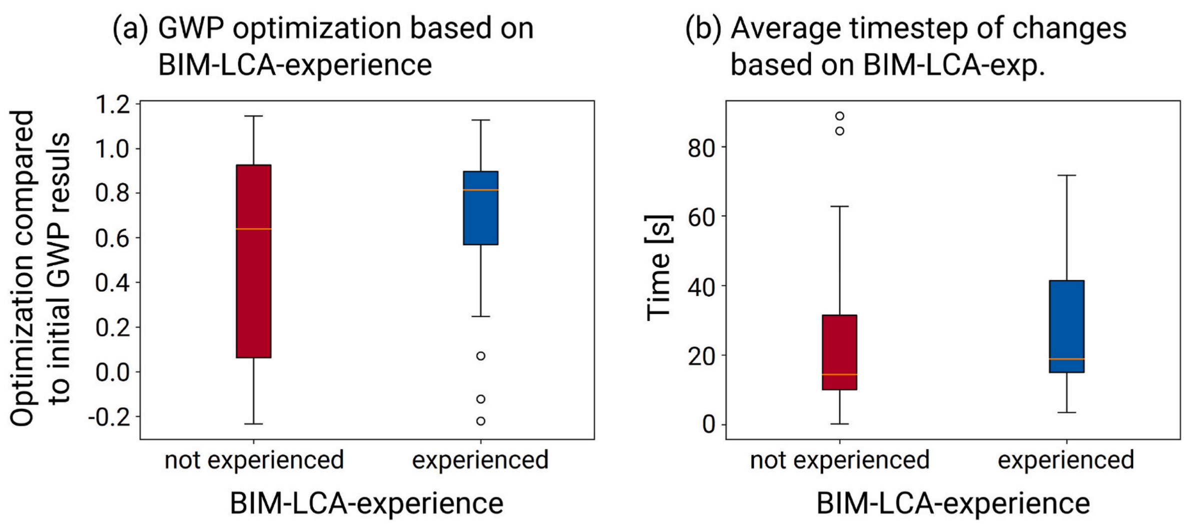

Fig. 12. Measurement of resulting GWP optimization (a) and timestep (b) of participants' decision-making in dependency with BIM-LCA experience.

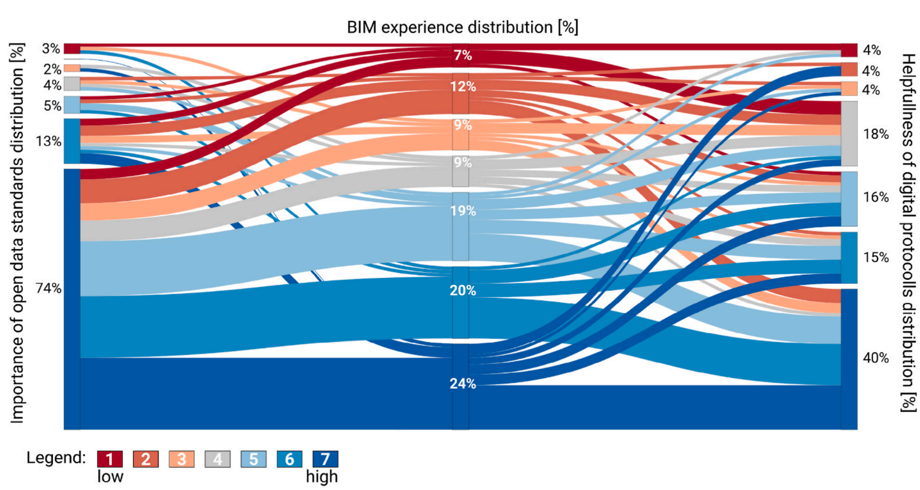

Fig. 13. Distribution of participants' BIM experience in correlation to their opinion on the importance of open BIM standards (left), and on the helpfulness of digital collaboration protocols (right).

LCA experience and BIM-LCA experience indicates that those participants with little LCA experience mostly have no prior BIM-LCA experience, showing the lowest GWP optimization performances. Considering the results from Subfigure 11 (a), already a little LCA experience (score 2) leads to a marginal difference in the optimization performance compared to participants with more or even high LCA experience.

5.2. Qualitative evaluation of open BIM data formats

First, we evaluate the participants' feedback on open BIM data formats before discussing the prototypical implementation to answer the first research question and evaluate the suitability and utility of the proposed workflow. We consider IFC and BCF as open BIM data formats.

In Fig. 13, the results of the participant's feedback on the importance of open BIM data formats (Question 14) and the support of the automatic creation of digital collaboration protocols are shown (question 16). 74% of the participants, independent of their BIM expertise, are considering open data standards of the BIM method (e.g., IFC models) for LCA as "very important", while only a small minority of 5% find it rather unimportant. On the right side of Fig. 13, the correlation between BIM experience and the helpfulness of digital communication protocols is shown. A significant correlation between participants with high BIM experience and helpfulness can be determined (40% for "very helpful"). In contrast, those with little BIM experience tend to find it not helpful at all (4%) or have a neutral perspective on this topic (in total 18%).

This trend becomes even more apparent when correlating participants familiar with the BIM Collaboration Format (BCF), as shown in Fig. 14. First, a clear correlation between BIM-experienced participants and their knowledge of BCF can be identified on the left side of the figure. More than 80% of those participants with more than average BIM experience know BCF for BIM-based issue management. Most participants with BCF knowledge also find that the implemented digital communication protocol from the prototypical implementation is helpful (ca. 80%), as shown on the right side of Fig. 14.

The suitability of IFC for semantic model healing and integration in the LCA calculation process in early design stages has already been successfully evaluated in a previous publication (Forth et al., 2023a). The IFC data format was successfully used to visualize the case study in a model viewer and integrate it into the design decision-making process. In Section 5.3, we analyze in more detail the support of color-coded BIM models for decision-making.

The second open BIM data format considers BCF. As shown in Figure A.19 from Appendix A.2, the proposed extension according to Section 4.2.3 is successfully implemented using buildingSMART's BCF API (GitHub, 2023) and setup on mongoDB (MongoDB, 2023). After implementation, it is used in the user study for storing all issues for each design change of each participant. All necessary information is automatically stored as topics and viewpoints on the server and accessed afterward for evaluation. In total, 272 issues were created and later accessed to further assess the results. The snapshots of the viewpoints are stored as binary code using base64, which can be later transferred back to image data in PNG format. Appendix B.3 shows a representative overview of most of the snapshots.

To answer the first research question, open BIM data formats support the design decision-making process considering environmental impacts by automating the LCA calculation process using IFC for semantic model healing, visualizing LCA results interactively in an IFC model viewer, and communicating the design decision back to the designer or BIM modeler via an extended BCF schema.

5.3. Qualitative evaluation of LCA-visualization strategies for decision-making of non-experts

The decision-making of non-LCA-experts vs. LCA experts is first evaluated by the survey of the different LCA visualization strategies and afterward by tracking the improvement towards GWP that the participants achieved.

Fig. 15 shows the distribution of the participants' LCA experience in correlation to their support of color-coded 3D-BIM models and the support of color-coded heat maps. The left side indicates that most of the participants, independent of their LCA experience, find the colored 3D model for LCA optimization potential very helpful (44%) or more than average helpful (20% with a score of 6 and 17% with a score of 5).

A similar trend can be identified with the visualization strategy of color-coded heat maps of the element variants and material options. While only 11% of the participants tend to find this visualization strategy less helpful, the majority of around 78% find it more than average helpful. A clear correlation or dependency between the LCA experience and visualization strategy can not be identified.

Fig. 16 presents the results on the question of how well the box plot diagrams of the LCA results helped the participants make decisions concerning their LCA experience. The average of the results is 5.11 out of a maximum of 7 points, which indicates that they found box plot diagrams rather helpful, with a tendency to a neutral middle. Only a minority of 20% rather disagreed, while generally, most of those responses were from less LCA-experienced stakeholders. Most who voted for the highest score have high or very high LCA experience.

These results generally indicate that these chosen visualization strategies I and II found high acceptance across all LCA experience levels of the participants. The results on LCA visualization strategy III indicate

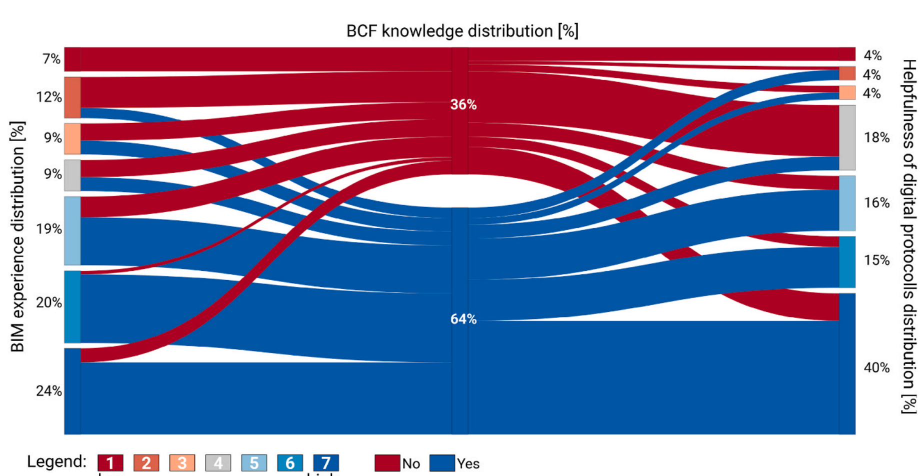

Fig. 14. Distribution of participants' knowledge of BCF format, in correlation with their BIM experience (left), and on the helpfulness of digital collaboration protocols (right).

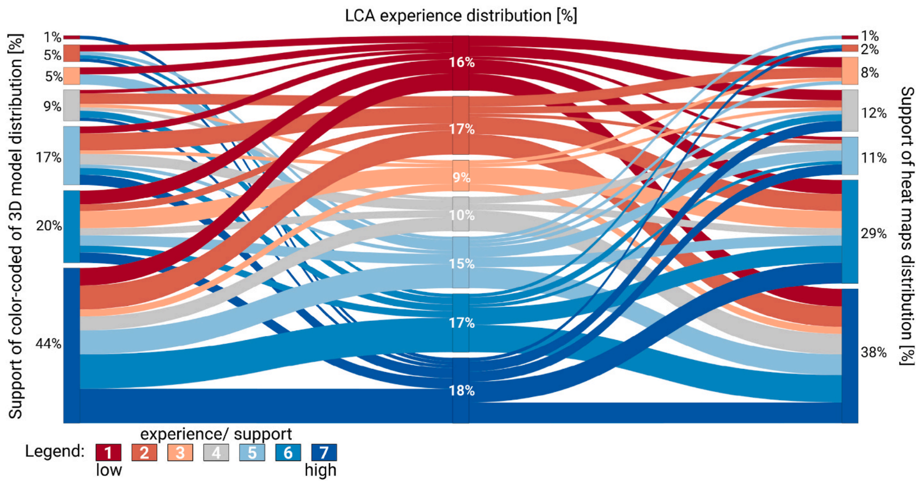

Fig. 15. Distribution of participants' LCA experience in correlation to their support of color-coded 3D models (left), and on the support of heat maps (right). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

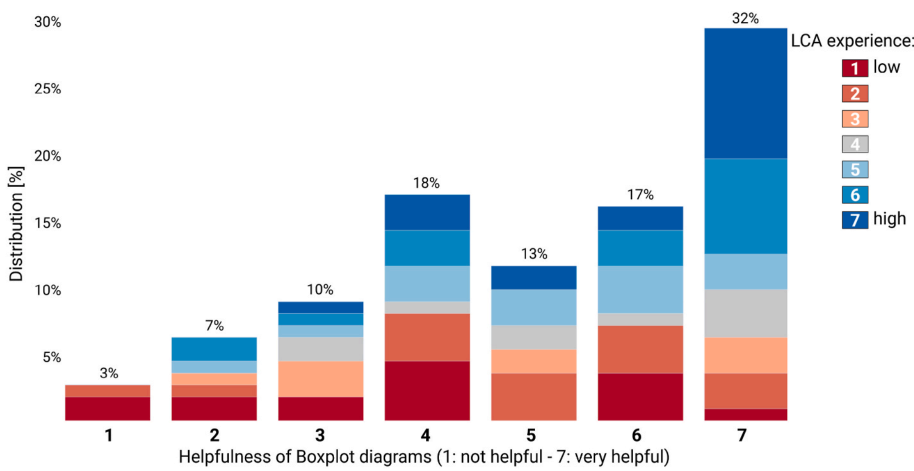

Fig. 16. Helpfulness of the box plot diagrams in relation to the participants LCA experience.

a tendency for box plots as a visualization strategy for more advanced LCA experts and, therefore, also for visualizing uncertain LCA results.

5.4. *Qualitative evaluation of decision-making based on uncertain LCA results*

In Fig. 17, the correlation between the participants' LCA experience

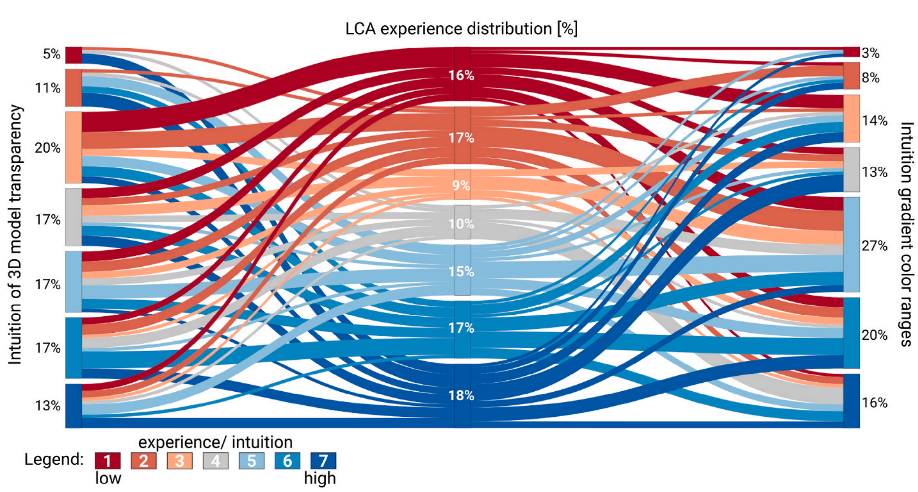

Fig. 17. LCA experience (middle) in correlation to the intuition of uncertainty visualization considering 3D model transparency (left) and gradient color range heat maps (right). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

and their rating on how intuitive the uncertainty visualization of model transparency (left) and gradient coloring (right) is shown. The average score of the transparency intuition is 4.34, and of the gradient coloring, 4.77 out of a maximum of 7, so rather a neutral score. Focusing on transparency, only an overall minority of 47% found it rather intuitive, only 13% "very intuitive", and 36% rather unintuitive. These results were also independent of the participants' LCA experience. The gradient coloring for uncertainty visualization seems to have better results than the model-based transparency. A majority of 63% of the participants found it rather intuitive, with only 25% rather unintuitive. No clear correlation between LCA experience and intuition can be identified here.

The third uncertainty visualization strategy is already analyzed together with the other LCA visualization strategies in Section 5.4. In general, it can be stated that these results indicate significant support for box plots for the majority of the stakeholders.

In summary, the highest average scores of uncertainty visualization strategies could be found in the box plot diagrams, but rather for participants with higher LCA experience. Furthermore, a majority of more than 60% of the participants found the gradient coloring and the box plot intuitive and helpful in showing uncertain results. The model-based transparency showed relatively neutral results, independently of the participants' LCA experience. Several participants commented in the written feedback section about the intuitiveness of the transparency visualization.

5.5. Limitations

The user study and its results showed some limitations and potentials for improvement in the future. First, the participant numbers could be extended to different countries to have even more reliable results. Nevertheless, for the conducted survey and experiments, the amount and distribution of different stakeholders and experience levels of BIM and LCA is sufficient. Second, some participants gave written feedback that combining different element variants is unrealistic and does not always make sense. We previously considered this topic with a method of "Connected Design Decision Networks" but excluded it from the scope of this project (Forth et al., 2022c). More information on other criteria, such as costs, fire safety, etc., was suggested in the written feedback and an extension to different environmental impact categories and their related costs.

Furthermore, the case study is a small office building to simplify the elements' complexity. Testing the proposed visualization strategies with another case study with a more complex geometry might produce different results and needs to be tested. We also pre-defined the goal and scope of the LCA to have comparable system boundaries, such as period, life cycle phases, etc. More transparent information on the calculation was referred to the previous publication (Forth et al., 2023a) and was not mentioned in detail, as we also wanted to include non-LCA-experts. Extending the scope beyond architectural models but also to HVAC planing, increases the complexity, too.

6. Conclusion and future works

This paper proposes and evaluates an interactive visualization approach for design decision-making based on uncertain LCA results using open BIM in early design stages. Three research questions were defined, including the support of open BIM data formats, which LCA visualization strategies, and which uncertainty visualization approaches are suitable and intuitive for non-LCA-experts in the decision-making process. The proposed workflow's first steps, such as the element matching approach and LCA calculations, were described in a previous publication (Forth et al., 2023a).

The objective of the suggested decision-making workflow was to support non-LCA experts in making design decisions regarding construction-element and material-related options in the early design phases. Different visualization strategies were proposed to support decision-makers during these early stages. These strategies were further developed to incorporate uncertainty visualizations, such as transparency for the 3D BIM-model color-coding, gradient color ranges for the heat maps, and box plot diagrams. Furthermore, we prototypically implemented the proposed workflow based on open BIM data formats using the IFC.js library for the model viewer and buildingSMART's International BCF API for extending the BCF schema for feedback communication.

We evaluated the three research questions by evaluating the prototype through a user study and a survey. The answer to the first research question on how to open BIM data formats support decision-making includes that IFC models can automatically derive LCA results and visualize them in a color-coded model viewer. Furthermore, an extended BCF schema can be used to communicate the decision back to designers and BIM modelers. For the following research question about LCA visualization strategies, we analyzed that besides the color-coded IFC model viewer, the heat maps of design variants are found to be most supportive for non-LCA-experts. LCA experts prefer box plot diagrams. The last research question is about how uncertainties of LCA results in early design stages can be visualized intuitively. Using transparency in the IFC model for visualizing uncertainties is found to be less intuitive than gradient color ranges and box plots. In contrast, gradient color ranges were rather non-LCA-expert friendly, and box plot diagrams were more intuitive for LCA experts.

The user study had limitations such as a simple office model as a case study, the focus on only embodied GHG emissions, and the number of participants, which can be extended in the future. Some element variant combinations seem unrealistic, which was neglected in this paper as it was previously discussed (Forth et al., 2022c).

To conclude, we could show in this paper the importance and acceptance of open BIM data formats for early design decision support considering LCA. Color-coded 3D models based on IFC models and heat maps also support non-LCA-experts, such as designers, clients, or project developers, to identify LCA hotspots and make design changes to optimize the GWP performance. Therefore, we strongly recommend that LCA software developers implement an interactive model viewer, including color coding, for design optimization in early design stages. This also includes more and different stakeholders in the decision-making process, who are usually not LCA experts, such as project developers or designers.

The aspect of digital protocols, such as BCF, supports automatically communicating all decisions digitally and without information loss and can be used to close the gap in communication loops. We propose that LCA software providers consider these BCF protocols and implement these in their tools. Doing so, non-BIM experts can use them intuitively without having detailed knowledge of BCF and participate in a fully open BIM workflow. Nevertheless, standardization of these LCA-related extensions is still needed. Furthermore, different approaches to visualizing LCA results' uncertainties were not intuitive enough for every participant and expertise. Consequently, new visualization strategies need to be researched and tested in the future.

In our ongoing research, we plan to integrate several other criteria in the proposed workflow, such as whole building simulation of the annual energy demand, thermal comfort, and daylight simulations. As there are similar challenges of incomplete semantic information in early design phases for such simulations, we want to extend the proposed semantic healing process with established databases and multi-lingual Large Language Models (LLM). As shown in a first proof-of-concept, current multi-lingual LLMs are not sufficient and need further domain-specific fine-tuning (Forth, 2023). Furthermore, fuzzy or uncertain information are handeled by sampling over a range of design options, as previously shown (Forth et al., 2023a).

The limitations of the LCA knowledge database can be solved by integrating the proposed Connected Design Decision Networks and testing the prototype with more complex case studies. Furthermore, the harmonization of extending the BCF schema using BCF snippets to integrate existing LCA data standards such as the International Life Cycle Data System (ILCD) by the European Commission (European platform on lca |, 2023) is a further goal of future work.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Kasimir Forth reports financial support was provided by Siemens Real Estate GmbH und Co OHG.

Data availability

Data will be made available on request.

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Appendix A. Prototypical implementation

Appendix A.1. Implementation of Material option selection

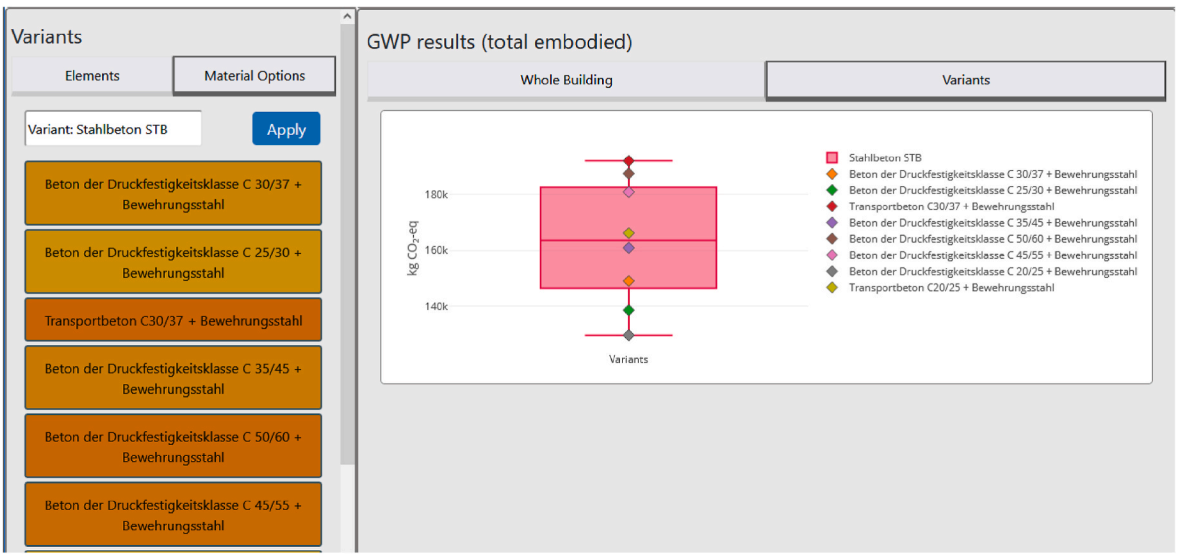

Fig. A.18. Prototypical implementation of the material option comparison of reinforced concrete (step 4.c)

Appendix A.2. Example BCF implementation

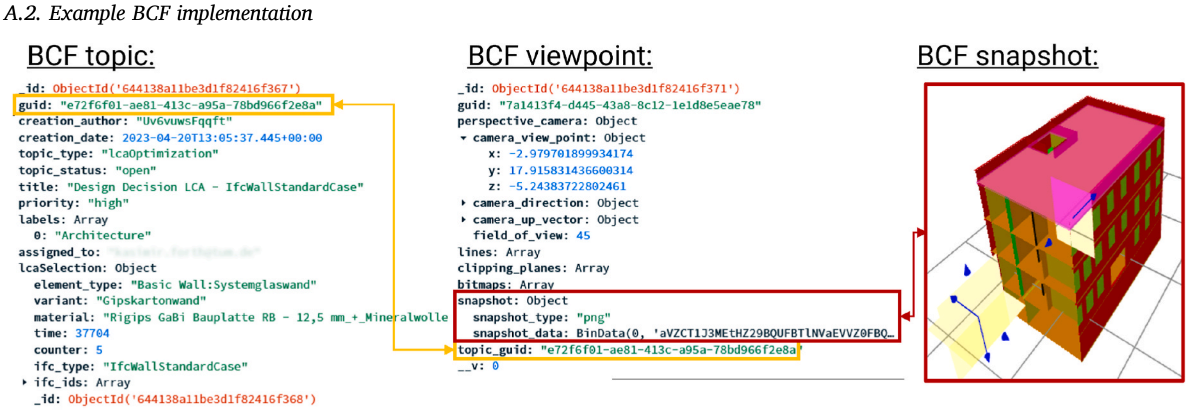

Fig. A.19. Screenshot of one example BCF issue implemented using BCF API and extended

Appendix B. User study

Appendix B.1. Participants

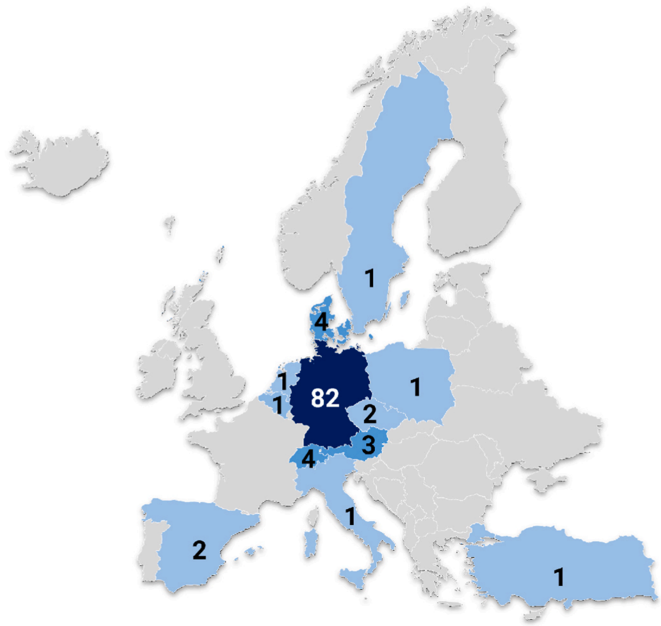

Fig. B.20. Distribution of participants' work countries

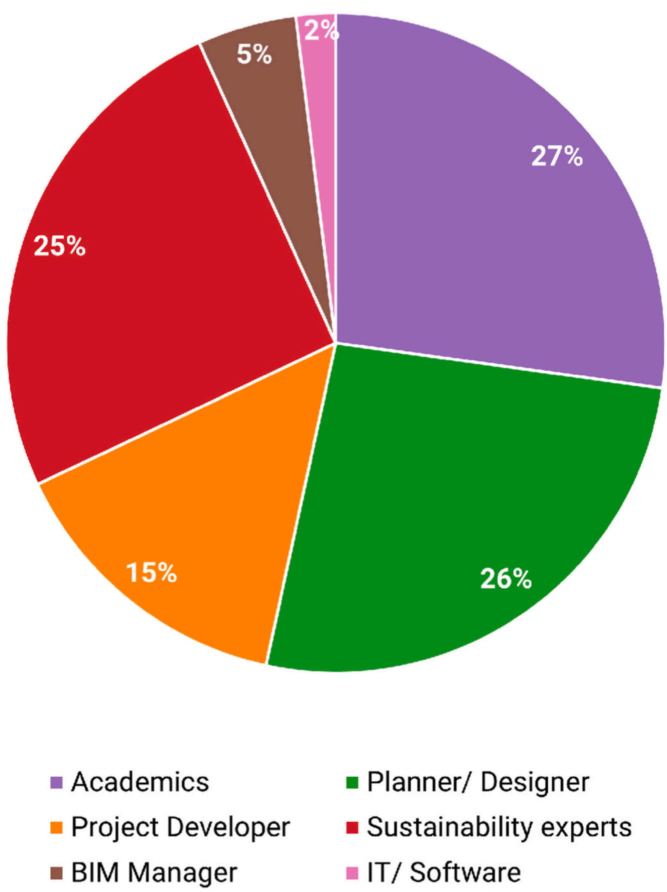

Fig. B.21. Distribution of participants' stakeholder background

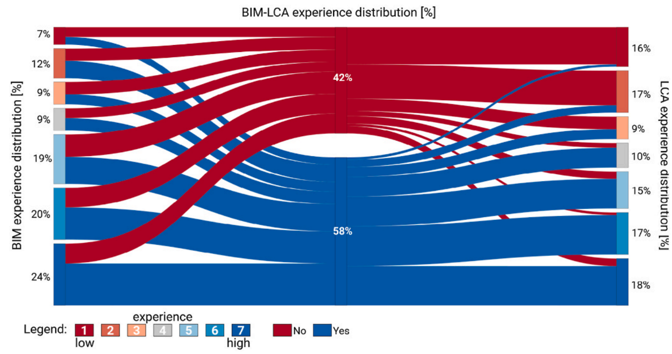

Fig. B.22. Profession of the user study participants in relation to their BIM experience (left) and LCA experience (right)

Appendix B.2. Survey questions

Table B.1
Survey questions of user study, part 1: general and background questions

Nr.	Question	Answer options
1	In which country do you work?	Germany, Austria, Switzerland, others
2	What is your professional background?	Project Developer/Client/Housing association, Portfolio Manager/Investor, Planner (architect, structural engineer, HVAC/MEP engineer, etc.), Sustainability expert/Building physicist/Energy consultant, Student/researcher
3	How experienced are you with BIM workflows and models?	1–7
4	How experienced are you with Life Cycle Assessments (LCA) of Buildings?	1–7
5	Have you already gained experience with BIM-based life cycle assessments?	Yes/No
6	Who do you think should have significant influence on component and material decision-making based on environmental impact?	Project Developer/Client/Housing association, Portfolio Manager/Investor, Planner (architect, structural engineer, HVAC/MEP engineer, etc.), Sustainability expert/Building physicist/Energy consultant

Table B.2
Survey questions of user study, part 2: evaluation questions

Nr.	Question	Answer options
7	In general: how easy was the task of the whole decision-making process?	1–7
8	How well did the colored 3D model help you identify LCA optimization potential?	1–7
9	How intuitive do you find the transparent display of the colored 3D elements to show the uncertainties of the results?	1–7
10	How well did the coloring of the element variants and material options help you in making decisions?	1–7
11	How intuitive do you find the gradient coloring of the element variants and material options to show the uncertainties of the results?	1–7
12	How well did the box plot diagrams of the LCA results help you in making decisions?	1–7
13	How important do you consider open data standards of the BIM method (e.g. IFC models) for LCA?	1–7
14	Do you know the exchange format BCF - BIM Collaboration Format for BIM-based Issue Management?	Yes/No
15	How helpful do you find the automatic creation of digital collaboration protocols (via BCF - BIM Collaboration Format) for communicating the final decisions to the BIM modeler?	1–7
16	Finally: how difficult was the task of the whole decision-making process?	Yes/No

Appendix B.3. Viewpoints

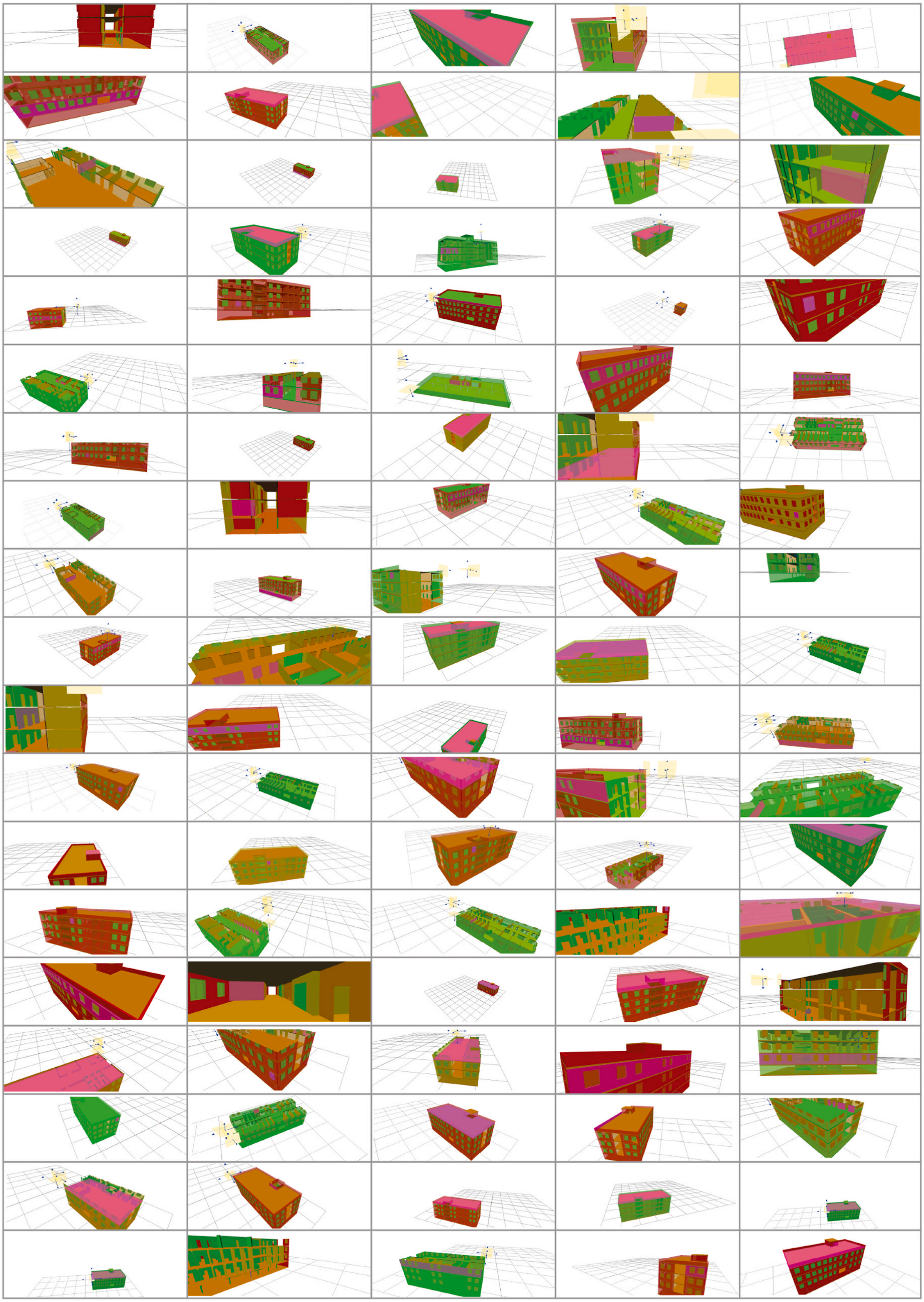

Fig. B.23. Viewpoints of most BCF issues about selected variants for decision-making (part 1)

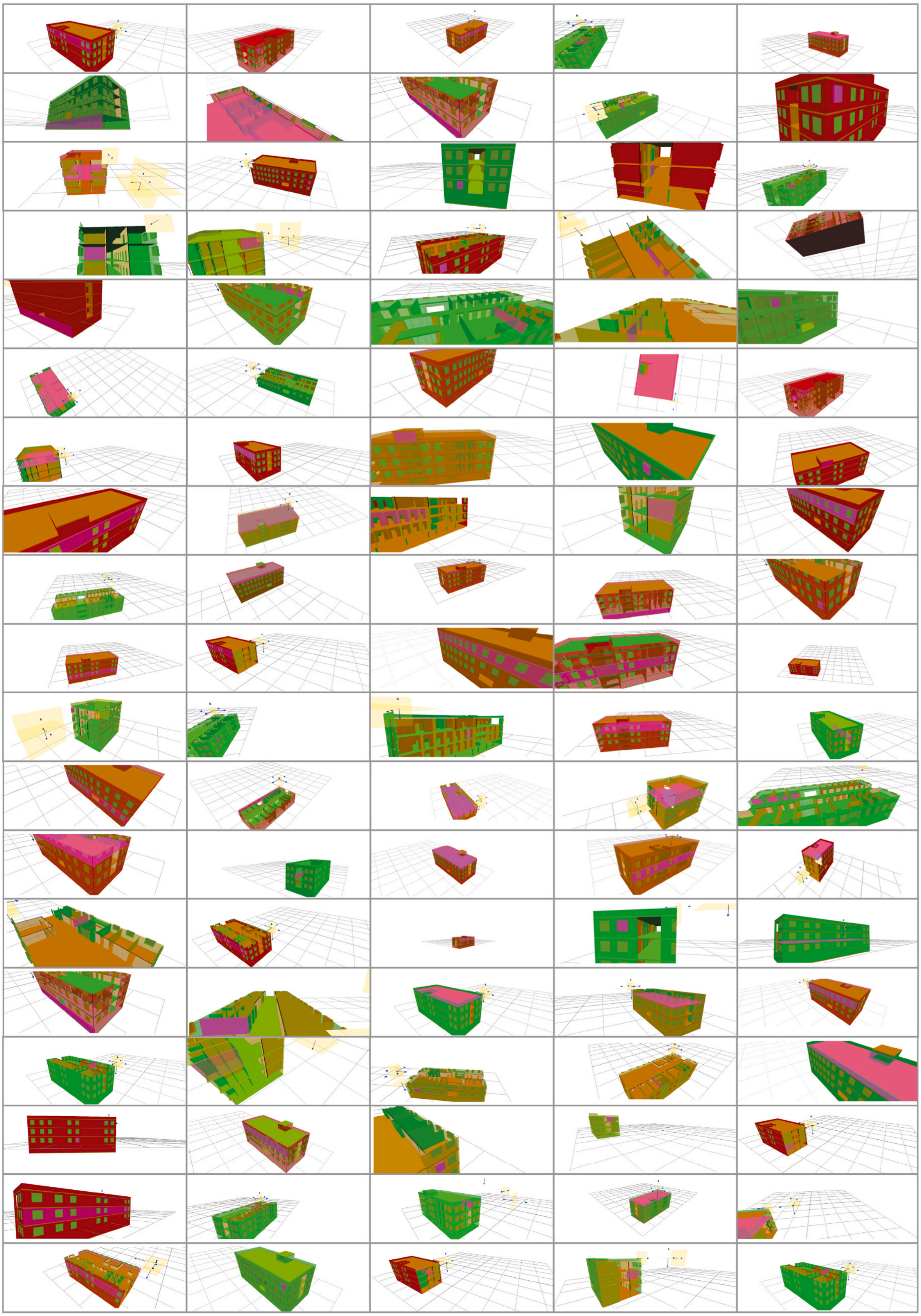

Fig. B.24. Viewpoints of most BCF issues about selected variants for decision-making (part 2)

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