A Framework for User Centric LCA Tool Development for Early Planning Stages of Buildings

Citation for the original published paper (version of record):
Hollberg, A., Tjader, M., Ingelhag, G. et al (2022). A Framework for User Centric LCA Tool Development for Early Planning Stages of Buildings. Frontiers in Built Environment, 8.
http://dx.doi.org/10.3389/fbuil.2022.744946

(article starts on next page)

frontiers | Frontiers in Built Environment

ORIGINAL RESEARCH
published: 08 June 2022
doi: 10.3389/fbuil.2022.744946

Check for updates

A Framework for User Centric LCA Tool Development for Early Planning Stages of Buildings

Alexander Hollberg[1], Maria Tjäder[1,2], Gerda Ingelhag[2] and Holger Wallbaum[1]*

[1]*Research Group Sustainable Building, Division of Building Technology, Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden,* [2]*Bengt Dahlgren AB, Gothenburg, Sweden*

As the high greenhouse gas (GHG) emissions caused by the construction and real estate sector receive more attention, more and more countries include an environmental assessment of buildings based on Life Cycle Assessment (LCA) in their building regulations. Sweden introduced mandatory climate declarations in January 2022, for example. To support stakeholders in conducting the climate declarations and using the results to reduce GHG emissions, user-friendly tools for early planning stages are needed. The aim of this study is to develop and test a framework for user centric development of such tools. The framework builds on three steps; 1) interviewing stakeholders to define tool requirements, 2) developing a prototype tool according to the requirements, and 3) evaluating it based on user feedback. We developed and tested the framework in the Swedish context to provide a blueprint applicable to other countries and contexts. The primary target users are architects with computational design experience but also engineers and real estate developers working in early phases. The results show that the users' expectations can be met when the requirements are integrated from the very beginning. In the current version, the developed building LCA tool only targets the embodied GHG emissions from the production and construction phase of the building, but it could be extended to include further life cycle phases in the future.

Keywords: life cycle assessment, stakeholders, buildings, parametric design, tools, interviews

OPEN ACCESS

Edited by:
Ben Amor,
Université de Sherbrooke, Canada

Reviewed by:
Assed N. Haddad,
Federal University of Rio de Janeiro, Brazil
Jonathan Villot,
Institut Mines-Télécom, France

****Correspondence:***
Alexander Hollberg
hollberg@chalmers.se

Specialty section:
This article was submitted to Sustainable Design and Construction, a section of the journal Frontiers in Built Environment

Received: *21 July 2021*
Accepted: *11 May 2022*
Published: *08 June 2022*

Citation:
Hollberg A, Tjäder M, Ingelhag G and Wallbaum H (2022) A Framework for User Centric LCA Tool Development for Early Planning Stages of Buildings. Front. Built Environ. 8:744946. doi: 10.3389/fbuil.2022.744946

1 INTRODUCTION

On a global level, the greenhouse gas (GHG) emissions caused by the building sector have reached a record high in 2019 and contribute to 38% of global emissions (Hamilton and Rapf, 2020). In Sweden in 2019, the construction and real estate sector was responsible for 11.7 million tons of CO_2-equivalents (CO_2-e), which corresponded to 21% of Sweden's total GHG emissions[1]. An additional 7.7 million tons of CO_2-e are related to the import of construction materials. Especially considering the long lifetime of buildings and the resulting lock-in effects, a rapid transition to planning climate-friendly buildings is needed to achieve the Swedish target of net zero GHG emissions by the year 2045.

[1]Boverket, 2020. Emissions of greenhouse gases from the construction and real estate sector https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/miljoindikatorer—aktuell-status/vaxthusgaser/ (accessed 8.8.20).

Life Cycle Assessment (LCA) is becoming more and more established as a common method to evaluate the environmental performance of buildings (Hu and Milner, 2020). LCA is widely recognized as a powerful tool to predict the environmental impacts of buildings during their life cycle (Chen et al., 2010; Russell-Smith et al., 2015). LCA covers the entire life cycle of buildings from raw materials extraction and processing, manufacturing of building components, to use and end-of-life. The general method is standardised in the ISO 14040/44 (ISO 14040, 2006; ISO 14044, 2006) framework. EN 15804 (CEN, 2012) has been developed for the LCA of building materials and provides a basis for Environmental Product Declarations (EPDs). EN 15978 (CEN, 2011) specifies further guidelines for LCA of buildings and defines life cycle modules.

More and more countries integrate LCA of buildings into national regulations in some form (Hollberg et al., 2021). The Swedish government decided to introduce a mandatory *climate declaration* in January 2022[2]. The climate declaration should be conducted when applying for a building permit and the purpose is to decrease climate impacts and increase knowledge in the field. The legislative proposal builds on EN 15978. The first version does have any thresholds that must be met and only looks at cradle to handover (life cycle modules A1-A5 according to EN 15978). From 2027 onwards, thresholds will be introduced. The scope will be extended to include the use phase and end of life (life cycle modules A1–A5, B2, B4, B6, C1–4). Additional environmental information, such as biogenic carbon storage or net export of locally produced electricity shall also be added.

To make sure the climate declaration fulfills its purpose and contributes to reducing GHG emissions effectively, two aspects are important. First, LCA of buildings must be mainstreamed. LCA is often considered a complicated method for experts (Malmqvist et al., 2011; Meex et al., 2018). The Swedish National Board of Housing, Building and Planning (Boverket) has published an open database of generic GHG emission factors for 172 building materials[3] to allow planners to access the data. The product data and energy mix are representative for Swedish conditions. A supplement 25% has been added to the generic data to incentivise the use of product specific data in the form of EPDs. However, the availability of EPDs of building materials is still limited for the Swedish market. The generic database is a first step towards mainstreaming but the stakeholders also need tools to support them to carry out a climate declaration. Current LCA tools for buildings in the Swedish context include *Byggsektorns miljöberäkningsverktyg* (BM)[4] and *OneClick LCA*[5], amongst others. The second aspect is that only carrying out a climate declaration does not improve the environmental performance of the building by itself. LCA in the building industry as of today is often applied at late stages and hence it is not used to improve the building design, but rather being descriptive (Röck et al., 2018) or reactive (Roberts et al., 2020). Therefore, a "proactive assessment" (Roberts et al., 2020) and optimization is needed. In general, the optimization potential is the biggest in the early stages of the project (Davis, 2013). However, the "dilemma" is that the accurate information needed for LCA is missing in early stages and when it is available in later stages, it is too late to implement major changes to reduce GHG emissions (Hollberg and Ruth, 2016).

Digital approaches and tools can support both aspects. Building Information Modelling (BIM) is becoming increasingly popular in the planning process (Abbasnejad et al., 2020). BIM allows different stakeholders to manage digital data of the building throughout its entire life cycle (Succar, 2009). As such, it seems natural to use BIM to support LCA of buildings. Early works include studies by Basbagill et al. (2013) and Antón and Díaz (2014) and tools such as Tally[6] or OneClick LCA. Recently, there was a rapid increase of BIM-based LCA literature and tool development (Potrč Obrecht et al., 2020; Kong et al., 2021; Safari and AzariJafari, 2021). As such, BIM seems to be a promising approach towards mainstreaming LCA of buildings. However, to influence the design and decision making process based on the LCA results, a high Level of Development is needed (Hollberg et al., 2020), which is usually not available in early stages.

Especially in early stages, architects compare many variants to improve the building design (Lawson, 2005). In this context generative design has become popular because it allows to generate and evaluate variants quickly. Visual scripting tools such as Grasshopper 3D[7] are increasingly used by architects (Caetano and Leitão, 2020). A number of tools for LCA have been developed as plugins, e.g., Bombyx (Basic et al., 2019) or Beetle (D'Amico and Pomponi, 2018). Usually, the tools are published by researchers or consultants that have used them for their own work. Researchers develop the tools usually for a specific study or project, for example Hester et al. (2018) have developed the Building Attribute to Impact Algorithm for guiding the design in early stages, Lobaccaro et al. (2018) developed a tool to minimize the embodied GHG emissions in a zero emission building, Kiss and Szalay (2020) developed a workflow for multi-objective environmental optimization of buildings, and Pomponi et al. (2021) applied machine learning to support structural design decision while Basic et al. (2019) developed Bombyx mainly for teaching purposes. In some cases, the tools are published free or open source, e.g., Bombyx and Beetle. However, as they have been developed for a very specific purpose in a specific context, they are usually not suitable for a wide range of stakeholders. According to Roberts et al. (2020) these approaches have only seen limited uptake and require further standardization and validation to see an uptake in use within industry. How useful these tools are for practitioners depend on the stakeholders' requirements and the local regulations. However, the

[2]Boverket, 2021. Climate declaration for new buildings https://www.boverket.se/en/start/building-in-sweden/developer/rfq-documentation/climate-declaration/ (accessed 7.16.21).

[3]Climate database from Boverket https://www.boverket.se/en/start/building-in-sweden/developer/rfq-documentation/climate-declaration/climate-database/ (accessed 7.16.21).

[4]IVL, 2020. Byggsektorns miljöberäkningsverktyg https://www.ivl.se/sidor/vara-omraden/miljodata/byggsektorns-miljoberakningsverktyg.html (accessed 4.10.20).

[5]Bionova, 2015. OneClickLCA, https://www.oneclicklca.com/(accessed 7.7.21).

[6]KT Innovations, 2014. Tally http://www.choosetally.com/(accessed 10.10.20).

[7]Rutten, D., 2015. Grasshopper3D. http://www.grasshopper3d.com/(accessed 8. 8.20).

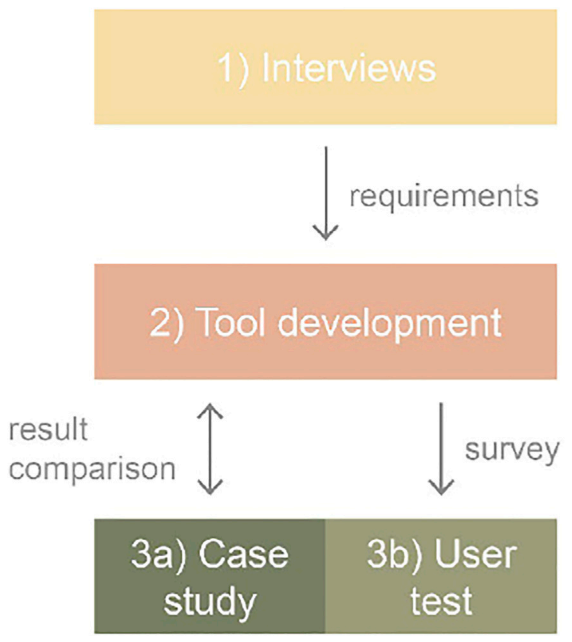

FIGURE 1 | Overview of the tool development framework.

authors and tool developers mentioned above did not integrate the users in the development. While an increase of building LCA tool development can be seen in the literature, there is a lack of integration of user requirements into the tool development process.

Few researchers have studied stakeholder requirements regarding building LCA tools. Meex et al. (2018) provide a list of requirements mainly derived from the literature and architects in the Belgian context. Kanafani et al. (2021) report on user requirements derived in workshops in Denmark. Nair et al. (2021) present an overview of user requirements derived from discussions with six practitioners in the Swedish town of Umeå. One common and highly rated requirement is that the tool should be simple, especially for early stages where time and information is limited. Simplification has been an important topic in the LCA community since the 1990s (Gradin and Björklund, 2021). Beemsterboer et al. (2020) provide a recent overview over the most common strategies with regards to simplification of LCA for buildings found in the literature. However, what is considered simple by the intended tool users highly depends on the existing common workflows in a company or a country. Tabrizi and Brambilla (2019) developed a simplified LCA tool for buildings in Australia while Naneva et al. (2020) developed a simplified LCA workflow and a tool following a Swiss cost structure that was highly appreciated by Swiss construction companies, for example. However, it is probably useless to stakeholders in other countries having different building decomposition strategies or internal workflows. This example shows that there is a need to consider the current and local practice and requirements in building LCA tool developments. Currently, there is no tool that allows for simplified LCA in the generative design process while following the Swedish regulations.

The aim of this study is to develop a framework for user centric LCA tool development for early planning stages of buildings. The framework builds on interviewing stakeholders to define the tool requirements, developing a prototype tool according to the requirements and finally evaluating it based on user feedback. We developed and tested the framework in the Swedish context with the aim to provide a blueprint applicable in other countries and contexts. The primary target users are architects but also engineers and real estate developers working in early phases. In the current version, the tool only targets the embodied GHG emissions from the production and construction phase of the building, but it could be extended to include further life cycle phases in the future.

2 MATERIALS AND METHODS

The tool development framework follows three main steps, see **Figure 1**. The interviews with stakeholders are essential to define the tool requirements. A prototype tool is then developed based on the stakeholders' feedback and the national regulation. The validation is split into two parts. A) validation of the correct calculation of the tool and B) usefulness and applicability of the tool. For part A, a case study is calculated with the new tool and the results are compared with the results a sustainability engineer had produced using the Swedish LCA tool BM. For part B), the potential users of the novel tool test it and answer a survey regarding their satisfaction with key features derived from the interviews in step one.

2.1 Interviews

Thirteen stakeholders from twelve different companies covering different professional backgrounds were interviewed (see **Table 1**). These included five architects from medium to large Swedish architectural office (80 to <400 employees). Furthermore, three engineers were interviewed, two from a large engineering consultancy and one from a software and consultancy company. Five real estate developers from medium to large companies were included. The interviewees were asked to rate their level of experience in LCA and computational design from one (low) to five (high) after carrying out the interviews per e-mail.

All stakeholders received the following five questions:

1) How do you define early stages?
2) Which software is used for modelling in early stages? (e.g., Revit, ArchiCAD, Sketchup, Rhinoceros, AutoCAD)
3) How and when could an LCA tool be useful?
4) What would be the reasons for you to use an LCA tool? (e.g., To make a baseline for later stages or to use for climate declarations and certifications)
5) What are important features for an early stage LCA tool?

The interviews were conducted as online meetings due to the prevailing Covid-19 pandemic. To support with Question 1, five planning stages were predefined which are common in Sweden. 1) Investigations, 2) Program and project definition, 3) Procurement, 4) Production, 5) Administration and maintenance (see **Supplementary Material**). The participants could draw on a slide to indicate their definition during the online meeting. To structure the answers for Question 5, the participants were provided the features shown in the

TABLE 1 | Interviewees participating in the study.

Company category	Profession	LCA experience	Computational design experience
Architect	Architect	1	5
Architect	Architect	2	5
Architect	Energy and environmental engineer	2	5
Architect	Architect	2	4
Architect	Architect, BIM manager	2	5
Engineer	Associate sustainability director	3	3
Engineer	Graduate sustainability engineer	4	3
Engineer	Sustainability consultant	4	4
Real estate developer	Sustainability strategist	2	2
Real estate developer	Real estate developer	3	4
Real estate developer	Sustainability manager	4	1
Real estate developer	Sustainability strategist	4	2
Real estate developer	Sustainability manager	3	2

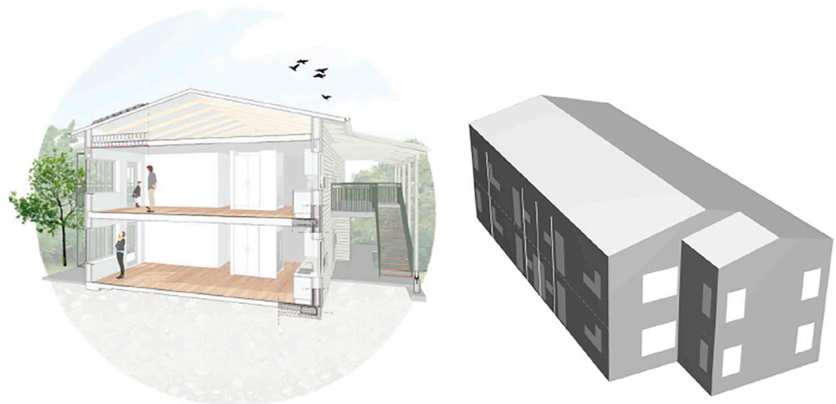

FIGURE 2 | The case study building[8].

Supplementary Material. The presented features were inspired by user requirements described by Meex et al. (2016), Meex et al. (2018) and Kanafani et al. (2021). Furthermore, the participants had the opportunity to add own features they found important. The participants were asked to rank the features from less to more important on a visual analogue scale. It was assumed that the scale is interpreted as symmetric by the participants.

2.2 Tool Development

The visual programming addon Grasshopper3D for Rhinoceros was used as rapid prototyping platform for the tool. The interface is easy to use also for non-expert software developers and the many existing plugins allow to use existing visualization tools. Even if not used by the majority of architects yet, the computational designers in leading architecture offices rely on it and its use can be expected to rise. This assumption has been confirmed in the interviews.

We decided to focus on the Swedish context and rely on the framework of the current version of the climate declaration. This means that the tool only includes the life cycle modules A1–A5 in the current version. Further boundary conditions and assumptions such as the reference study period and the considered building components are also based on the climate declaration. Other decisions are based on interview responses and requirements from stakeholders, as far as possible.

2.3 Validation

To validate the correct calculation, the results of a case study produced by the developed tool are compared with the established Swedish LCA tool BM. The case study building is a multi-residential building. The building holds apartments with 2–4 rooms, and sizes of 66–91 m^2. A vision image and the 3D model of the building are shown in **Figure 2**.

To validate the usefulness and fulfillment of the user requirements, twelve target users received a demo and the possibility to test the developed tool and then filled out a survey. The participants included four of the interviewees. In total, six architects from four different architecture office, three engineers from one large consultancy and three real estate developer each from different companies provided feedback (see **Table 2**). Similar to the interviewees, the test users were asked to rate their level of experience in LCA and computational design one to five per e-mail after carrying out the test.

TABLE 2 | Participants in the user tests.

Company category	Profession	LCA experience	Computational design experience
Architect	Sustainability manager	4	2
Architect	Architect	1	5
Architect	Architect	2	5
Architect	Architect	3	5
Architect	Architect	3	5
Architect	Architect	2	3
Engineer	Energy and environmental engineer	3	4
Engineer	Energy and environmental engineer	4	3
Engineer	Innovation leader	2	5
Real estate developer	Sustainability strategist	2	2
Real estate developer	Sustainability strategist	4	2
Real estate developer	Project developer	3	4

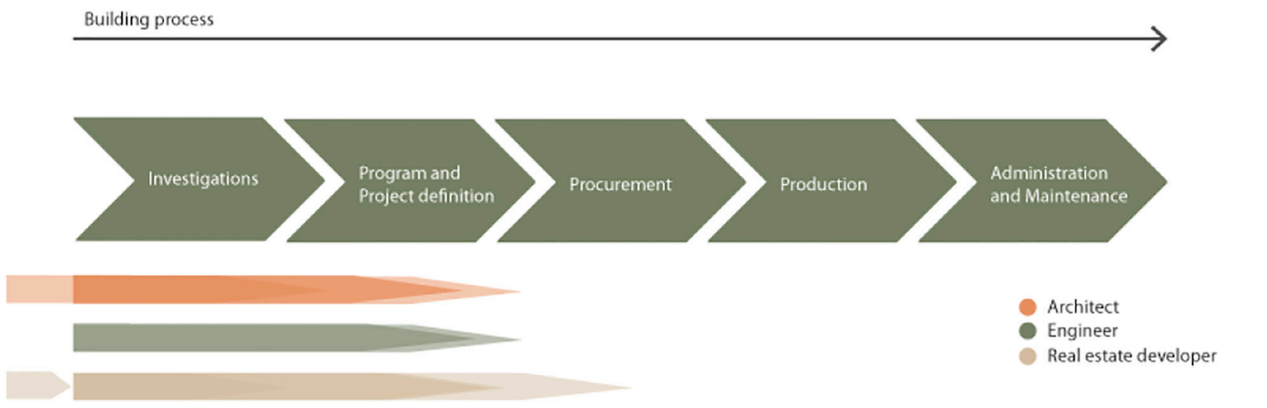

FIGURE 3 | Definition of early stages.

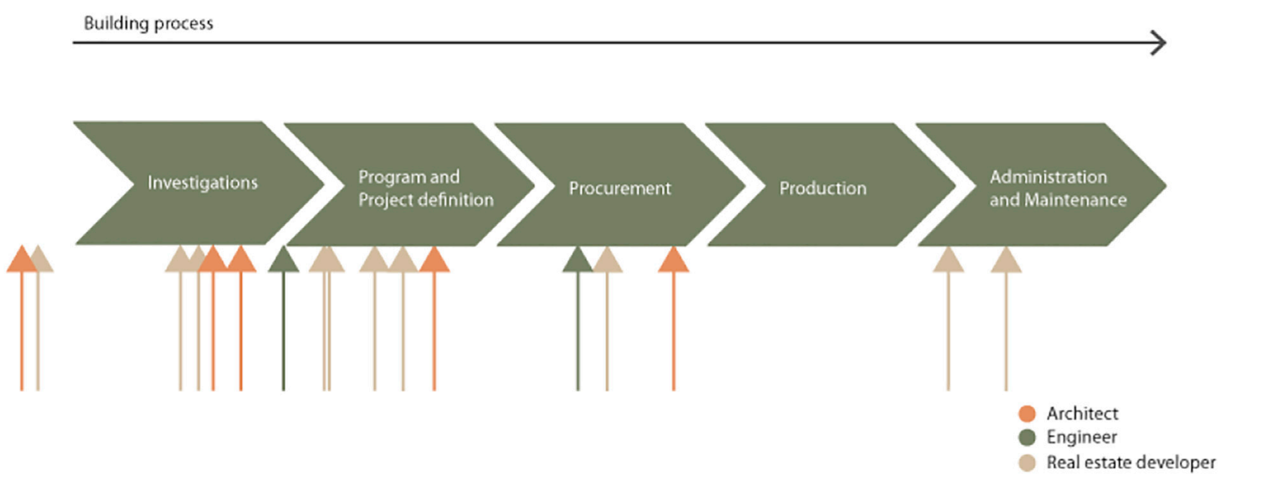

FIGURE 4 | The interviewees suggestions on when to conduct early-stage LCA.

Due to the COVID-19 pandemic, the tests were conducted through online meetings and the participants tested the tool via remote control on one of the author's computer. Two participants tested the script on their own computers. A survey was sent out afterwards for the participants to fill in. Eleven questions in four categories regarding usability (U), modelling (M), transparency (T) and required knowledge (K) were formulated. The questions relate to the features described as important by the participants in the interviews and requirements described in the literature (Meex et al., 2018; Bach et al., 2019; Kanafani et al., 2021). As the link to the 3D model was highlighted as especially important, it was introduced as an own category. Transparency is mentioned as important in the literature and was rated very highly by the participants. Furthermore, the calculation speed was mentioned as very important and was integrated as part of the overall usability. Six questions use a Likert-like scale from 1 to 5 while the other questions are qualitative, open questions. The questions are listed below in the chronological order that the participants received them.

1) (U) What is your first impression of the tool?
2) (U) Would you prefer it to be more or less detailed regarding e.g., LCA phases, building elements or material choices? (Rate 1–5)
3) (M) Can you update the 3D model and the material choices the way you wish to?
4) (M) Is a high level of 3D modelling experience needed? (Rate 1–5)
5) (T) Are the results presented in a satisfying way? If not, in what ways would you like to display the results?
6) (U) Is the tool fast enough? (Rate 1–5)
7) (T) Is the tool transparent enough? Can you understand how it works and how the calculations are made? (Rate 1–5)
8) (K) Is a high level of LCA knowledge needed? (Rate 1–5)
9) (K) Is a high level of knowledge of building materials and structures needed? (Rate 1–5)
10) (U) In what ways do you think that your company could use the tool?
11) (U) What do you think hinders an implementation of the tool?

3 RESULTS

3.1 Interviews

3.1.1 How do You Define Early Stages?

When asked about the definition of early stages, the different professions pointed at slightly different time spans in the building process (see **Figure 3**). Most interviewees think that early stages lay in the *investigations* and *program and project definition* stages. Some architects and real estate developers think it starts prior to the investigation stage and one of the interviewees thinks that it runs until the procurement stage. There was a statement that early stages are ended when it is hard to propose new ideas. An architect mentioned that in later stages, there is a lock-in of choices. Another architect talked about their office enabling testing designs until late stages.

3.1.2 Which Software Is Used for Modelling in Early Stages?

The architects talked about different ways of working in early stages: sketching by hand, in Rhinoceros, in Sketchup or simplified modelling in ArchiCAD. In later stages, they use BIM software such as Revit or ArchiCAD. An interviewee stated that architects do not have a lot of spare time and therefore it is hard to introduce new ways of working in early stages. The amount of time available in early stages depends on the project. Residential projects are short on time. As stated by an architect "The best thing would be to include all consultants in early stages! That is why indicative tools play a role, even if the accuracy is within 10–15%".

3.1.3 How and When Could an LCA Tool be Useful?

Regarding the question of when to make the early LCA calculations, the answers were widespread but most of them pointed at *investigations* and the *program and project definition* stage (see **Figure 4**). Some thought that as soon as there is a massing model, it is possible to start looking into the climate impact. An argument was that investment decisions are taken when working with rough massing models and hence it is important to take sustainability into account.

When to set materials and geometry varies between projects and sometimes it depends on the site. There are different experiences considering the possibility to conduct an LCA around the program stage. An architect acknowledged that some big building developers have strict processes and hence the end of the program is really detailed. For others, it can be less strict, and one might use massing models halfway through the program. A real estate developer said that early calculations must be done from an architects' drawings as structural engineers and other consultants are not involved in the program stage.

An engineer expressed that there is no point in having the tool early on, as one needs a few options to appraise and an architect said that it can be done whenever, until the building permit is made. The real estate developer that put lines in every stage (**Figure 4**) argued that it is interesting to follow up the calculations. By the last stage, one knows what actual products are used. A general positive comment on the early-stage tool from a real estate developer was that "It would be good if we as clients were better at demanding and promoting that we think it is important to conduct LCA calculations in the early stages."

Most real estate developers thought they would probably not use the tool themselves as they are not working with 3D models. Architects thought that they will make simplified LCAs but that engineers will probably make the final climate declaration calculations. An engineer said that architects would probably use it rather than sustainability consultants. Sustainability consultants join at a later stage and by that time not much can be changed as there is a lot of time and money invested in the drawings. Another engineer thought they could use it themselves in competitions.

3.1.4 If You Would Use an LCA Tool, for What Reason Would it be?

When asked about reasons for conducting an LCA at an early stage, the interviewees gave various responses including to

- provide reference values,
- compare designs,
- learn,
- convince others,
- show ambition and
- for economic reasons

A reference value is a baseline for later stages of the project or upcoming projects. With a baseline, the impact of design changes along the process can be tracked. An interviewee expressed that if

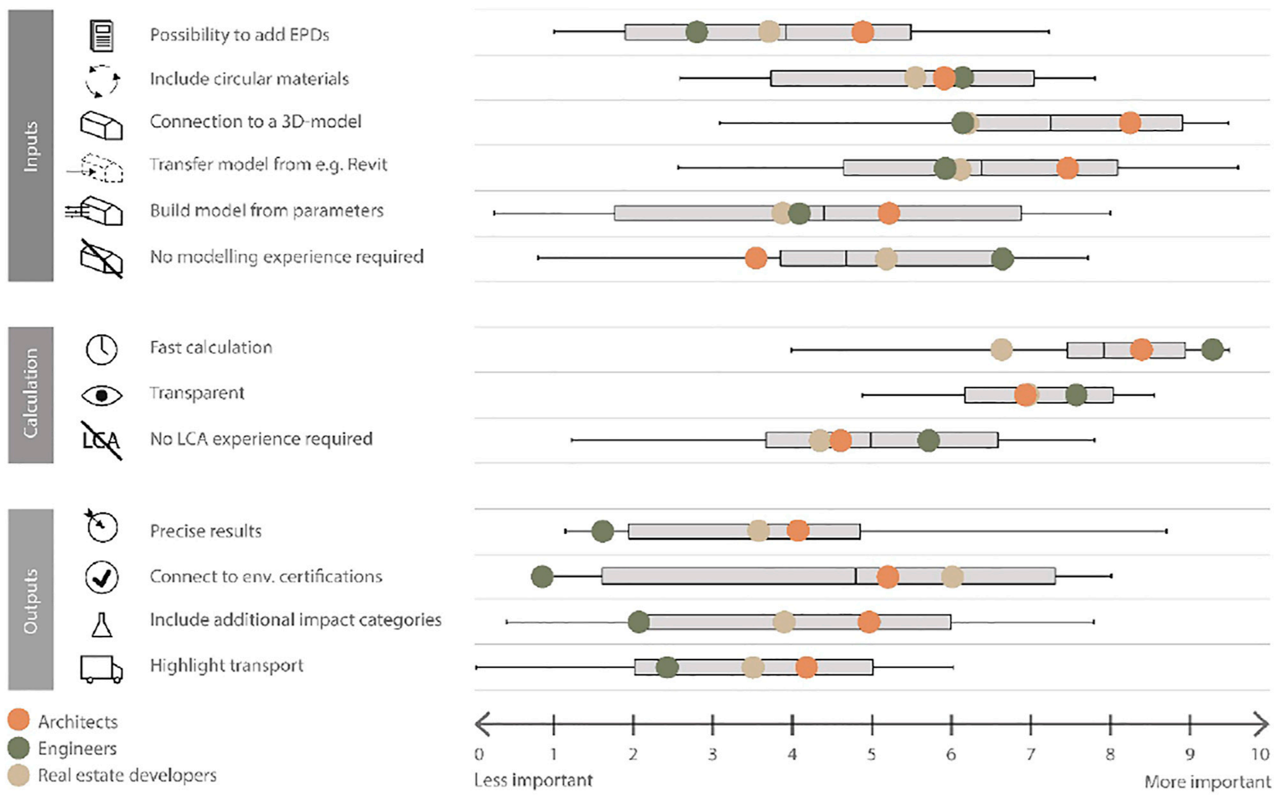

FIGURE 5 | Box plots showing the minimum and maximum values, 25 and 75 percentiles and mean value for all participants. Dots indicate the mean value for each profession.

there was a tool for simplified LCA available they could use it on their existing buildings to get reference values. Other reasons mentioned were making sustainable choices, stepping away from standard materials and comparing different phases. An engineer thought that providing quick answers to these questions would be a successful feature for a consultant. Another engineer thought it would be an interesting selling point for them to use the tool in competitions, where one must keep down costs and hence work efficiently. Other reasons included target setting and identifying easy winners in terms of strategies.

The learning part was mentioned as seeing consequences of choices made and increasing awareness. It was stated that it is beneficial to have a calculated number when entering a discussion, especially if there are a lot of aspects to consider. The number could be used to convince the project team or the investor. As changes are costly, one must motivate the investments. Continuing the economic terms, an idea lifted was that early-stage LCA calculations can help justify loans. As costs are calculated early in the projects, sustainability targets need to be set for them to be considered in the budget.

3.1.5 What are Important Features for an Early Stage LCA Tool?

The features were categorized into 1) inputs, 2) calculations, 3) output. The respondents ranked them on a symmetric, continuous visual analogue scale from less important to more important. The detailed answers to the individual features are provided in the **Supplementary Material**. The visual analogue scale was transferred to a numerical scale from 0 to 10 as it is common practice in medical studies on pain (Heller et al., 2016). The mean value was calculated and used as indicator for the overall importance of a certain feature. Furthermore, the minimum and maximum values and the 25 and 75 percentiles were calculated to indicate the level of agreement on the importance of a certain feature. These values are provided as box plots in **Figure 5** and can be found in the **Supplementary Material**. As the importance is ranked differently be the three different professions, the mean values for each profession are shown in addition.

3.1.5.1 Inputs

Regarding the inputs, all three professions mentioned that it would be nice to be able to add EPDs, however there was a large spread between the answer. Overall, it was not considered as very important in early phases. Architects mentioned that often it is not yet known which actual products will be used.

Architects mentioned that it seems difficult to include reused materials in LCA today, but it would be nice to show if a product is reusable and if it stores CO_2. Real estate developers said that reused materials become more important in later stages and can be left out in the early stages.

With a mean value of 8.4, the connection to a 3D model is the most important feature regarding inputs for architects. It gives a connection to the actual project rather than just comparing materials. As almost all projects are made in 3D models today, there is a wish to have a running connection between the LCA calculation and the project's 3D model. Even if most real estate developers interviewed are not working with 3D models, some saw the relevance of a connection to 3D models. One of them thought that they are not going to conduct the calculations themselves but rather have consultants like architects and structural engineers do it.

Regarding the transfer of the geometry from BIM software, several architects saw a link to ArchiCAD as important while other preferred Sketchup and Rhinoceros. An engineer expressed that using a Revit connection would be future proof as architects will probably use Revit increasingly. However, the likelihood of having multiple Revit models produced by the architects to compare different variants is low.

When asked about the parametric definition of a building as input, some architects expressed that Grasshopper is hard to understand and that it is not suitable as a modelling environment. However, they acknowledged that the industry will be more digitalized and in a couple of years there will be a more parametric view where data informs the design. An engineer mentioned that "model from Revit" and "model by parameters" could be two different tools.

While for architects the required modelling experience does not seem to be very important, the engineers agreed that a high level should not be required.

3.1.5.2 Calculation

In this category of features, fast calculation was most important for architects with a mean value of 8.6. They said that the tool must give instant feedback. Also, the engineers rated the fast calculation highest. It is less important for real estate developers, but they agreed that the tool should be fast and enable quick testing of different material combinations and designs. With a total mean value of 8.0 this feature was ranked most important overall.

All professions agreed that transparency is important. It shows the lowest spread of the answers. An argument against transparency was that some architects do not want to be showered with technical information and numbers, but rather just trust the results. The engineers highlighted that the need for transparency depends on the user and is different depending on if it is an engineer or architect. For them, transparency is more important when moving towards later stages.

All groups agreed that deep LCA experience should not be required. However, architects mentioned that if it is an advanced tool with a lot of settings, prior knowledge of LCA is needed. An engineer mentioned that early-stage tools risk focusing too much on details. However, the tool cannot be too basic either, as it would not provide any new information then.

3.1.5.3 Outputs

All professions agreed that precise calculations are not important in early stages. One real estate developer emphasized that different tools must show similar results and the tools should use the same system boundaries as defined for the climate declaration.

Architects mentioned that the connection to certifications is rather a question of formatting the results than a crucial tool development issue. Real estate developers saw a connection to certifications relevant in the program stage but probably not in the detailed development plan stage. Furthermore, they would like to compare results with legislative thresholds.

Regarding the impact categories, architects would like to focus on climate change to begin with. In contrast, one real estate developer expressed "It is important to include multiple impact categories and we must be able to keep multiple things in mind, by not only focusing on climate impact." Both groups mentioned that it would be nice to also include economic costs in the assessment.

Including the transport was less important to all groups and it was ranked lowest overall with a mean value of 3.5. Engineers mentioned that showing transports might be misleading, as it is not the major impact.

In summary, connection to a 3D model, fast calculation, and transparency were ranked highest. In addition, all groups emphasized the importance of visualizations. Architects would like communicative and pedagogical visualizations. An engineer said that it would be helpful to show a heatmap on the 3D model. A quote was "It is good to show the result in the form of architecture! Everything is visual in those stages and hence it is good to emphasize on visualizations."

3.2 Tool Development

The most important aspects of the tool development are summarized in the following. For a detailed description, see the **Supplementary Material**.

3.2.1 Methodological and Tool Design Choices

Identified important features from the interviews include fast calculations, transparency, and a connection to a 3D model. Less important are exact calculations, calculating transport distances, building the model by parameters in Grasshopper, and studying additional impact categories.

We chose architects as main target users as they typically work with 3D models in early stages, compared to real estate developers and engineers. The main use cases for the tool are to create baselines, reduce the climate impact of the building, compare the LCA modules A1–A5, and for learning. The tool was designed to be general enough to be used in different project stages and hence follow the design process, as mentioned by several interviewees.

As the aim was to limit the required LCA experience, the user is not expected to make methodological choices. An overview of the predefined methodological choices is provided in **Table 3**. They were chosen to be in line with the upcoming climate declarations. There are many ways to structure a building into different components (Soust-Verdaguer et al., 2020). To be in line with the upcoming climate declarations, nine different elements were included here. Installations were not included due to missing data, even if they are a considerable part of a buildings' climate impact (Ylmén et al., 2019; Kiamili et al., 2020).

An interviewee thought that a heatmap on the 3D model to visualize the results in a pedagogical way would be helpful, and it was included in the tool. To support the interpretation, reference values were integrated as wished for by the users. The connection to certifications was not prioritized by interviewees and hence it was left out from the development.

3.2.2 Inputs

Two different versions of inputting the geometry were integrated into the tool. Version 1 is based on drawing a geometry in Rhinoceros and assigning building elements manually onto layers. It was chosen as it provides freedom and flexibility when shaping the building. It also allows for connections to

TABLE 3 | Methodological choices.

	–
Functional unit	$1m^2$ of heated area (A_{temp}) of a building
Reference study period	50 years
Life cycle modules according to EN 15978	A1-A3 (the production stage), A4 (transport to site) A5.1 (spill, packaging, and waste management)
Geographical system boundary	Sweden
Impact category	Climate change
Indicator	GWP 100 in kg CO_2-eq
Included components	Foundation Structure Ground floor Intermediate floors Roof Exterior walls Interior walls Windows Doors

other CAD and BIM software. Version 2 is based on modelling geometry by using parameters in Grasshopper. It was chosen to make the modelling more parametric and easier to change the design. For more details, see the **Supplementary Material**. If building the geometry in Rhinoceros (Version 1), the user must model the load-bearing structures by drawing them. Hence, the freedom to choose between combinations of load-bearing walls, columns, beams, and slabs is enhanced. If building the geometry parametrically in Grasshopper (Version 2), the choice is set to use load-bearing walls or structural frames made of concrete, steel, or wood (see the **Supplementary Material**).

The interviewees discussed that a tool with too many details would not be suitable for sketching in early stages, whereas a too basic tool would not allow for new insights. Therefore, the tool should allow for detailed modelling with customized elements and basic modelling with pre-set elements. As a result, two paths were implemented to assign the constructions and materials to the geometry. The first one builds up a construction by adding a material for each layer. For example, for a wall, insulation type, bricks, plaster, etc. are chosen. The thickness of each layer has to be assigned as well. This alternative allows for full control of the material use in detail; however, it is time consuming. The second path relies on predefined construction set-ups, e.g., when choosing a standard wall, the tool automatically assigns a certain cladding, an insulation type, etc. This requires less inputs from the user but also decreases the transparency. Both paths of assigning constructions can be combined. Hence the flexibility of building up specific constructions and the fast way of choosing between pre-set building elements are kept.

3.2.3 Calculation

To calculate the mass of material used, the tool extracts the areas of the surfaces from the nine layers from the 3D model and multiplies them with the thicknesses and densities of each assigned material. However, when creating the 3D model, some elements such as columns are modelled as volumes instead of surfaces. In those cases, the thickness of materials does not need to be added. To allow different ways of modelling, the component assigning environmental data was made general enough to make use of the different units kg, m^2, and m^3.

As many interviewees thought that generic and national data was of higher value in early stages than EPDs, the Swedish national database with generic environmental data from Boverket was used (see **Supplementary Material**). The database includes 172 resources following the calculation standard EN 15804: A1. A factor of 1.25 to add a surcharge of 25% for uncertainty is included in the datasets. Boverket provides the database in JSON format which was used to import it into Grasshopper. The calculation steps were implemented as C# script in Grasshopper.

3.2.4 Outputs

Four visualization types for the tool were chosen based the goal of the study (see **Figure 6**). The main goal is to compare design options as a basis to reduce the climate impact. To enable the identification of hotspots, a pie chart allows comparing building elements and a heatmap coloring the nine different building elements in the 3D model depending on their global warming potential (GWP) was implemented. Bar charts can be used to show building elements or compare the impact caused in different life cycle modules. To compare the results with thresholds, a benchmarking bar chart was used. In this bar chart, the LCA results are compared with thresholds from LFM30[8,9] and the Finnish Ministry of Environment[10] as national Swedish thresholds are not available, yet. These thresholds have originally been developed using different reference areas, namely gross floor area (GFA) and net floor area (NFA) instead of the heated area (A_{temp}) used in the tool. Comparing to them introduces a small error. However, they are the best thresholds available in the regional context and the introduced error is negligible in the early stages. Therefore, these values were used but they should be replaced as soon as better ones are available.

3.3 Validation

3.3.1 Results Comparison

The case study building was modelled in Rhinoceros using architectural drawings. The building elements were modelled as surfaces and the concept of load-bearing walls was used. A simplification made in the model was to not model internal doors. In reality, there are several different internal wall types and window types used. This was simplified when assigning the environmental

[8]Östlund, E., Borseman, H., Hörngren, C., Brick, K., Ander, A., Stridsberg, E., Perzon, M., Högberg, A., Ljungstedt, H., 2020. Final report CIX https://goteborg.se/wps/wcm/connect/fbe4a872-9f22-4df1-b477-31a2e03b8bf3/Slutrapport-CIX-projektet-2020-webb.pdf?MOD=AJPERES&CONVERT_TO=url&CACHEID=ROOTWORKSPACE-fbe4a872-9f22-4df1-b477-31a2e03b8bf3-nAtRTI- (accessed 7.16.21).

[9]Holmgren, A and Erlandsson, M. 2021. LFM30:s klimatbudget. https://lfm30.se/wp-content/uploads/2021/02/LFM30-Anvisningar_LFM30-Metod-klimatbudget-projektniva˚-nya-byggnader_Version-1.4-AH210208.pdf.

[10]Bionova. 2021. Carbon Footprint Limits for Common Building Types. https://mrluudistus.fi/wp-content/uploads/2021/01/Bionova_MinEnv_Finland_embodied_carbon_limit_values_report_FINAL_19JAN2021_ed.pdf.

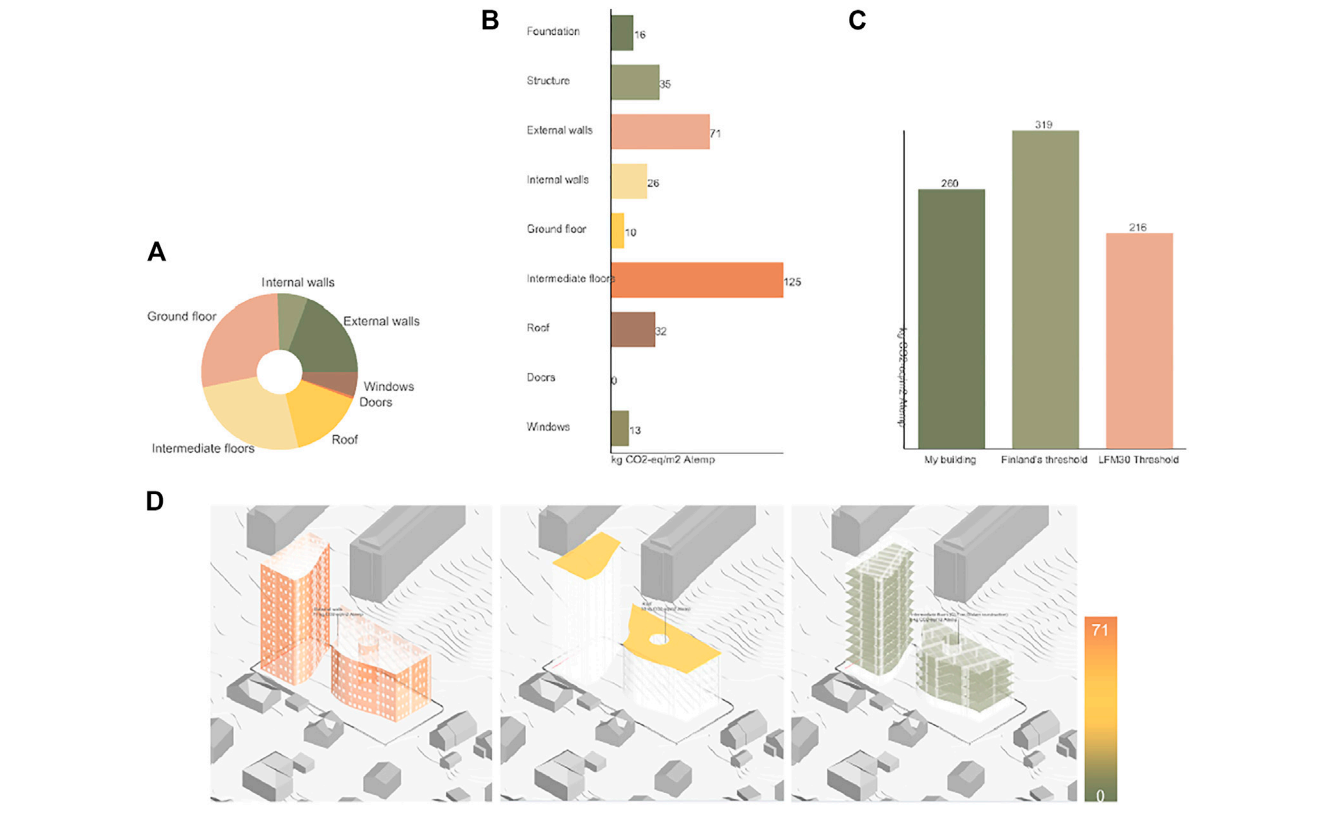

FIGURE 6 | Visualization types in the tool **(A)** pie chart of the impact of each element, **(B)** bar chart of the impact of each element **(C)** comparison with reference values, **(D)** color-coded 3D model showing GWP of different elements in kg CO_2-e/m^2.

data, e.g., by using the same building element types for all internal walls.

To validate the correct calculation of the tool, the results were compared with calculations made in BM by a sustainability engineer (see **Figure 7**). The comparison was carried out only for module A1–A3. According to the sustainability engineer who conducted the reference calculation, the categorization of materials in BM might have errors and floor slabs are sometimes referred to as roofs and vice versa, affecting the results. The total results in this case study differ by 3%. Hence, they are within the 10–15% accuracy that was mentioned by one of the interviewees as accurate enough for early stages. If studying the elements separately, some of the elements show a higher difference which can be explained by simplifications made or errors in the BM calculation.

3.2.2 Stakeholder Feedback

The stakeholder feedback from the survey is summarized for each question in the following. The results for the questions with a rating on the Likert-like scale from 1–5 are shown in **Figure 8**. Boxplots indicate mean, minimum, and maximum values and the 25 and 75 percentiles.

1) What is your first impression of the tool?

The test users expressed that the visualizations and use of colors in the graphs and the model are well made. There is a clear connection to the 3D model. The tool can be used to get a fast overview of climate impact. It is structured, pedagogical and user-friendly. One test user would like to see more details about the load-bearing structures.

2) Would you prefer it to be more or less detailed regarding e.g., LCA phases, building elements or material choices?

There was quite a spread of answers but most test users thought that the level of detail is too low (mean 2.3) and that they want to make more choices (see **Figure 8**). The next question provides more explanations to this. Two of the test users thought that there is a good balance of details.

3) Can you update the 3D model and the material choices the way you wish to?

Eiht of the testers answered yes on the question, but most had additional comments. Several of the users commented that they want to choose how many layers to have e.g., in a wall. A user thought that it was hard to understand why and how it is limited to three materials. This was the case at the time of testing and more layers were added to the tool

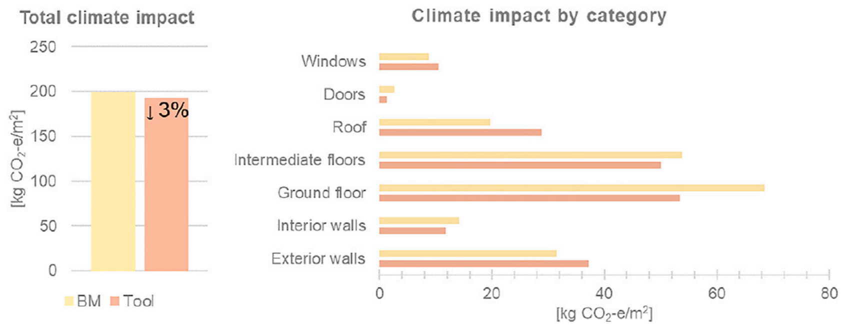

FIGURE 7 | Comparison of the results calculated in BM and in the tool.

afterwards. It was also mentioned that the level of details is a balancing act, and it can be hard to know the building element details in early stages. Several of the testers thought that a lot of pre-set elements would be good. A suggestion was to only focus on pre-set elements, including e.g., standard walls and more sustainable choices. Adding materials that are not in the database was also wished for. A further suggestion was to not have the same materials on every internal wall in the model, but rather have different internal wall types. It would be useful to be able to mark different surfaces in Rhinoceros and apply a specific wall type. The same tester wished for some adjustments in the Grasshopper script but emphasized that the current version of the tool is a good starting-point.

4) Is a high level of 3D modelling experience needed?

Most testers thought that a medium knowledge of 3D modelling is needed, but there was a spread of responses (see **Figure 8**). Most architects who are usually drawing the 3D model thought a medium to low experience is needed, while the other professions thought higher skills are needed.

5) Are the results presented in a satisfying way? If not, in what ways would you like to display the results?

Most test users were satisfied with the presentation of results. The connection to benchmarks such as LFM30 was appreciated. A suggestion was to create export features such as a PDF report or Excel spreadsheets. In the current tool version, a plug-in is needed for the results visualization, and one of the testers commented that it would be easier to use the script if one did not need to install an additional plug-in.

6) Is the tool fast enough?

There was a spread in the perceptions from medium to high of how fast the tool is as shown in **Figure 8**. However, most of the testers thought that it is fast enough (mean 4.1).

7) Is the tool transparent enough? Can you understand how it works and how the calculations are made?

The transparency was rated on a mid-to-high level with a mean of 4.2 (see **Figure 8**). An additional comment was that the tool's calculation based on quantities and factors is straight forward and it is easy to double check the results.

8) Is a high level of LCA knowledge needed?

A low-to-mid level of LCA knowledge was perceived to be needed to use the tool (see **Figure 8**). The mean was 2.4.

9) Is a high level of knowledge of building materials and structures needed?

Most testers thought that some knowledge of building materials and structures is needed to use the tool. Two of the testers perceived that a high level of knowledge in the field is needed. The mean value was 3.5 with a large spread of the answers.

10) In what ways do you think that your company could use the tool?

Two testers acknowledged that the tool is really relevant in early stages. It is useful to get an indication of the climate impact and it is good if the results are overestimating the impact rather than underestimating. The testers said that it can be useful in meetings when optimizing material choices, and that it will make nice diagrams in a report. Another tester thought that they could use a direct connection to their model in another software. The Grasshopper model could feed into that model or the other way around. A real estate developer thought that the tool could be something that they demand from their architects to use, or that they could use it internally for educational purposes.

11) What do you think hinders an implementation of the tool?

The balance between simplicity and flexibility was highlighted as a crucial point when implementing the tool. Another barrier mentioned is the "business as usual" way of working. The tool user might not be the one making decisions. Lack of knowledge and data on the foundation and

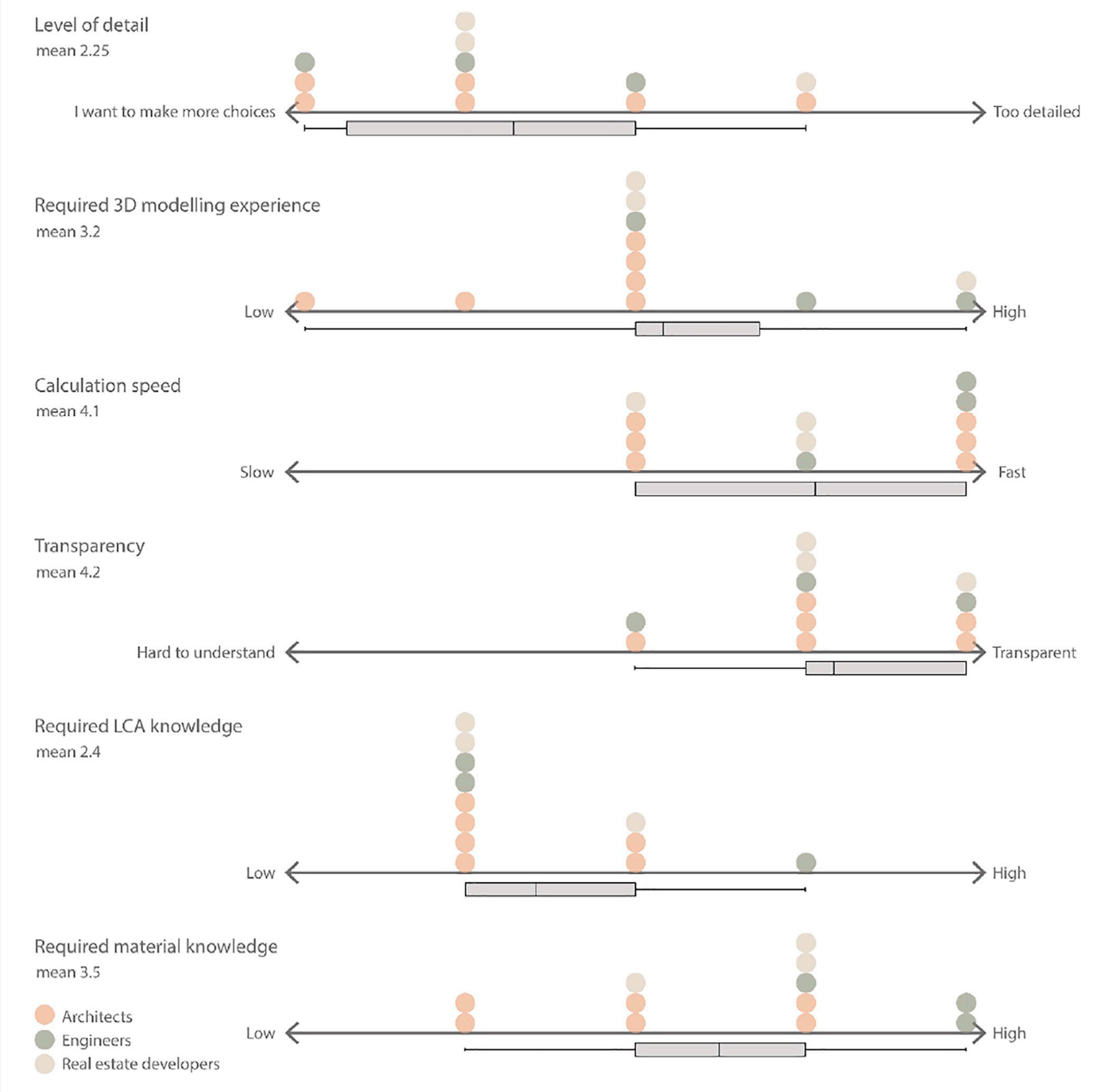

FIGURE 8 | User rating with individual answers and box plots with mean, minimum, and maximum values and the 25 and 75 percentiles for each question.

the load-bearing elements, especially deep foundations might stand in the way of implementation. Architects might not know the structures at an early stage, and clients do not assign structural engineers until later stages. An idea raised was that multiple users could work together in the model, if possible. One test user thought that the tool is useful but that the costs for using such a tool and the workflow are critical.

4 DISCUSSION

4.1 Experiences From Interviews and Tool Development

The authors generally experienced a great interest from the interviewees about an early-stage LCA tool. One reason for the interest was that the soon upcoming climate declaration in Sweden.

The interviewees had slightly different perceptions in their definition of early stages, and this might be affected by when they enter projects. When comparing the interviewees' responses with definitions found in the literature (Hollberg et al., 2021), it was chosen to set the *investigations* and *program and project definition phases* as early stages.

As expected, the interviews revealed different requirements and feature wishes. The key features fast calculations, transparency, and a connection to a 3D model match the requirements defined in Meex et al. (2018) and also reflect some of the experiences reported by the developers of a building LCA tool in Denmark (Kanafani et al., 2021). Furthermore, ideas to visualize the results such as a heat map on the 3D model were mentioned by Meex et al. (2018) and had previously been implemented, e.g., by Röck et al. (2018). Other features such as the high importance of the assessment of the load-bearing foundations were especially emphasized by the test users went beyond the main requirements defined in the literature. Some features were only mentioned by one or a few interviewees and finally the authors sorted out those they considered relevant for an early-stage LCA tool based on the Swedish climate declaration, the literature, and their own experiences. Some of the interviewees talked about the relevance of using sector EPDs in simplified tools and early stages, for example. This was however not implemented, as the use of generic values in the national database was valued higher. Most interviewees did not put high value in connecting the tool to certifications at this stage. The question about visualizing transport distances in the tool confused some of the interviewees. It turned out to not be a relevant question to ask, as the same question was not asked regarding other LCA modules. In summary, it can be stated that the interviews confirmed most requirements mentioned in the literature but provided answers with much higher detail in the local context.

Some interviewees already provided valuable ideas how to meet their requirements. Furthermore, the interviews provided a local stakeholder perspective that is influenced by the national regulation. For example, it was agreed upon between most interviewees that using GWP as single indicator and limiting the system boundaries to A1–A5 is sufficient for the first version of the tool. These perspectives will probably be different in other countries with other national regulations. In Germany, for example, the certification systems by the German Sustainable Building Council (DGNB)[11] is a common reference with regards to LCA and it includes five output related environmental indicators and the life cycle modules A1–A3, B4, C3, C4, and D. This shows that a local stakeholder perspective is important to consider.

Regarding the tool development, there is a fine line between simplifying the workflows making the results less accurate, and detailing the workflows making the tool harder to use but the results more trustworthy. The tool developed in this study is trying to balance this by providing the opportunity to have either pre-set or customized combinations of materials. On the same note, the geometry built in Rhinoceros can be detailed providing an accurate modelling alternative or be modelled in a parametric way in Grasshopper, with less detail but with more flexibility.

To reach the climate targets, there is a need for negative GHG emissions. Hence, it is of value to study bio-based materials as carbon sinks (Hoxha et al., 2020) and visualize materials that store CO_2. As this is not accounted for neither in the Boverket database nor the climate declarations of 2022, it was not included in the current version of the tool.

When asked about potential barriers to implementing such a tool in their work, the first point that was mentioned was not the limitations of the tool but the current "business as usual" way of working. The tool user might not be the one making decisions and the workflow in the companies might not be adapted for the climate declaration, yet. This shows that LCA tools can support and be a small part of the transition to climate-friendly building design but the architectural, engineering and construction sector has to evolve as a whole. The interviewees acknowledged that the industry will be more digitalized and in a couple of years there will be a more parametric approach where data informs the design. As one interviewee framed it "LCA calculations is a staggering new subject. A lot of people are working on it, and I think it is only the beginning. The tools developed today is only the first iteration of upcoming, more comprehensive tools."

4.2 Limitations

The interviews were limited to thirteen stakeholders. Most of the answers aligned well. Therefore, we assumed that increasing the number of participants would not have provided many more insights and that we have reached a point of saturation with regards to the most important tool features. However, we did not follow a structured approach to define the required sample size. Guest et al. (2006) explain the challenges of finding the point of saturation in qualitative methods and report reaching saturation after twelve interviews, while at the same time cautioning against assuming that twelve interviews will always be enough to achieve a desired research objective. Therefore, this aspect should be considered when applying the proposed framework in the future. Galvin (2015) provides a statistical framework to define the probability of a certain theme being mentioned in the interviews depending on the number of interviewees. Following his approach, 13 interviews reveal all the themes that at least 20% of the targeted population share with a probability of 94.5%. However, this requires the sample to be random. Here, the choice of interviewees might have introduced biased results as most of them are sustainability or digitalization experts within their organizations. This also explains the high interest and motivation for the topic. The interviewees rated their experience of digital tools with an average of 3.5 higher than their LCA experience with 2.8 on a scale from one to five. Within the group of architects, the experience with computational design was rated 4.8 while the LCA experience was rated with an average of 1.8. Most

[11]German Sustainable Building Council, 2015. DGNB system. http://www.dgnb-system.de/en/(accessed 02.02.2022).

participants came from medium to large companies. Therefore, the results from the interviews cannot be seen as representative for all architects, real estate developers and engineers in Sweden. However, we assume them to be representative for the share within each group with a certain interest in sustainability or digitalization working in medium to large companies. This group can be expected to be the early adopters of a novel LCA tool.

The user test with twelve participants was more limited. The survey brought valuable feedback regarding the applicability of the developed tool. However, additional tests should be carried out to confirm the answers. Eight of the test users had not participated in the interviews earlier, which could make the results from the interviews and the user tests less comparable. The question of how much knowledge of 3D modelling is needed resulted in a wide spread of the responses, see **Figure 8**. Different backgrounds of the test users might affect their apprehension of what is advanced 3D modelling and architects rated the required experience lower than the other professions. This could be explaind by their experience in computational design. The architects who tested the rool rated their experience high with an average of 4.2, while real estate developers rated their experience with an average of 2.7.

The functional unit of m^2 A_{temp} currently does not consider the comparability of e.g., structural ability, thermal mass, and overall U-value of the building. Users need to compare these performance criteria separately. As the tool currently only includes the production and construction phases, trade-offs with the operational phase, for example the energy use (module B6), do not become apparent directly. Design for disassembly and circularity aspects are also not considered, which would affect the end-of-life phases. In the current database from Boverket, the data in the modules A4 (transport to site) and A5.1 (spill, packaging, and waste management) might be less accurate than the data in A1–A3 (the production stage), as A4 and A5.1 can have a great variation depending on the project. The validation of the correct calculation of the tool was only done by comparing the results of one case study to an established Swedish building LCA tool BM. The mapping of materials in BM were at times hard to interpret. Furthermore, the detailed drawings do not show every cross-section of each building element in the building and hence it was not possible to model each element accurately in the tool. The case study served the purpose of a first validation of the developed prototype; however, further validation would be needed before applying it in real projects. Another future possibility would be an external validation by a certification institute, as it is done for LCA software for BREEAM[12] or the Swiss Minergie Eco system[13], for example. However, there is currently no valiation process provided by the Swedish Green Building Council.

4.3 Future Developments

In this study, the tool was implemented in Grasshopper, which is increasingly used for building design, but multiple interviewees stated that Grasshopper is hard to learn. The approach and the script could also be linked to ArchiCAD, Sketchup or Revit through other visual scripting tools like Dynamo or RhinoInside.

Many interviewees stressed the need to focus on structures, especially deep foundations, that are deeply affected by the choice of site. The impact of load-bearing elements and foundation is hard to predict in early stages. The load-bearing concepts in the tool are taken from a structural engineering report and the foundation is set by stating a thickness of a ground slab; however, piles were not modelled. Therefore, we would like to encourage further studies in the area.

In the future, additional life cycle modules should be added to provide a more holistic life cycle perspective. The operational energy use (module B6) could be integrated by linking other tools for Grasshopper, e.g., BeDOT (Gomez et al., 2019). As preparation for the future adaptions to the climate declaration in 2027, the life cycle modules B2, B4, and C1–C4 should also be added, as soon as Boverket provides the data in their database or a representative number of EPDs is available for the Swedish context.

The user test confirmed the importance of visualizing the results. The 3D heat map shows the impact of each element, but not the room for lowering the impact. Both average values for building components and best practice examples as yardstick would support users in identifying the optimization potential. Hollberg et al. (2019) developed such benchmarks for the Swiss context that could be adapted for the Swedish context.

5 CONCLUSION

This paper described a structured process to involve target users in the design and development process of a building specific LCA tool for early stages. Interviews with thirteen stakeholders from medium to large companies defined the requirements and most important features for the tool. A prototype was developed based on the interview responses and the national regulation in Sweden. The prototype was tested by twelve intended users and a survey was used to collect feedback. The responses show that the tool meets most expectations of the users. It allows getting a quick overview of the climate impact of a building. It was perceived as structured, pedagogical, and user-friendly. Suggestions for further improvement mainly consisted of adding more predefined building components, improving the assessment of foundations and structural parts, and providing more export and visualization options for the results.

[12]https://kb.breeam.com/knowledgebase/building-lca-tools-recognised-by-breeam/(accessed 24.04.2022).

[13]https://www.ecobau.ch/de/instrumente/oekobilanzen/fuer-softwareentwickler (accessed 24.04.2022).

Previous tool developments did not involve the target users in a structured way. The results presented here show the importance of involving the target users in the tool development process and that the expectations can be met when the requirements are integrated from the very beginning. The interview and survey process in the paper was limited due to the limited number of participants. Furthermore, the development of the tool reached a prototype level, but further user tests and workshops are needed to iteratively improve the tool. Nevertheless, the initial success shows that the structured approach followed in this paper can serve as a blueprint for building LCA tool developers in other countries.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

Conception or design of the work; MT, AH, GI, and HW. Data collection; MT. Data analysis and interpretation; MT, AH, and GI. Drafting the article; AH. Critical revision of the article; AH, MT, GI, and HW. Final approval of the version to be published; AH, MT, GI, and HW.

FUNDING

We thank the Swedish Energy Agency for providing funding for this work via the E2B2 grant 51715-1.

ACKNOWLEDGMENTS

We would like to thank all interviewees and test users for their participation and valuable feedback. Furthermore, we would like to thank Alina Galimshina for her support with the statistical treatment of the results.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2022.744946/full#supplementary-material

REFERENCES

Abbasnejad, B., Nepal, M. P., Ahankoob, A., Nasirian, A., and Drogemuller, R. (2020). Building Information Modelling (BIM) Adoption and Implementation Enablers in AEC Firms: a Systematic Literature Review. *Archit. Eng. Des. Manag.* 17, 411–433. doi:10.1080/17452007.2020.1793721

Antón, L. Á., and Díaz, J. (2014). Integration of Life Cycle Assessment in a BIM Environment. *Procedia Eng.* 85, 26–32. doi:10.1016/j.proeng.2014.10.525

Bach, R., Mohtashami, N., and Hildebrand, L. (2019). Comparative Overview on LCA Software Programs for Application in the Façade Design Process. *J. Facade Des. Eng.* 7, 13–26. doi:10.7480/jfde.2019.1.2657

Basbagill, J., Flager, F., Lepech, M., and Fischer, M. (2013). Application of Life-Cycle Assessment to Early Stage Building Design for Reduced Embodied Environmental Impacts. *Build. Environ.* 60, 81–92. doi:10.1016/j.buildenv.2012.11.009

Basic, S., Hollberg, A., Galimshina, A., and Habert, G. (2019). "A Design Integrated Parametric Tool for Real-Time Life Cycle Assessment - Bombyx Project," in IOP Conference Series: Earth and Environmental Science(Bristol, UK: IOP Science), 323 012112. doi:10.1088/1755-1315/323/1/012112

Beemsterboer, S., Baumann, H., and Wallbaum, H. (2020). Ways to Get Work Done: a Review and Systematisation of Simplification Practices in the LCA Literature. *Int. J. Life Cycle Assess.* 25, 2154–2168. doi:10.1007/s11367-020-01821-w

Caetano, I., and Leitão, A. (2020). Architecture Meets Computation: an Overview of the Evolution of Computational Design Approaches in Architecture. *Archit. Sci. Rev.* 63, 165–174. doi:10.1080/00038628.2019.1680524

CEN (2012). *EN 15804: Sustainability of Construction Works - Environmental Product Declarations - Core Rules for the Product Category of Construction Products (Government Document)*. Brussels, Belgium: European Committee for Standardization.

CEN (2011). *EN 15978: Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method (Brussels, Belgium: European Committee for Standardization)* .

Chen, C., Habert, G., Bouzidi, Y., Jullien, A., and Ventura, A. (2010). LCA Allocation Procedure Used as an Incitative Method for Waste Recycling: An Application to Mineral Additions in Concrete. *Resour. Conservation Recycl.* 54, 1231–1240. doi:10.1016/j.resconrec.2010.04.001

D'Amico, B., and Pomponi, F. (2018). Accuracy and Reliability: A Computational Tool to Minimise Steel Mass and Carbon Emissions at Early-Stage Structural Design. *Energy Build.* 168, 236–250. doi:10.1016/j.enbuild.2018.03.031

Davis, D. (2013). *Modelled on Software Engineering : Flexible Parametric Models in the Practice of Architecture*. Melbourne: RMIT University.

Galvin, R. (2015). How Many Interviews Are Enough? Do Qualitative Interviews in Building Energy Consumption Research Produce Reliable Knowledge? *J. Build. Eng.* 1, 2–12. doi:10.1016/j.jobe.2014.12.001

Gomez, R. B., Fantin Do Amaral Silva, G., Tillberg, M., and Sasic Kalagasidis, A. (2019). "Energy Performance Modelling: Introducing the Building Early-Stage Design Optimization Tool (BeDOT)," in Proceedings of Building Simulation 2019: 16th Conference of IBPSA.

Gradin, K. T., and Björklund, A. (2021). The Common Understanding of Simplification Approaches in Published LCA Studies-A Review and Mapping. *Int. J. Life Cycle Assess.* 26, 50–63. doi:10.1007/s11367-020-01843-4

Guest, G., Bunce, A., and Johnson, L. (2006). How Many Interviews Are Enough? Do Qualitative Interviews in Building Energy Consumption Research Produce Reliable Knowledge? *J. Build. Eng.* 1, 2–12. doi:10.1016/j.jobe.2014.12.001

Hamilton, I., and Rapf, O. (2020). *Executive Summary of the 2020 Global Status Report for Buildings and Construction*.

Heller, G. Z., Manuguerra, M., and Chow, R. (2016). How to Analyze the Visual Analogue Scale: Myths, Truths and Clinical Relevance. *Scand. J. Pain* 13, 67–75. doi:10.1016/j.sjpain.2016.06.012

Hester, J., Miller, T. R., Gregory, J., and Kirchain, R. (2018). Actionable Insights with Less Data: Guiding Early Building Design Decisions with Streamlined Probabilistic Life Cycle Assessment. *Int. J. Life Cycle Assess.* 23, 1903–1915. doi:10.1007/s11367-017-1431-7

Hollberg, A., Genova, G., and Habert, G. (2020). Evaluation of BIM-Based LCA Results for Building Design. *Automation Constr.* 109, 102972. doi:10.1016/j.autcon.2019.102972

Hollberg, A., Kiss, B., Röck, M., Soust-Verdaguer, B., Wiberg, A. H., Lasvaux, S., et al. (2021). Review of Visualising LCA Results in the Design Process of Buildings. *Build. Environ.* 190, 107530. doi:10.1016/j.buildenv.2020.107530

Hollberg, A., Lützkendorf, T., and Habert, G. (2019). Top-down or Bottom-Up? – How Environmental Benchmarks Can Support the Design Process. *Build. Environ.* 153, 148–157. doi:10.1016/j.buildenv.2019.02.026

Hollberg, A., and Ruth, J. (2016). LCA in Architectural Design-A Parametric Approach. *Int. J. Life Cycle Assess.* 21, 943–960. doi:10.1007/s11367-016-1065-1

Hoxha, E., Passer, A., Saade, M. R. M., Trigaux, D., Shuttleworth, A., Pittau, F., et al. (2020). Biogenic Carbon in Buildings: a Critical Overview of LCA Methods. *Build. Cities* 1, 504–524. doi:10.5334/bc.46

Hu, M., and Milner, D. (2020). Visualizing the Research of Embodied Energy and Environmental Impact Research in the Building and Construction Field: A Bibliometric Analysis. *Dev. Built Environ.* 3, 100010. doi:10.1016/j.dibe.2020.100010

ISO 14040 (2006). *Environmental Management-Life Cycle Assessment-Principles and Framework(Geneva, Switzerland: International Organization for Standardization).*

ISO 14044 (2006). *Environmental Management-Life Cycle Assessment-Requirements and Guidelines(Geneva, Switzerland: International Organization for Standardization).*

Kanafani, K., Kjær Zimmermann, R., Nygaard Rasmussen, F., and Birgisdóttir, H. (2021). Learnings from Developing a Context-specific LCA Tool for Buildings-The Case of LCAbyg 4. *Sustainability* 13, 1508–1523. doi:10.3390/su13031508

Kiamili, C., Hollberg, A., and Habert, G., 2020. Detailed Assessment of Embodied Carbon of HVAC Systems for a New Office Building Based on BIM. *Sustainability*, 12, 3372. doi:10.3390/su12083372

Kiss, B., and Szalay, Z. (2020). Modular Approach to Multi-Objective Environmental Optimization of Buildings. *Autom. Constr.* 111, 103044. doi:10.1016/j.autcon.2019.103044

Kong, M., Lee, M., Kang, H., and Hong, T. (2021). Development of a Framework for Evaluating the Contents and Usability of the Building Life Cycle Assessment Tool. *Renew. Sustain. Energy Rev.* 150, 111475. doi:10.1016/j.rser.2021.111475

Lawson, B. (2005). *How Designers Think: The Design Process Demystified*. 4th edition. New York: Routledge, Taylor and Francis Group.

Lobaccaro, G., Wiberg, A. H., Ceci, G., Manni, M., Lolli, N., and Berardi, U. (2018). Parametric Design to Minimize the Embodied GHG Emissions in a ZEB. *Energy Build.* 167, 106–123. doi:10.1016/j.enbuild.2018.02.025

Malmqvist, T., Glaumann, M., Scarpellini, S., Zabalza, I., Aranda, A., Llera, E., et al. (2011). Life Cycle Assessment in Buildings: The ENSLIC Simplified Method and Guidelines. *Energy* 36, 1900–1907. doi:10.1016/j.energy.2010.03.026

Meex, E., Hollberg, A., Knapen, E., Hildebrand, L., and Verbeeck, G. (2018). Requirements for Applying LCA-Based Environmental Impact Assessment Tools in the Early Stages of Building Design. *Build. Environ.* 133, 228–236. doi:10.1016/j.buildenv.2018.02.016

Meex, E., Knapen, E., and Verbeeck, G. (2016). "User-friendliness of Current Building Environmental Impact Assessment Tools: an Architect ' S Perspective," in *Sustainable Built Environment* (Hamburg: ZEBAU GmbH, 1306–1315.

Nair, G., Fransson, Å., and Olofsson, T. (2021). Perspectives of Building Professionals on the Use of LCA Tools in Swedish Climate Declaration. *E3S Web Conf.* 246, 13004–13006. doi:10.1051/e3sconf/202124613004

Naneva, A., Bonanomi, M., Hollberg, A., Habert, G., and Hall, D. (2020). Integrated BIM-Based LCA for the Entire Building Process Using an Existing Structure for Cost Estimation in the Swiss Context. *Sustainability* 12, 3748. doi:10.3390/su12093748

Pomponi, F., Anguita, M. L., Lange, M., D'Amico, B., and Hart, E. (2021). Enhancing the Practicality of Tools to Estimate the Whole Life Embodied Carbon of Building Structures via Machine Learning Models. *Front. Built Environ.* 7, 1–11. doi:10.3389/fbuil.2021.745598

Potrč Obrecht, T., Röck, M., Hoxha, E., and Passer, A. (2020). BIM and LCA Integration: A Systematic Literature Review. *Sustainability* 12, 5534. doi:10.3390/su12145534

Roberts, M., Allen, S., and Coley, D. (2020). Life Cycle Assessment in the Building Design Process - A Systematic Literature Review. *Build. Environ.* 185, 107274. doi:10.1016/j.buildenv.2020.107274

Röck, M., Hollberg, A., Habert, G., and Passer, A. (2018). LCA and BIM: Visualization of Environmental Potentials in Building Construction at Early Design Stages. *Build. Environ.* 140, 153–161. doi:10.1016/j.buildenv.2018.05.006

Russell-Smith, S. V., Lepech, M. D., Fruchter, R., and Meyer, Y. B. (2015). Sustainable Target Value Design: Integrating Life Cycle Assessment and Target Value Design to Improve Building Energy and Environmental Performance. *J. Clean. Prod.* 88, 43–51. doi:10.1016/j.jclepro.2014.03.025

Safari, K., and AzariJafari, H. (2021). Challenges and Opportunities for Integrating BIM and LCA: Methodological Choices and Framework Development. *Sustain. Cities Soc.* 67, 102728. doi:10.1016/j.scs.2021.102728

Soust-Verdaguer, B., García Martínez, A., Llatas, C., Gómez de Cózar, J. C., Allacker, K., Trigaux, D., et al. (2020). Implications of Using Systematic Decomposition Structures to Organize Building LCA Information: A Comparative Analysis of National Standards and Guidelines- IEA EBC ANNEX 72. *IOP Conf. Ser. Earth Environ. Sci.* 588, 022008. doi:10.1088/1755-1315/588/2/022008

Succar, B. (2009). Building Information Modelling Framework: A Research and Delivery Foundation for Industry Stakeholders. *Automation Constr.* 18, 357–375. doi:10.1016/j.autcon.2008.10.003

Tabrizi, T. B., and Brambilla, A. (2019). Toward LCA-Lite: A Simplified Tool to Easily Apply LCA Logic at the Early Design Stage of Building in Australia. *Eur. J. Sustain. Dev.* 8, 383. doi:10.14207/ejsd.2019.v8n5p383

Ylmén, P., Peñaloza, D., and Mjörnell, K. (2019). Life Cycle Assessment of an Office Building Based on Site-specific Data. *Energies* 12, 2588. doi:10.3390/en12132588

Conflict of Interest: Authors GI and MT were employed by Bengt Dahlgren AB.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.