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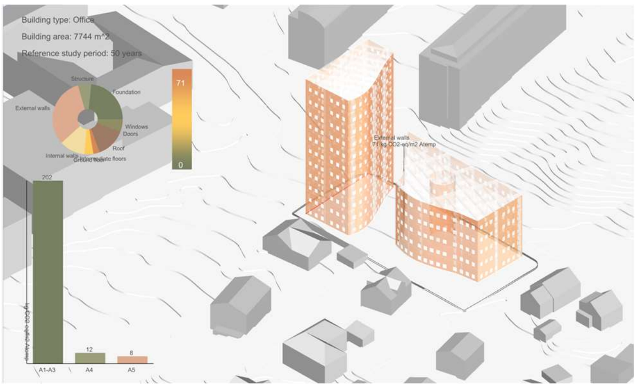

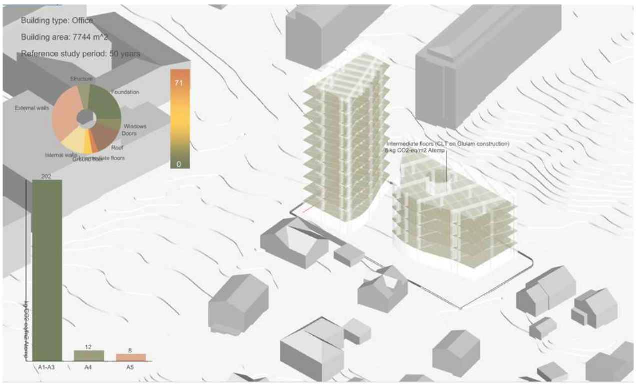

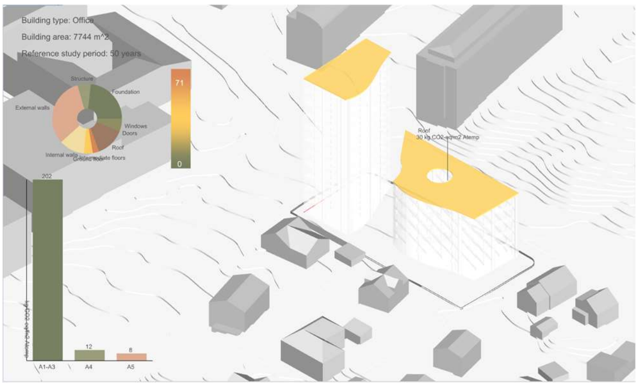

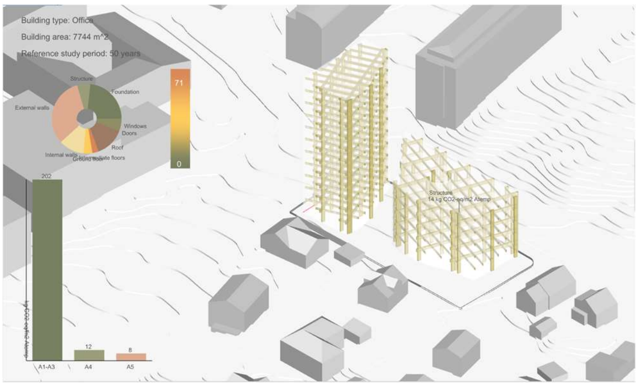

Optimized early-stage life cycle assessment of buildings

Developing a tool enabling early-stage parametric life cycle assessment

Master's thesis in Industrial Ecology

MARIA E. TJÄDER

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF BUILDING TECHNOLOGY

CHALMERS UNIVERSITY OF TECHNOLOGY
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MASTER'S THESIS ACEX30

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Cover:
Results shown in the tool. Further explanation in Chapter 6.
Department of Architecture and Civil Engineering.
Göteborg, Sweden, 2021

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ABSTRACT

In the early stages of a building project, there is low quantity and quality of data regarding building materials while the ability to influence the environmental impact is high. Easy ways of assessing environmental impact of materials in these stages can make a big difference and shift buildings' contribution to global warming towards a more sustainable track.

The aim of the thesis project was to develop a parametric tool enabling early-stage Life Cycle Assessment (LCA) of buildings. The tool focus at guiding the user in lowering the embodied carbon from buildings by assessing building materials and building shapes. The tool also seeks to be educational about the climate impact from the production phase of buildings, and the intended user group is architects. The method of the thesis followed three steps:

- requirement definitions based on interviews and a tool and literature review
- tool development
- case studies for validation

The interviews were a crucial step to inform the later tool development and to make sure the tool is usable by the intended target group. From the interviews it was found that important features of an early-stage LCA tool are to use national, generic data, show the results in a visual way and make it fast and easy to use. Additional results from the interviews are identified industry needs and challenges.

The case studies included user tests and numerical tests. The developed tool fills most criteria set by the interviewees; however, further validation of the load-bearing concepts is asked for. The tool manages to balance a high level of detail and a user-friendly interface, and the calculated results are within a 15% accuracy. The thesis project shows that the integration of the users' needs and expectations from the very beginning of the development of assessment tools will ensure the tools' applicability in the design process.

Key words: Life cycle assessment, early-stage design, optimization tools, climate impact, sustainable architectural design

Optimerad livscykelanalys av byggnader i tidiga skeden

Utveckling av ett verktyg som möjliggör parametrisk livscykelanalys i tidiga skeden

Examensarbete inom mastersprogrammet Industriell Ekologi

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SAMMANFATTNING

I byggnaders tidiga designskeden är kvaliteten och kvantiteten på data kring byggnadens material låg men det finns en stor potential att sänka miljöpåverkan. Förenklade sätt att uppskatta klimatpåverkan i dessa skeden kan göra stor skillnad och styra byggnaders bidrag till den globala uppvärmningen i en mer hållbar riktning.

Examensarbetets syfte var att utveckla ett parametriskt verktyg som möjliggör livscykelanalys (LCA) i tidiga skeden. Verktygets fokus är att leda användaren till sänkningar av inbyggd klimatpåverkan från byggnader genom att utvärdera olika byggnadsmaterial och byggnadsutformningar. Verktyget fokuserar även på att vara utbildande kring klimatpåverkan från produktionsfasen av byggnader och målgruppen är arkitekter. Examensarbetets metod följde tre steg:

- definition av behov baserat på intervjuer samt litteratur- och verktygsstudier
- verktygsutveckling
- fallstudier för validering

Intervjuer som metod påverkade utvecklingen av verktyget och säkerställde användbarheten för målgruppen. Från intervjuerna kom det fram att det för ett LCA-verktyg i tidiga skeden är viktigt att använda nationell, generisk data, visa resultaten på ett visuellt sätt och att verktyget är effektivt och enkelt att använda. Ytterligare resultat är identifierade behov och utmaningar som branschen står inför.

Fallstudierna bestod av användartest samt numeriska test av verktyget. Det utvecklade verktyget uppfyller de flesta önskemålen från intervjuobjekten men en ytterligare validering av konstruktionstyperna önskas. Verktyget balanserar en hög detaljeringsgrad med en god användarvänlighet och de beräknade resultaten är inom en 15% felmarginal. Examensarbetet visar att om man integrerar användares behov och förväntningar tidigt i utvecklingen av analysverktyg så kan man säkra tillämpligheten i designprocessen.

Nyckelord: Livscykelanalys, design i tidiga skeden, optimeringsverktyg, klimatpåverkan, hållbar arkitektur

Contents

Preface

In this study, early-stage life cycle assessment (LCA) has been explored through interviews, tool and literature reviews, tool development and case studies. The work has been carried out from January to May 2021. The report is the result of a Master's thesis of 30 ECTS in the Master's programme of Industrial Ecology.

The work has been conducted at the department of Architecture and Civil Engineering, division of Building Technology, at Chalmers University of Technology, Sweden with external supervision from Bengt Dahlgren AB (BDAB), Gothenburg, Sweden. The project has been carried out with Assistant Professor Alexander Hollberg and Energy and Environmental Engineer Gerda Ingelhag as supervisors and Full Professor Holger Wallbaum as examiner.

I would thereby like to thank Alexander Hollberg for giving academic guidance and excellent support in the field of tool development and LCA. I would also like to thank Gerda Ingelhag for widening perspectives, sharing her great knowledge and experience, and for providing the Swedish building industry perspective on LCA. Further, I would like to thank Holger Wallbaum for giving valuable feedback.

Thank you to the employees at Bengt Dahlgren AB, especially Linda Wäppling, Giovana Fantin Do Amaral Silva and Maria Perzon for your endless support and inspiration. Thank you for sharing resources and opening up your network enabling the interviews.

Further, it should be noted that the thesis could never have been conducted without the rewarding meetings with the interviewees. A special thanks to Alexander Radne and Fraser Greenroyd for computational development advice, encouragement and good laughs. Thank you Martin Lindholm and Elin Lidén for providing a site model for the parametric modelling.

Lastly, I would like to bring a special thanks to my family and friends. Thank you for the support and encouragement throughout my educational years at Chalmers University of Technology.

Gothenburg, May 2021

Maria Eleonora Tjäder

Abbreviations and Definitions

Atemp	Heated building area excluding external walls
BBR	Boverket's Building Regulations
BDAB	The company Bengt Dahlgren AB
BIM	Building Information Modelling
BM	Byggsektorns Miljöberäkningsverktyg (LCA Software)
BOA	Building area for residential use
Boverket	The Swedish National Board of Housing, Building and Planning
BRA	Building area excluding external walls
BTA	Building area including external walls
CAD	Computer Aided Design
CO_2-eq	Carbon dioxide equivalents
Cradle to gate	Resource extraction to finished product A1-A3
Cradle to grave	Resource extraction to end of life A1-C4
Cradle to handover	Resource extraction to construction and installation A1-A5
Cradle to site	Resource extraction to transport to site A1-A4
EPD	Environmental Product Declaration
Functional unit	Measure of function and provides reference flow in LCA
GWP	Global Warming Potential
IVL	The Swedish Environmental Research Institute
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LOA	Building area for premises
NTA	Building area excluding external and internal walls
VPL	Visual Programming Language

Life cycle phases for buildings

A1-A3	Production
A4-A5	Construction and installation
B1-B7	Use
C1-C4	End of life
D	Benefits and loads

Tables and figures

Tables and figures stated without source are made by the author of the thesis.

1 Introduction

In this chapter the background, aim, research questions, delimitations, audience and outline of the thesis are presented.

1.1 Background

Society today is facing severe environmental problems that has accelerated with population growth and the great impact of current technologies (Hedenus et al., 2018). Some of the challenges are climate change, chemical risks and resource constraints on land, materials, and energy (Baumann & Tillman, 2004). The building industry has a great part to play in the sustainability transition, as the construction and use of buildings in the EU accounts for approximately half of the used energy and extracted resources in the region (European Commission, 2014). The shift from local materials with low energy costs to global materials like cement, aluminium, concrete, and PVC has brought high environmental impact (Bribián et al., 2009).

Life Cycle Assessment (LCA) is a recognised methodology for assessing the environmental impact of products and services (Baumann & Tillman, 2004). It gives a holistic view of a product or service life cycle and can include the phases of extraction, manufacturing, use and end-of-life (SIS, 2006). LCA is used within the building industry and is part of environmental certifications like Miljöbyggnad, BREEAM and LEED (Boverket, 2019). Starting from January 1st, 2022, climate declarations will be required for new construction in Sweden (Boverket, 2020b), putting the spotlight on LCA even more.

The thesis focuses on assessing the climate impact of design changes in early project stages through LCA. In the early stages, decisions taken by designers and architects have a large impact on the final design of the building, while the costs of decisions and design effort are still very low (Li, 2017). The building's systems and materials are decided in these early stages, and the choices can deeply affect the final climate impact.

To create a design-integrated workflow a tool is developed in the thesis. The tool is connected to the work by Fantin do Amaral Silva & Bergel Gómez (2018) and Wäppling (2019) and the LCA part takes inspiration from the work by Berger-Vieweg (2020).

1.2 Aim

The aim of the thesis is to develop a tool for early-stage LCA. The tool should be rooted in the Swedish building industry and seeks to encourage life cycle thinking in early-stage building design by exploring its application and variations. The tool should focus at guiding the user in lowering the embodied carbon from buildings by assessing building materials and building shapes. The tool also seeks to be educational about the climate impact of the production phase of buildings, and the intended user group will be specified from the interview results.

The developed tool aims to inform the designer of potential effects of decisions and hence give the user the freedom to focus on conceptual design in early stages. The tool is developed in Grasshopper which is a Visual Programming Language (VPL) plug-in within the Computer Aided Design (CAD) software Rhinoceros.

1.3 Research question

Below, the research question is presented.

- How can design-integrated early-stage tools based on LCA be applied to increase the understanding of and help decrease the climate impact from the production phase of buildings?
    - [part 1] What is required…
      …in terms of input data and results?
      …in terms of transparency?
      …in terms of connection to a 3D model?
      …in terms of calculation speed?
      …in terms of software skills and LCA experience of the user?
    - [part 2] Does the developed tool fulfil the above-mentioned requirements?
    - [part 3] Are the LCA results from the developed tool within a 15% accuracy?

1.4 Delimitations

From interviews with stakeholders, the development of the tool will be narrowed down to focus on few, specific users. LCA specific delimitations are presented in section 5.1.5.

1.5 Audience

The targeted audience of the thesis is architects, sustainability and building technology engineers, real estate developers and software developers. The audience is also the research field of LCA and sustainable building design.

1.6 Outline of thesis

The thesis report consists of 8 chapters. The first chapter holds the introduction, and the second chapter provides theory on building floor area definitions, parametric design, LCA and its connection to the building industry, environmental certifications and climate declarations. Chapter 3 introduces the method of research for the literature review, the interviews and the tool review and chapter 4 the results of them. Chapter 5 introduces the method of research for the tool development and the case studies, influenced by the results in chapter 4. Chapter 6 presents the results of the tool development and case studies. The discussion is presented in chapter 7 and, finally, conclusions are made in chapter 8.

2 Theory

The theory chapter gives a brief overview of floor area definitions, parametric design and introduces LCA and its connection to the building industry. The chapter also handles how LCA is accounted for in environmental certifications and the upcoming Swedish climate declarations.

2.1 Building floor area definitions

There are several building floor area definitions in Sweden, and they are used in different ways in LCA calculations. Some of them will be presented in this section.

Bruttoarea (BTA) is the area of spaces measured from the outside of the external walls (SIS, 2005). It includes all floor levels, the attic and the basement. Area covered by e.g. internal walls, stairs and ramps are included. Floor slab openings without stairs and ramps are not included.

Nettoarea (NTA) is the area of spaces measured from the inside of adjacent building elements (SIS, 1989) and hence it is an addition of all spaces in a building without the internal walls.

Bruksarea (BRA) is the area of spaces measured from the inside of the external walls (SIS, 2005). It includes all floor levels, the attic and the basement. Area covered by e.g. internal walls thinner than 0.3m and stairs and ramps are included. Shafts thicker than 0.3m are not included, if not directly connected to a wall. BRA can be divided into Biarea (BIA), Boarea (BOA), Lokalarea (LOA) and Övrig area (ÖVA).

BOA is the area of a building that is meant for residential use (SIS, 2005). LOA is the area for garage, business, staff rooms and stairs and ramps within the apartment.

Atemp is the area of spaces measured from the inside of the external walls (Boverket, n.d.). The spaces included must be intended to be heated more than 10°C, and it includes all floor levels, the attic and the basement if heated. Area covered by e.g. internal walls and stairs is included while built-in garages are not included.

2.2 Parametric design

In conventional design, values defining the design are fixed (Graciano, 2020). In parametric design however, chosen values are rather defined by parameters enabling variable and dynamic inputs. One or several values are assigned to each parameter, affecting the output. More parameters make a greater number of possible solutions. The applications of parametric tools in architecture are within simulations, automation, optimizations and digital fabrication, to name a few (Radziszewski & Cudzik, 2019). The use of parametric design is further described in the citation below.

Designers have begun using parametric design software, which allows them to specify relationships among various parameters of their design model. The advantage of such an approach is that a designer can then change only a few parameters and the remainder of the model can react and update accordingly (Jabi, 2013, p. 9-11).

Rhinoceros is a 3D modelling software that can create, edit, analyse, document, render, animate, and translate different types of geometry with high complexity (Rhino3D, 2021). Grasshopper is a graphical algorithm editor integrated with Rhinoceros (Grasshopper3D, 2021). It allows designers to build form generators, but it does not require programming or scripting knowledge.

The programming language C# is an object-oriented and type-safe language (Microsoft, 2021). It enables users to build applications running in the .NET ecosystem. Visual studio is an integrated development environment which is a workspace for editing, debugging and building code (Microsoft 2019). The code can be written in C# and components built in Visual studio can be used in Grasshopper.

The master theses by Fantin do Amaral Silva & Bergel Gómez (2018), Wäppling (2019) and Berger-Vieweg (2020) include parametric tool development in Grasshopper. It has served as an inspiration for the tool development in this thesis. The work by Fantin do Amaral Silva & Bergel Gómez (2018), Wäppling (2019) has resulted in a BeDOT – a tool for early-stage energy calculation and daylight analysis.

2.3 Life cycle assessment

LCA assesses the environmental impact of a product or service across its life cycle (SIS, 2006) . The standard ISO 14040 sets the principles and framework for LCA whereas ISO 14044 provides requirements for conducting the assessment. Applications of LCA are decision making (e.g. for policy instruments), learning/exploration (e.g. identification of improvements) and communication (e.g. labelling and environmental product declarations). The assessment is divided in four steps: Goal and scope definition, Inventory analysis, Impact assessment and Interpretation as shown in Figure 1.

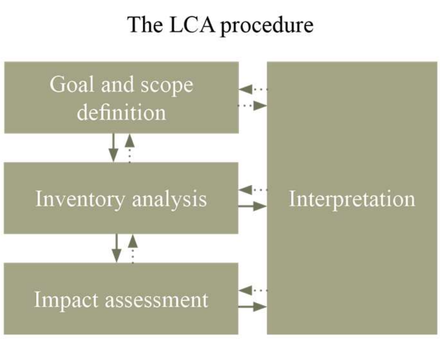


Figure 1. The procedure of LCA. Adapted from SIS (2006).

2.3.1 Goal and scope

The product to be studied and the purpose of the study are decided in the goal and scope definition (Baumann & Tillman, 2004). Specifications as functional unit, system boundaries, environmental impacts considered, and level of detail are set. The functional unit expresses the function in quantitative terms and makes the study comparable to other studies. Examples of functional units for different products and services are presented below.

Product/service	*Functional unit*
Wallpaper/paint	m^2 and year
Passenger transportation	person and km
Light bulbs	specified lux and year (use time)
Building	m^2 heated area and year

The system boundaries specify the boundaries in relation to natural systems, technical systems, geography and time. Boundaries to the natural and technical systems are set by specifying which life cycle phases to be studied (Figure 2) and how to handle allocation. The environmental impacts to be studied are decided in the goal and scope and they are divided into impact categories. Examples of impact categories are land use, global warming, eutrophication, and acidification.

Figure 2. Life cycle phases. Adapted from Golsteijn (2020).

In the goal and scope, one also defines whether the study is attributional or consequential (Baumann & Tillman, 2004). An attributional LCA looks at questions like "What environmental impact can be associated with this product?" while a consequential LCA looks at "What would happen if…?". The different types affect system boundaries, allocation, choice of data and system subdivision.

2.3.2 Inventory analysis

The inventory analysis consists of the construction of a flow model, data collection and calculation (Baumann & Tillman, 2004). The flow model holds activities like production, processing, transport, use and waste management and the flows between the activities. The data collection consists of collecting information of what goes into the system such as resources in the form of e.g. materials, water and energy. The data collection also handles emissions and solid waste that leaves the system and goes into air, ground and water. The calculation part looks at what enters the system (e.g. mineral use) and what leaves the system (e.g. pollutant emissions) in relation to the functional unit.

2.3.3 Impact assessment

The impact assessment connects the inventory results to the chosen impact categories (Baumann & Tillman, 2004). The process consists of the mandatory steps of classification and characterisation and the optional step of weighting. The classification classifies what inventory results contributes to what impact categories. Characterisation looks at the relative contribution to the impacts and aggregates e.g. the emissions to one indicator. An example of characterisation is the contribution of methane (CH_4) and Carbon dioxide (CO_2) to the impact category global warming. The contribution of 1kg CH_4 is about 50 times higher than the contribution of 1 kg CO_2, if looking at 20 years of global warming. To be able to compare different product's contributions to global warming, the different trace gases are measured in kg CO_2-eq. 1kg CH_4 gives 56 kg CO_2-eq and 1kg CO_2 gives 1 kg CO_2- eq. To aggregate the impact assessment even further, weighting can be done. Weighting puts the impact categories on the same yardstick and hence it introduces a subjective judgement. It makes products comparable with a one-dimensional index by summarising the impact categories.

2.3.4 Interpretation

Interpretation is a way of making sense of the results, to make comparisons and to draw conclusions (Baumann & Tillman, 2004). Identifications of significant issues and evaluation through e.g. completeness and consistency checks are made.

2.4 LCA in the building industry

Environmental product declaration (EPD) is a standardised environmental market communication report and provides a specific format for the LCA information (Baumann & Tillman, 2004). In the Swedish building industry, the EPDs follow the standard SS-EN 15804 (Boverket, 2020b). LCAs in the building industry tend to focus on the impact category global warming and it is the category studied in the upcoming climate declarations in Sweden. The functional unit is often m^2 heated area and year (Sweden Green Building Council, 2017; Boverket, 2020b). Figure 3 illustrates how the LCA phases in Figure 2 are translated into building specific phases when applying LCA in the building industry.

Looking at the whole life cycle from resource extraction (module A1) to end of life (phase C) is called a cradle-to-grave study while looking at resource extraction to finished product (module A3) is called a cradle-to-gate study (Fan & Fu, 2017). Studying module A1-A4 is called cradle-to-site while module A1-A5 is called cradle-to-handover (Malmqvist et al., 2018). Benefits and loads beyond the system boundary are included in phase D, where circularity can be studied (Boverket, 2020b). For example, the impact of energy recovery from wood as a fuel replacing a fossil fuel can be studied in module D. Carbon emissions from different phases is sometimes referred to as embodied carbon and operational carbon (Rodrigo et al., 2019). Embodied carbon considers emissions from the production phase (A) while operational carbon handle emissions in the use phase (B).

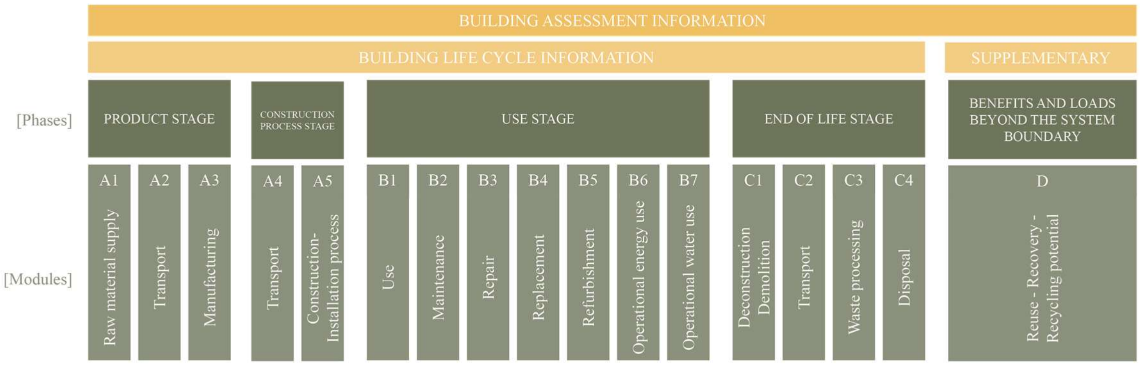


Figure 3. The LCA phases in the building industry. Adapted from SIS (2011).

A reference study period needs to be set for calculating environmental impacts of the use phase of the building (Boverket, 2020b). The calculations are made for the set period; however, it is not to be mixed up with expected technical life length of the building. As buildings have long life length compared to many other consumer products, scenarios describing a distant future need to be set. LCAs for buildings are often not considering dynamic building properties (Su et al., 2017). Dynamic building properties are identified as technological progress, variation in occupancy behaviour, dynamic characteristic factors and dynamic weighting factors. The accuracy of results can be greatly influenced by such factors, as the life cycle of a building is long.

The Paris Agreement states that there is a need for negative carbon emissions, to reach the climate targets (Erlandsson et al., 2018). For the building industry, carbon sinks (e.g. bio-based materials) and carbonation of concrete are examples of processes achieving negative emissions. The bio-based materials wood, hemp, and straw contain around 50% carbon by dry mass (Hoxha et al., 2020). The building materials as a carbon sink is a great possibility for carbon reductions, but it is important that calculations are transparent and comparable to avoid misleading information.

Bribián et al. (2009) identify drivers for using LCA in the building sector to be loans and subsidies from environmental impact reduction, environmental targets and labelling, marketing, and simplified data acquisition. Barriers identified are weak links to energy certification applications, lack of legal requirements, poor knowledge of LCA and environmental impact, inconsistent applications, prejudice about complexity, accuracy and arbitrary results, low demand, costs, complicated calculations, poor cooperation between manufacturers and customers, and a lack of standardised interfaces. Socio-economic costs of emitting greenhouse gases are according to Trafikverket (2019) 7SEK/kg CO_2-eq. The report handles the use of environmental policy instruments in the transport sector to hinder emissions and achieve socio-economic benefits. The policy instrument "climate declaration" of buildings is described in 2.6 below.

2.5 LCA in environmental certifications

There are several optional environmental certifications for buildings in Sweden (Boverket, 2019). A simplified LCA for building elements is included in the Swedish certification Miljöbyggnad (MB) while a more comprehensive LCA is fostered in the international certifications Building Research Establishment Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED).

MB has 15 indicators where one of them focuses on LCA of the foundation and the load-bearing system (Boverket, 2019). The analysis is limited to the A1-A3 modules to get the bronze score and A1-A4 to get silver and gold scores. It looks at global warming 100 years (Sweden Green Building Council, 2017). To get silver or gold level, EPDs holding specific data are needed (50% and 70% of the data for silver and gold respectively). For the gold level, a 10% lower global warming result compared to the silver calculation needs to be achieved.

BREEAM looks at the building parts roof, windows, exterior walls, and floor slabs (Boverket, 2019; Sweden Green Building Council, 2018). Three impact categories must be studied, where global warming must be one of them. An early-stage LCA must be conducted, and points are given if improvements are shown throughout later stages.

LEED studies the foundation, the load-bearing system, and the climate shell (Boverket, 2019). The phases encouraged are A-D and hence it is a cradle to grave study (U.S Green Building Council, 2020). However, points can be gathered if looking at a limited set of phases as well. As in BREEAM, early-stage LCA should be reported and a lowered environmental impact throughout the project stages must be shown (Boverket, 2020b). The impact categories studied are Global Warming Potential (GWP), depletion of the stratospheric ozone layer, acidification of land and water sources, eutrophication, formation of tropospheric ozone and depletion of non-renewable energy resources (U.S Green Building Council, 2020). A decrease of 10% must be shown in 3 out of the 6 categories, where one of them must be global warming (Boverket, 2019). The use of local materials can give extra credits and re-using of existing materials is encouraged (U.S Green Building Council, 2020).

2.6 Climate declarations

The Swedish government has put in a legislative proposal of mandatory climate declarations, starting from January 1st, 2022 (Boverket, 2020b). The proposal states that a climate declaration should be conducted when applying for a building permit. The legislative proposal builds on the European standard SS-EN 15978 of declaration of environmental performance of buildings and the purpose is to increase knowledge in the field and decrease climate impact.

The climate impact in the declaration should have the functional unit kg CO_2-eq/m^2 BTA and the LCA type is attributional (Boverket, 2020b). The reference study period is proposed to be 50 years which is analogous with the period chosen by several Nordic and European countries. The 50-year period is in line with a thought need of comprehensive refurbishment after that time. A fear is that such a short reference period might disfavour the use of products with long life cycles, but it is argued that this consequence is rarely seen in studied cases. Having a longer period on the other hand, creates a contingency as scenarios are hard to predict due to changes in future production methods. Increased efficiency in manufacturing and the energy mix shifting to more renewable energy will probably affect the scenarios (Su et al., 2017). Background emission concentrations influence the level of impact of the emissions (Collinge et al., 2013) and as the concentrations might vary in a future point of time, it affects the scenarios.

The Swedish government will hold a database of generic environmental data to be used for climate declarations (Boverket, 2020b). The product data and energy mix are representative for Swedish conditions. The data is put higher by a factor of 25% in the database to make incentives for using EPDs of specific products instead of the generic data. To make informed choices, the project developer needs specific environmental information of the products on the market. However, the developer has no right to claim it from the producers in today's situation. The EU commission has decided and pushed on a framework for describing building products' environmental impact. The standard SS-EN 15804 has been developed to bring forward EPDs for building products. A legal connection between an EPD according to SS-EN 15804 and the harmonised building product standards is not set. This is one of the reasons that the government will hold the database of environmental data.

Installations accounts for a considerable part of a buildings' climate impact, around 18-46% (Boverket, 2020b). But they are often ignored in LCA calculations as data is missing. Installations are not a part of LCA in environmental certifications (Boverket, 2019). By 2027, installations will be included in the declarations as data is believed to be compiled and accessible (Boverket, 2020b). It is also thought that digitalisation is more developed at that time, enabling more comparable and precise calculations including additional building parts. Generic data for additional building parts as well as standard values for interior claddings and room elements should be made available in the database by 2027. Data for biogenic carbon of wooden based products and standard values for deconstruction and demolition (C1) and transport in the end-of-life module (C2) need to be compiled and made available.

The production phase (A1-A3) and the operational energy use (B6) have the highest climate impact of a building's life cycle (Boverket, 2020b). An example of a relation between the different phases is shown in the LCA results of a multi-residential building (Figure 4). The modules to be included in the 2022 declaration are the construction modules (A1-A5) in order to focus on the greenhouse gas emissions occurring today. One reason for the limited number of modules is to be able to evaluate effects and consequences gradually. Another reason is that it is possible to verify the emissions and impacts of today, but it is harder to verify future emissions and impacts. The limited number of phases steers towards interventions for reducing climate impact of the A1-A5 modules. There is however a risk of sub optimizing if lowering emissions in these phases and letting higher emissions pass in later phases.

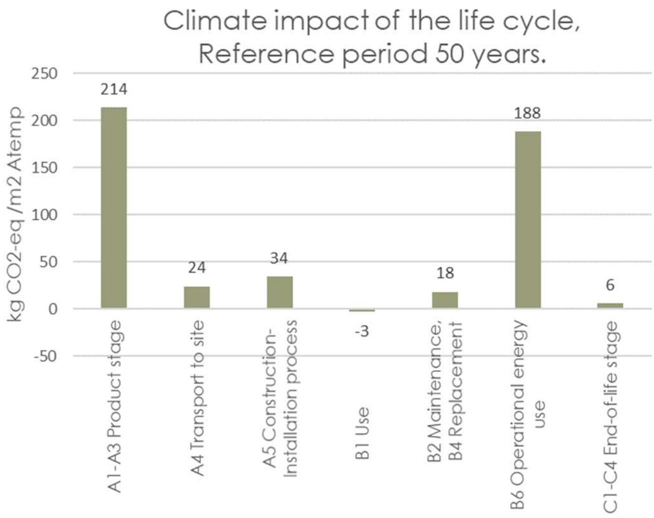


Figure 4. Example of LCA calculation of climate impact. Adapted from Malmqvist et al. (2018).

The construction sector works towards a net-zero impact, in line with the national climate target of 2045 (Boverket, 2020b). The roadmap of the construction sector is shown in Figure 5. This national target states that Sweden should have net zero greenhouse gas emissions into the atmosphere by 2045 and it sets out the Swedish implementation of the Paris Agreement (Ministry of the Environment and Energy, 2018).

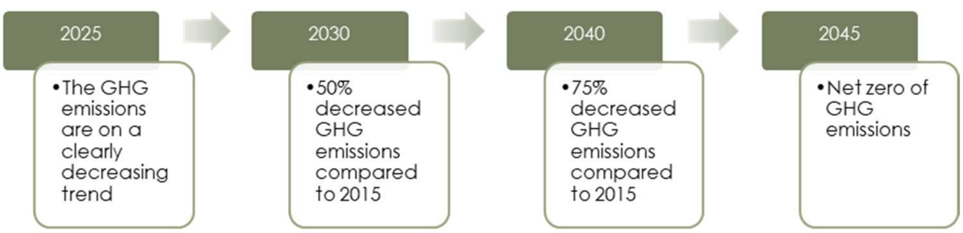


Figure 5. The roadmap of the construction sector. Adapted from Boverket (2020b).

Benchmarking is important in the field to steer the industry towards a lower climate impact (Boverket, 2020b). From 2027, threshold limit values are suggested to be introduced and additional LCA modules to be included. The threshold limit values are proposed to be sharpened year 2035 and yet sharpened year 2043 as illustrated in Figure 6. The thresholds will be differentiated for premises, detached/semi-detached houses and multi-residential buildings. The differentiation of buildings is analogous with the energy demands of Boverket's Building Regulations (BBR). In 2027, the threshold refers to reference buildings. When calculating results for reference buildings, it will be beneficial to provide additional properties of the buildings. Additional properties include describing the relation between areas of different use (e.g. office, apartment), the relation between BTA and Atemp, the form factor, the floor to ceiling height and the climate zone.

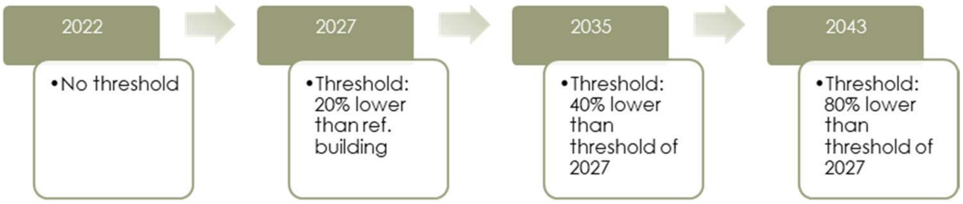


Figure 6. Planned threshold lapse. Adapted from Boverket (2020b).

As the construction of buildings has a high climate impact, a more rapid transition towards low emissions is needed (Boverket, 2020b). Legislations such as the climate declaration are needed to influence the construction stages. Table 1 summarises the system boundaries of the climate declaration and Figure 7 and Figure 8 illustrates the LCA modules included.

Table 1. Summary of system boundaries in the Climate declaration. Adapted from Boverket (2020b).

Year	2022	2027
Threshold limit value	No threshold	Threshold that covers A1–A5
Modules to be included	A1–A5	A1–A5, B2, B4, B6, C1–4, Additional environmental information, biogenic carbon storage, net export of locally produced electricity
Parts of building to be included	• Load-bearing elements • Building envelope • Interior walls	• Load-bearing elements • Building envelope • Interior walls • Installations • Interior claddings • Room elements
Reference study period	-	50 years

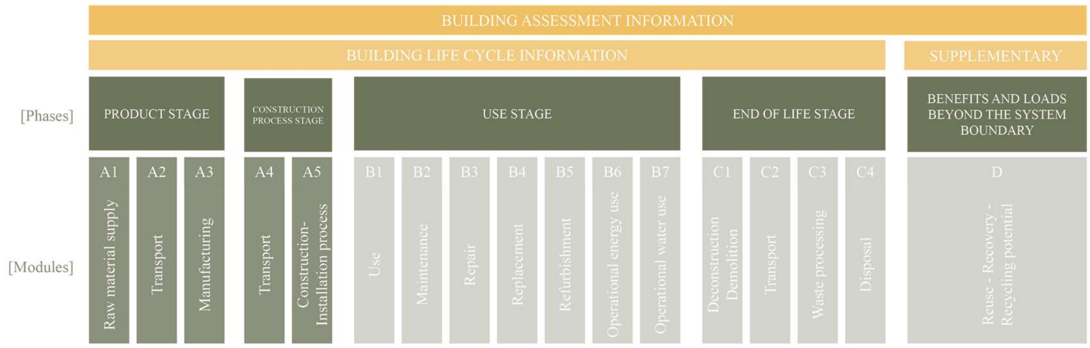


Figure 7. LCA modules included in the climate declaration from 2022. Adapted from SIS (2011) and Boverket (2020b).

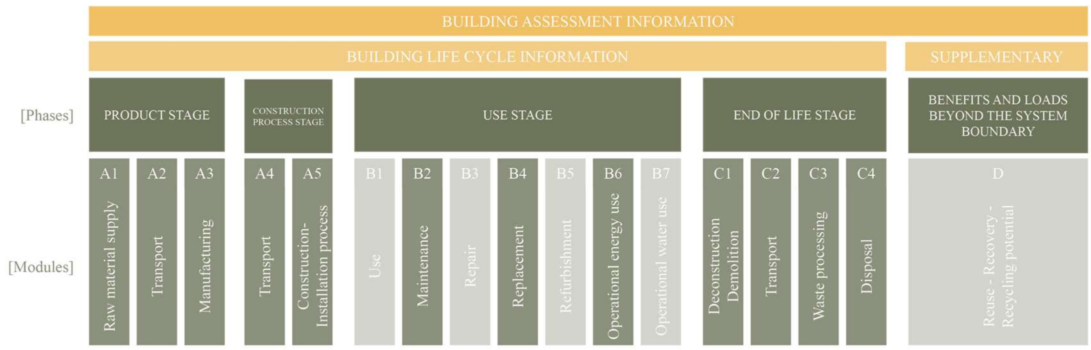


Figure 8. Proposal of LCA modules to be included in the climate declaration from 2027. Adapted from SIS (2011) and Boverket (2020b).

Predicted consequences of climate declarations according to building firms are increased transparency in the sector, speeded up innovation of sustainable materials, higher demands on producers in terms of transparency and sustainability, higher apartment costs and updated frameworks of procurement and land allocation that takes emissions into account (Boverket, 2020b). According to the same report, there is a belief that architects will not be highly affected by the declarations until 2035, when the threshold limit values are sharpened. Then it will affect the design at a larger extent as it must meet the demands of low climate impact. Architects will need to get the competence of climate calculations.

Despite the absence of threshold values in the climate declaration until 2027, several initiatives have developed their own values. LFM30 uses the EN 15978 standard (IVL, 2021) and their threshold values presented are shown in Table 2. The Finnish Ministry of Environment has also set threshold values and they are presented in Table 3. It should be noted that LFM30 has BTA in their functional unit, whereas the Finnish Ministry of Environment uses NTA which is closer to Atemp that will be used in the Swedish climate declarations.

Table 2. LFM30's threshold values [kg CO_2-eq/ m^2 light BTA/year] (IVL, 2021).

	Premises	Multi-residential	Small houses
A1-A5	270	216	171

Table 3. The Finnish Ministry of Environment's threshold values [kg CO_2-eq/ m^2 NTA/year] (Bionova Ltd, 2021).

	Residential	Office	Service	School	Commercial
A1-A3	282	259	282	255	215
A4	10,2	10,2	10,2	10,2	10,2
A5	27,3	27,3	27,3	27,3	27,3
Total	319,5	296,5	319,5	292,5	252,5

3 Method: Literature review, interviews and tool review

The methods of the thesis consisted of literature review, interviews, tool review, tool development and case studies. They were all qualitative except one of the case studies that was quantitative and handled numerical comparisons. The first three methods are described in this chapter, and a method timeline is shown in Figure 9. The tool development and case studies are further described in chapter 5. The reason for splitting the method chapters in two is that the method of tool development and case studies are influenced by the results from the first three methods.

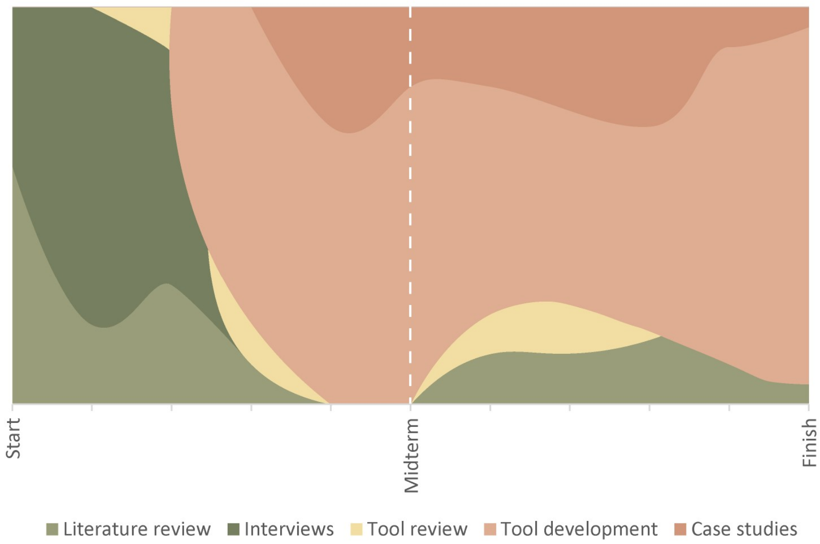


Figure 9. The methods of conducting the thesis shown on a timeline.

The literature and tool review were made in order to put the project in a context, map existing knowledge and to identify how the project contributes to new knowledge. The literature review brought knowledge to ask relevant questions in the interviews. The interviews were made to get the industry perspective of early-stage LCA, and the tool review was made to bring inspiration for tool development paths. The literature review, interviews and tool review together fed into the tool development. The tool development was the main part of the thesis project, with the aim of encouraging life cycle thinking in early-stage building design. The first case study tested the numerical results of the tool. The second case study strived to see if the outcome of the development is of use to the stakeholders.

The overarching research question was "How can design-integrated early-stage tools based on LCA be applied to increase the understanding of and help decrease the climate impact from the production phase of buildings?". Part one of the research question, "What is required in terms of input data and results, transparency, connection to a 3D model, calculation speed, software skills and LCA experience of the user?", was answered through the literature review, the interviews and the tool review.

Part two of the research question, "Does the developed tool fulfil the above-mentioned requirements?", was answered by the tool development and the user tests in the second case study. The numerical case study strived to answer part 3 of the research question; "Are the LCA results from the developed tool within a 15% accuracy?". Figure 10 illustrates the connection between the methods and their connections to the research question.

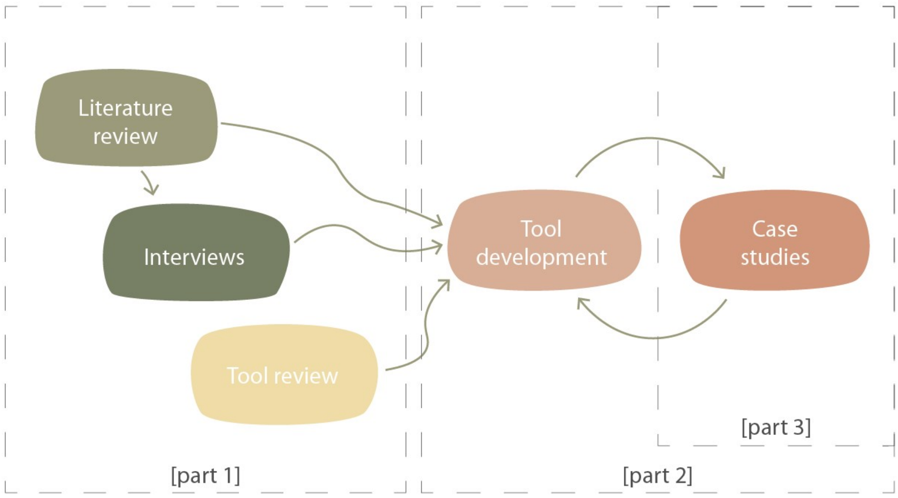


Figure 10. The methods and the connection to the research question.

3.1 Literature review

The literature review handled early-stage LCA, digital tools and strategies for lowered environmental impact. The review consisted of literature from the databases Google Scholar, ResearchGate and Svenska Byggbranschens Utvecklingsfond (SBUF) as well as other relevant reports and books. Key words searched for were "(LCA OR life cycle assessment AND Early-stage OR Simplified OR Simplification)" and "(LCA OR life cycle assessment OR building AND digital OR parametric OR optimization OR tool)" and "(building AND environment OR environmental impact OR climate OR climate impact)".

3.2 Interviews

Interviews with architects, real estate developers, sustainability and building technology engineers and software developers were made to understand what the early-stage workflows look like and the needs of support. The workshop material used in the interviews is found in Appendix I- Interview material. There were 20 interviewees asked to participate in the interviews. The interviews were conducted as online meetings due to the prevailing Covid-19 pandemic.

The interview questions for architects, real estate developers and engineers are stated below. Question 1-3 were asked to get company-specific perspectives on climate impact and climate declarations. Figure 69 in Appendix I- Interview material was used to define early stages and question 4-6 aimed to understand workflows in those stages. Question 7-8 were asked to get their view on how, when and why to use an LCA-tool for early stages, as well as what are important features in such a tool (Figure 70 in Appendix I- Interview material).

1. What project types is [the company] mainly working with?
2. From your position, what is the biggest challenge in lowering the climate impact from new construction?
3. What is your view on the upcoming climate declarations? [For Swedish interviewees]

4. How do you define early stages?
5. Which software is used for modelling in early stages? (E.g. Revit, Archicad, Sketchup, Rhinoceros, Autocad)
6. When is the construction type, materials and geometry defined?

7. How and when could an LCA tool be useful?
8. If you would use an LCA tool, for what reason would it be? (E.g. To make a baseline for later stages or to use for climate declarations and certifications)

The interview themes for software developers are stated below. They were chosen to get ideas of the development. The software developers also got to use the workshop material presented in Figure 70 in Appendix I- Interview material.

1. Usability and adaptability of tools
2. Inputs: geometry and environmental data
3. Outputs: visualisations and results extraction

3.3 Tool review

In the tool review, LCA tools were studied based on their connection to a 3D model, environmental data handling, reference study period, impact categories, LCA modules and whether it is an online/desktop/plug-in tool. The tools studied are stated below.

- Byggsektorns Miljöberäkningsverktyg (BM)
- OneClick LCA
- The Buildings and Habitats object Model (BHoM)

The reason for choosing BM and OneClick LCA was that they are used in Sweden (IVL, 2021; OneClick LCA, 2021) and the reason for choosing BHoM was to study a tool that can be used in the Grasshopper environment (BHoM, 2020). The tool review influenced and inspired the tool development.

4 Results: Literature review, interviews and tool review

The results from the literature review, the interviews and the tool review are presented in this chapter. By the end of the literature review and the interview parts, a connection to part 1 of the research question will be made.

4.1 Literature review

Below follows the literature review of early-stage LCA, digital tools and, lastly, strategies for lowered environmental impact. Around 20 papers were found and read, and the most interesting contributions are brought forward to the review.

4.1.1 Early-stage LCA

LCA in the building industry 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). Applying LCA in early building design can have different purposes and be focused on different stages (Bribián et al., 2009). A purpose for architects is comparing design options in early sketching and collaborating with engineers in detail design. The design options compared are geometry and technical choices. Property developers and consultants use it in preliminary stages. Property developers have the purpose of choosing building sites, sizing projects and setting environmental targets. Consultants' purposes are setting targets at municipal level and for development areas and defining suitable zones for buildings. Figure 11 illustrates when Boverket recommends conducting LCAs throughout the building process.

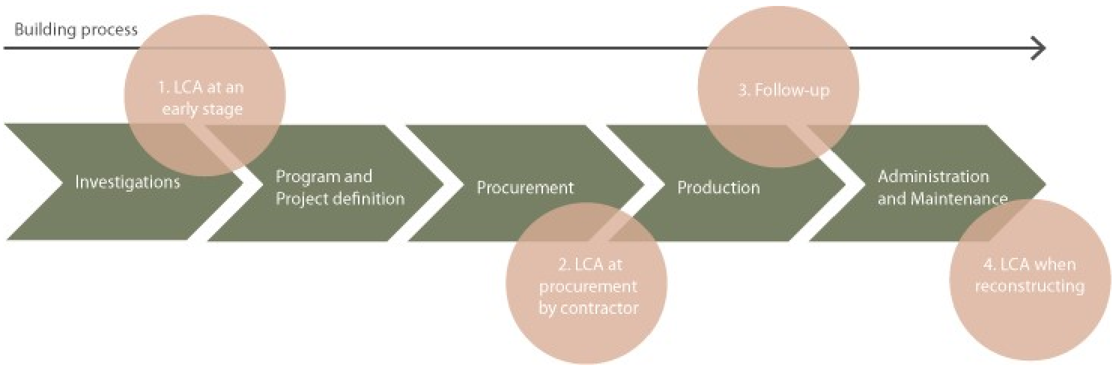


Figure 11. LCA in the building process. Adapted from Boverket (2020a).

The application of LCA in the building sector are by some doomed to fail by being too complex and difficult and hence simplification is needed (Soust-Verdaguer et al., 2016). A strategy for simplification regarding system boundaries is to reduce the amount of data and optimize data collection. Simplifying the functional unit can refer to looking at parts of the building (e.g. focusing on 1m^2 of window area) instead of looking at the whole building (e.g. 1 m^2 of usable floor area). Other studies are trying to find correlating environmental impact categories (Röck et al., 2018).

Quantifying building materials and energy use requires a lot of time (Bribián et al., 2009). As engineers and architects have a short amount of time to perform LCA, simplified applications with appropriate interfaces can be useful. Building Information Modelling (BIM) is a good way for quantifying materials (Soust-Verdaguer et al., 2016). Bribián et al. (2009) suggest handling geometry by extracting surface layers from the architectural model and multiplying with the thicknesses. Using the density, the final inventory data is the weight of each of the materials.

In early stages of building projects, it is hard to know accurately what building materials and products will be used (Boverket, 2020b). Therefore, it is suitable to use generic data in the LCA calculation. Figure 12 illustrates the ability to influence environmental performance throughout the building design process.

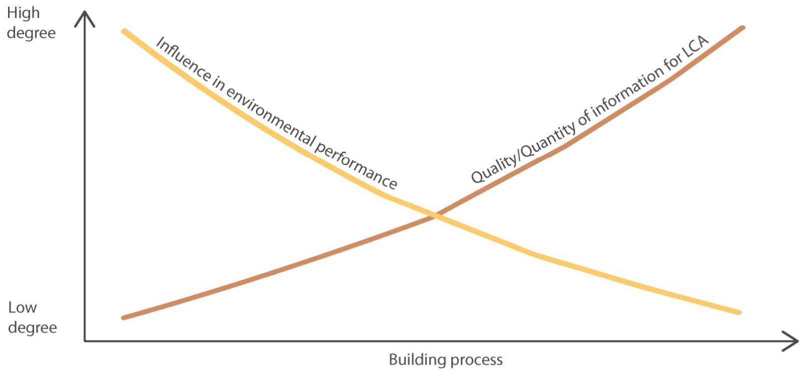


Figure 12. The ability to influence environmental performance through the building design process. Adapted from Roberts et al. (2020).

Building processes like transport, maintenance, repair, refurbishments, demolition, waste treatment or recycling are complex to model and are often simplified by referring to previous studies or regional data sources (Soust-Verdaguer et al., 2016). Bribián et al. (2009) and Soust-Verdaguer et al. (2016) suggests only including the A1-A3 and B6 modules in simplified LCAs.
Loads and benefits in phase D are hardly considered (Soust-Verdaguer et al., 2016).

For a simplified tool, project input data must be easy to find, and the impact categories chosen must be simple making architects, engineers and users understand the results (Bribián et al., 2009). Examples of well-known categories are water use, embodied energy, embodied carbon and waste generation, in contrast to e.g. eutrophication. Impact categories can be cut down by criteria such as regional representativeness, global impact, embodied versus operational impact, renewable versus non-renewable energy consumption in several cases (Soust-Verdaguer et al., 2016). It reduces the complexity and amount of data without modifying the comparability of the results. GWP is recognised globally to be the most significant indicator for climate change mitigation strategies.

4.1.2 Digital tools

Environmental data and LCA within the building industry are being digitalised, however the active users are cutting edge firms, while small and medium-sized firms lack resources and knowledge to use the digital tools (Boverket, 2020b). This brings obstacles to the information flows in the building process. Smaller companies that are not specialised in wooden construction are more worried about the legislative proposal that will come into force in January 2022, than larger companies and companies specialised in wooden construction, according to an interview study.

Digitalisation is a pre-requisite to bring out high-quality climate declarations made in a resource-efficient way (Boverket, 2020b). However, the building sector is not keeping up with other sectors with regards to digitalisation. Research that contributes to the digitalisation in the building industry should be supported by the government. The government does not intend to regulate which tools that can be used for climate calculations. The demand of digital tools will increase along with increased digital information. In 2027, when additional building parts will be added to the climate declarations, thousands of data items may occur, making a manual calculation hard to conduct. Building Information Modelling (BIM) is believed to have a leading role in calculation and modelling of climate impact from buildings, from early stages to finished product. Open, standardised formats for transferring information between platforms and tools are important parts of the digitalisation.

Roberts et al. (2020) studies the use of LCA throughout the design process by connecting it to the Royal Institute of British Architects (RIBA) plan of work. Most papers in the study were focusing on the LCA-BIM integration, the LCA-Life Cycle Cost (LCC) connection and environmentally led parametric design. There are challenges if undertaking LCA before BIM in projects. However, parametric led design can provide guidance in early stages and include different design alternatives from the conceptual design. Before parametric design tools and algorithms can hit the industry, the tools require more work, regionalisation, and verification. To ensure that LCA is used to its full potential, the stage of design must be considered. If implementing studies after the design concept is set, the assessment become reactive and responding to the design. Proactive results on the other hand have more potential to influence the design, making it possible to lower the environmental impact. Visual scripting interfaces like Dynamo and Grasshopper are encouraged in early-stage LCA and could support the connection to other types of analysis at different phases (Röck et al., 2018).

If looking at only parts of the life cycle, there is a risk of sub optimization, meaning that while the analysed phases are optimized, it might affect excluded phases in a negative way (Boverket, 2020b). An example of sub optimization is seen regarding energy certifications, that usually do not cover the whole life cycle (Bribián et al., 2009). A good energy classification might be produced while bringing a higher total energy consumption by lacking a holistic view.

Designers need more early-stage contextual information to make early-stage choices and develop the concept (Roberts et al., 2020). LCA and environmental assessments are not integrated in the design process, it is more considered as additional aspects. Things that are standing in the way for adoption of widescale design process LCA are accessibility of detailed information, time requirements and the appropriateness of early-stage tools. In addition, small firms and small to medium-sized projects might not have resources to employ LCA expertise. Even though LCAs in early stages can be used to make informed decisions, it will not replace detailed LCAs at the point of completion.

4.1.3 Strategies for lowered environmental impact

Bribián et al. (2009) propose to promote renewable energy while also emphasizing bioclimatic eco-design, bioconstruction and the use of local, low impact, natural and recyclable materials. Operational measures like water consumption minimisation by designing rainwater collection systems, grey water networks in buildings and the design of green roofs should be encouraged.

Recycling materials can lower life cycle energy by 30% and greenhouse gas emissions by 18% (Bribián et al., 2009). Looking at steel and aluminium, the embodied energy saving can be 50%. This brings arguments for the potential of recycled building materials to play a role in the reduction of environmental impact.

Erlandsson et al. (2018) have summarised strategies for a lowered climate impact, looking at a residential case study. The strategies are to

- use climate-improved concrete,
- prioritise sustainable choices for materials used to a high degree,
- use renewable fuels for transports,
- optimize the energy use on the site,
- choose low impact coating for balconies regarding maintenance,
- calculate climate impact for every single project, and
- increase the knowledge about climate impact in the entire value-chain, especially in the purchasing department.

4.1.4 Connection to part one of the research question

The connection of the literature review to part one of the research question is presented below.

What is required…
…in terms of input data and results?
Quantities and quality of data is low in early stages. To conduct early-stage LCA, the assessment must be simplified. Reducing the amount of data and optimizing data collection as well as simplifying the functional unit is recommended. Using BIM and generic data should be emphasized, and the risk of sub optimization should be kept in mind.

…in terms of transparency?
Understandable methodological choices, e.g. well-known impact categories should be set. The use of open, standardised formats calls for transparency.

…in terms of connection to a 3D model?
Multiple papers suggest BIM connections which leads to the connection to a 3D model. One paper recommends extracting surface layers from an architectural model. Parametric design is proposed as a way to provide guidance in early stages while studying different design alternatives.

…in terms of calculation speed?
The short amount of time to perform LCA and also the lack of resources points at the need of a high calculation speed.

…in terms of software skills and LCA experience of the user?
Most papers state that simplification is needed. To make assessments possible to conduct for someone with low LCA experience, the impact categories chosen must be well-known. Multiple paper points at the advancement of digitalization. Small and medium-sized firms might that lack resources and knowledge to use the digital tools and hence they should not be too complex.

4.2 Interviews

Out of 20 people asked, 17 people participated in the interview sessions. The interviewees are presented in Table 4 and the distribution of professions is shown in Figure 13. In the following text, the interviewees are categorized into architects, engineers, real estate developers and software developers.

Table 4. Interviewees participating in the study.

Category of company	Company	Profession	Interviewee
Architect	EttElva Arkitekter	Sustainability manager Architect	Emma Östlund Erik Björnhage
Architect	Liljewall Arkitekter	Architect	Alexander Gösta
Architect	White Arkitekter	Energy and environmental engineer	Carl Molander
Architect	Wingårdhs Arkitektkontor	Architect	Vera Matsdotter
Architect	ÅWL Arkitekter	Architect, BIM manager	Camilla Berggren-Tarrodi
Engineer	Buro Happold (Sustainability & Physics team)	Associate sustainability director Graduate sustainability engineer	Ben Richardson Loic Weisser
Engineer	eTool Life Cycle Design	Sustainability consultant	Marios Tsikos
Real estate developer	Catena fastigheter	Sustainability strategist	Anna Wallander
Real estate developer	Hemsö fastighets AB	Real estate developer	Emma Karlsson
Real estate developer	Riksbyggen	Sustainability manager	Karolina Brick
Real estate developer	Västfastigheter	Sustainability strategist	Mikaela Lenz
Real estate developer	Älvstranden Utveckling	Sustainability manager	Christine Olofsson
Software developer	Buro Happold (Computational team)	Software development lead Computational designer	Fraser Greenroyd Michael Hoehn
Software developer	StruSoft AB	Computational designer	Alexander Radne

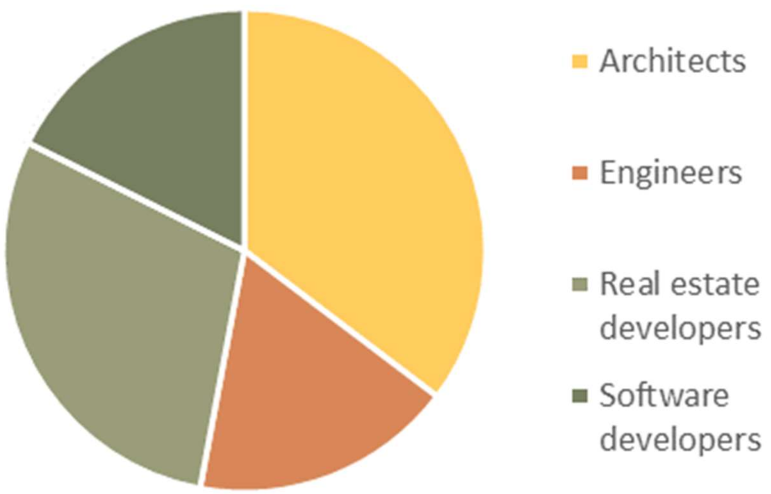


Figure 13. Distribution of professions in the interviews.

All interviewees are positive towards an early-stage LCA tool; however, the preferred functionalities differ a lot between and within professions. Some of the interviewees have great LCA experience while for others it is a completely new subject. Several of the interviewees have experience from developing early-stage and LCA tools. Figure 14 shows some of the most common words used in the interviews. The size of the words displays the frequency of use in the conversations. Words like "LCA", "early" and "tool" has been removed. The word cloud shows the variety of thoughts around early-stage LCA and how to mitigate climate change within the building industry.

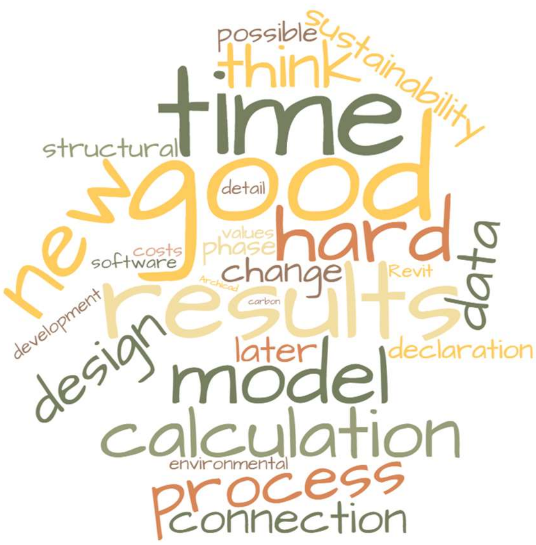


Figure 14. Word cloud from interviews.

4.2.1 The challenge of lowering climate impact

Discussing the climate impact from new construction, an urban developer stated that "the worst thing we can do is to build new constructions, but at the same time we have homelessness and want the city to grow. How can we solve that equation in the best possible way?" (Olofsson, C., interview on February 5th, 2021). The main challenges of lowering the climate impact from new construction stated by the interviewees are

- long building processes,
- traditional patterns of building processes,
- lack of knowledge and
- lack of time.

As the building processes are long, the projects change a lot along the way and many actors are involved. Another challenge is that the industry is stuck in current business models. Regarding technology, there is a tendency to avoid new things. There are also many factors in building processes besides climate impact like energy, fire safety and insurances. An architect stated that they are trying to find project specific solutions as challenges differ in each project.

Buildings carry large material quantities which induce a high climate impact. But the large quantities create a great potential to make a difference. Architects and real estate developers mentioned the difficulty of convincing clients to use wood and other materials considered sustainable. One of the architecture offices has introduced a policy to suggest wood structures in every project as a starting point. An architect within another firm mentioned that comparing concrete and wood is like comparing apples and oranges, and that the cost of wood structures always will be higher. Another architect stated that they have been building a lot with wood and have examples showing that it does not have to be more expensive. Other aspects when considering wood structures are higher floor slabs and thicker walls, which might not be feasible in the detailed development plan. A real estate developer said that wooden structures hinder the flexibility of adding heavy equipment to their spaces in the future. Another real estate developer working both with new construction and maintenance, mentioned that there is a balancing act between demands in different phases when considering building materials.

Several of the interviewees point at a knowledge gap, and that they need to investigate the climate impact of standard buildings to set targets. The lack of time and hence the difficulty of investigating materials was brought up as a challenge. As a consultant, one must be prepared to propose solutions. The strategy of one of the architecture firms is to have environmental consultants involved in all steps of the process and raise the overall sustainability knowledge among consultants.

There were also hopeful thoughts raised. There has been a shift in interest of sustainable building over the past years. The clients today look for architects with environmental design knowledge. This used to be a non-question. Several of the interviewees talked about their involvement in initiatives like LFM30 and Fossilfritt Sverige. There is a paradigm shift in the architecture profession. The way the industry has worked with sustainability until now is by adjusting existing models and processes. When starting to talk about reuse and circularity, there is a change in the core processes. An architect stated that the most sustainable building is the one that is not built at all and hence reused materials has great potential. The focus on reused materials must be defined at an early stage. Several of the interviewees stated that sustainability must be a natural part in early stages, regardless of the client and the project.

4.2.2 Climate declarations

When asking about the interviewees' views on the upcoming Swedish climate declarations, the answers were overall positive but most of them thought that the declarations are not strict enough. An architect compared the climate declarations with the energy and daylight regulations of buildings. He said that those regulations were hard to conduct in the beginning, but now it is a natural part of the projects. In a similar way, he thought that the climate declarations will be conducted naturally once people know the requirements and that it will have a great impact.

Regarding preparations, the interviewees stated that they are preparing for the climate declarations in different ways. Some mentioned that they are working with BIM modelling, some are outsourcing the calculations, and others are investigating differences between embodied carbon calculations in MB and climate declarations.

Several interviewees brought up that the declarations must be easy and cheap to conduct, but at the same time not leaving out elements. An interviewee thought that there is a possibility to be creative regarding what must be declared in the declaration and that there is nothing hindering from showing even more sustainability features as a way of marketing. Two of the interviewees think that pressure will be put on contractors and that there will be a rise in EPDs produced. A real estate developer hopes to see pioneering actors leading the way, showing that lowering the climate impact is possible and that unsustainable actors will be excluded. There was a general thought that the climate declarations will increase the environmental awareness in the industry.

Critique brought up was the focus on the product phase and the absence of threshold values. However, the operational phase was mentioned to be covered by the energy declaration. Regarding threshold values, an interviewee suggested that a high threshold value could be set from the start, and then at least the worst actors would have to change. A real estate developer said that they are not affected by the absence of a threshold, as they can set their own targets. It was generally expressed that coming up with their own threshold values is hard as LCA calculations is something new and information is hard to find. Some think that the learning period for climate declarations, until 2027, is too extensive, and others think that it is probably needed. It was expressed that the development of tools will go fast and the ones running the development will probably think that the climate declaration demands are quite weak and strive to widen the scope.

4.2.3 Early-stage definition

When asked about the definition of early stages, the professions clearly pointed at different time spans in the building process. Most interviewees think that early stages lay in the "investigation" and "program and project definition" stages. Some 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 as a creative and artistic workplace that enable testing things until late stages. Figure 15 illustrates the interviewees definitions of early stages.

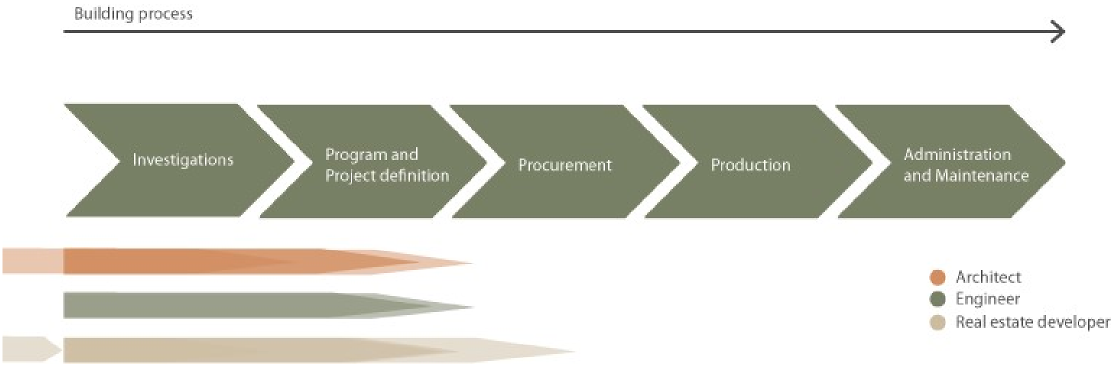


Figure 15. Definition of early stages.

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 are using BIM modelling in 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. It is hard to make a really good tool and a lot of testing is needed. The amount of time available in early stages depend on the project. Residential projects are pressed 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%" (Gösta, A., interview on February 9th, 2021). Another architect talked about making isolated LCAs, for example on the facade or on the structure as it has high impact. If the calculation includes all building elements, it might delay the project too much.

On the question of when to make the early LCA calculations, the answers were wide-spread but most of them pointed at investigations and the program and project definition stage (Figure 16). Some thought that as soon as there is a box model, it is possible to start looking into climate impact. An argument was that investment decisions are taken when working with rough box models and hence it is important to take sustainability into account.

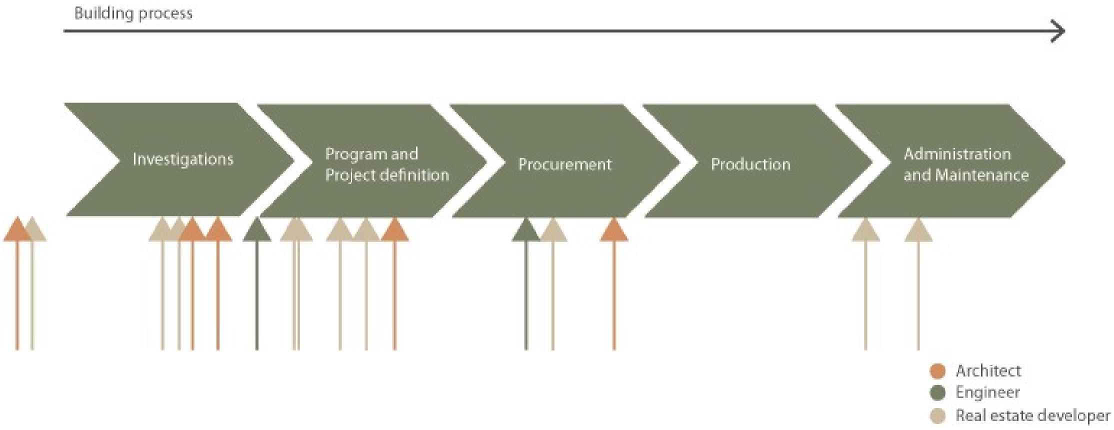


Figure 16. The interviewees suggestions on when to conduct early-stage LCA.

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 box 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 putting the dotted lines in every stage (Figure 16) had the argument 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" (Karlsson, E., interview on February 15th, 2021).

Figure 17 illustrates the ideas of user groups of an early-stage tool among interviewees. A software developer told to focus the user group on where the largest impact can be made which tend to be real estate developers, as they can make a great impact with a whole masterplan. 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 LCA 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.

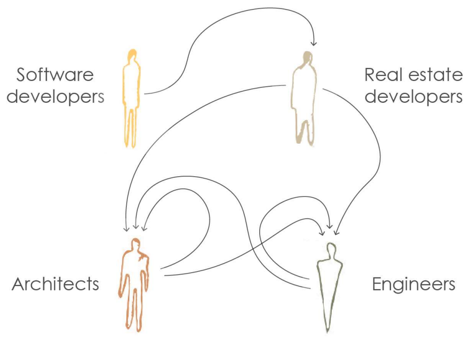


Figure 17. User groups as stated by interviewees.

A challenge was formulated as: "An assessment at an early-stage is as accurate as the information that you have got in an early stage, which is not accurate" (Tsikos, M., interview on February 5th, 2021). Many expressed the importance of using generic data as you do not know exactly what products to use in early stages. The geometry might not be in place, neither the demands on materials.

An engineer thought that load-bearing elements could benefit from being standardised per m^2 Atemp. Another engineer mentioned that material quantities for foundation and load-bearing elements changes based on the environment and the ground conditions, which can be interesting to study in a tool.

Both engineers and software developers distinguished between material and element take-off when making an LCA tool, where material take-off is looking at e.g. insulation, structure and cladding separately in a wall and element take-off is providing a number of climate impact for a standard wall. Some engineers thought that an element take-off might be useful in early stages.

4.2.4 Reasons for conducting an early-stage LCA

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 for upcoming projects. With a baseline, the impact of design changes along the process can be tracked. An interviewee expressed that if there was a tool for simplified LCA available they could use it on their old 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 are target setting and identifying easy winners in terms of strategies.

The learning part was mentioned as seeing consequences of choices made and increase the awareness. It was stated that it is beneficial to have a calculated number when entering an argument, especially if there are a lot of aspects to consider. The number could be used to convince the project team or the investor. As change is 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.

4.2.5 Inputs of an early-stage LCA tool

In the following figures, mean values are marked with clear colours, and boundaries are set around values that are closely connected .Figure 18 shows architects' values regarding inputs.

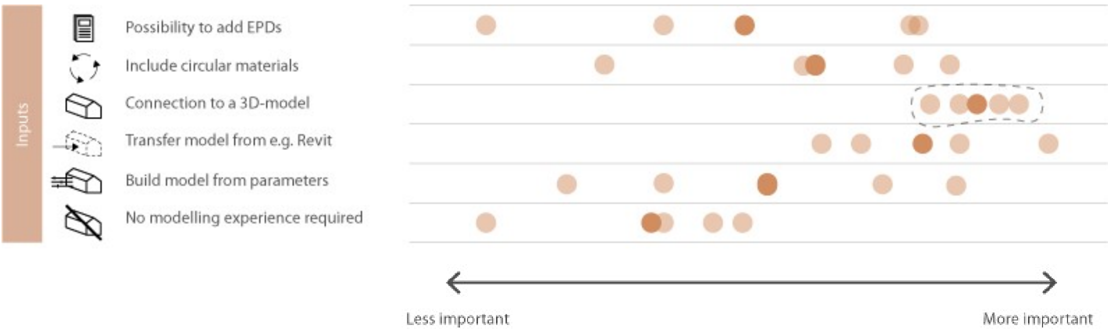


Figure 18. Priorities as stated by architects.

Opinions raised around the statements in Figure 18 are listed below.

- It is important to use national environmental data.
- Adding EPDs is not relevant in early stages as one does not know what actual products will be used.
- It seems hard to include reused materials in LCA today, but it would be nice to show if a product is reusable and if it stores CO2.

All architects think that a connection to a 3D model is important (Figure 18). 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. The architects had different preferences on ways of modelling. Common arguments for staying in their modelling environment were to

- have a smooth workflow,
- avoid licences,
- not having to learn a new software,
- save time and
- view the material changes directly in the model.

Linking to Archicad was important for several architects while Sketchup and Rhinoceros was preferred by others. Some expressed that people think Grasshopper is hard to understand and that it is not suitable as a modelling environment. They acknowledged that the industry will be more digitalised and in a couple of years there will be a more parametric view where data informs the design. "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" (Molander, C., interview on February 5th, 2021).

Figure 19 shows real estate developers' values regarding inputs.

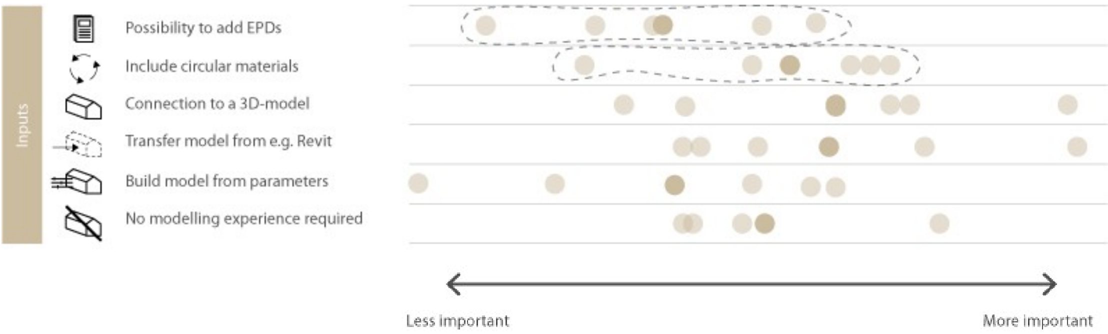


Figure 19. Priorities as stated by real estate developers.

Opinions raised around the statements in Figure 19 are listed below.

- The possibility to add EPDs and reused materials is more important at later stages and hence it can be left out in this tool.
- 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.
- To not make calculations of all building elements in every project but instead utilise similarities in projects. There might be strategies that can be applied in all projects, and it is important to think of what is generic and what is project specific. Money should be put where it really makes a change.

Figure 20 shows engineers' values regarding inputs.

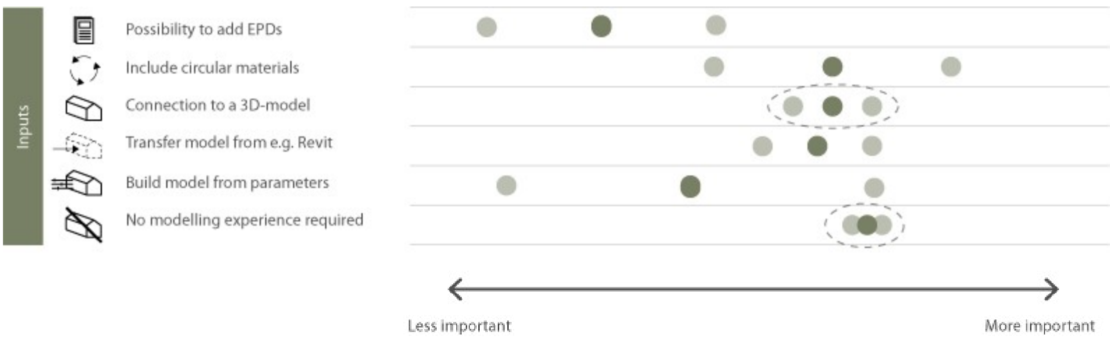


Figure 20. Priorities as stated by engineers.

Opinions raised around the statements in Figure 20 are listed below.

- It is important to use a qualitative and representative set of EPDs and it would be good to make it easy to input EPDs. Another engineer expressed that EPDs mostly refer to specific products and hence it is not appropriate for early stages.
- It would be interesting to see the climate impact of re-used materials at an early stage.

- Regarding the statements "no modelling experience" and "connection to a 3D model", it points at different tools. In a similar way, "model from Revit" and "model by parameters" could be two different tools.
- An engineer working with tool development mentioned that when developing the tool, one should not presuppose a box model and hence manage advanced geometry from the start.

An engineer expressed that using a Revit connection would be future proof as architects will probably use Revit increasingly. Revit is also suitable for pulling quantities in a quick manner. Connection to an existing model will keep more details while reconstructing the model probably will be hard unless you are just looking for rough calculations. On the other hand, reconstructing the model could be good if you want to use it as an optioneering tool and quickly change the design. It could be a different tool, or a different branch of the tool, for different stages. The likelihood of having multiple Revit models produced by the architects is low. The end goal of using the tool defines what model should be used. The engineers were united that a high level of modelling experience should not be required (Figure 20).

Figure 21 shows software developers' values regarding inputs.

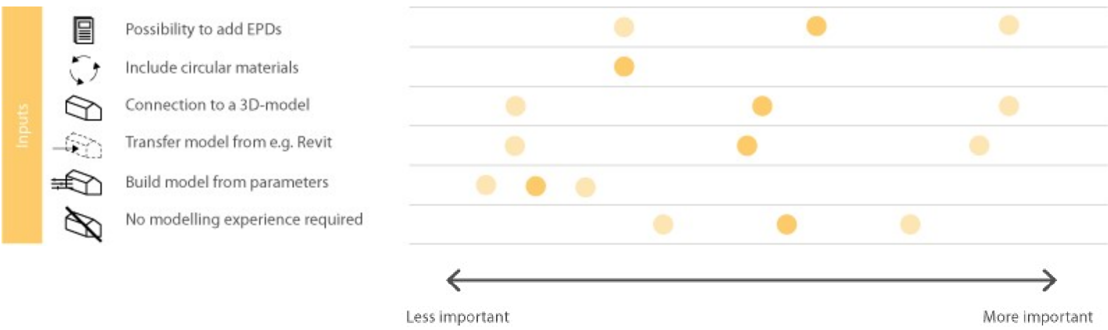


Figure 21. Priorities as stated by software developers.

Opinions raised around the statements in Figure 21 are listed below.

- If the tool is to be adapted to make further analysis, U-values and fire properties could be added.
- Some of the software developers highlighted that it is crucial to have a connection to a 3D model, but that it is important to be flexible in how you build the model. However, the modelling by parameters had low priority (Figure 21).
- The ability to influence the results by iterations and optimizations was discussed. An example is that a change in slab thickness changes the column placement and therefore it affects the material use in two ways.
- An idea raised by a software developer was to have an iterative process enabling optimization of design based on previous outputs.

4.2.6 Calculations of an early-stage LCA tool

Figure 22 shows architects' values regarding calculations.

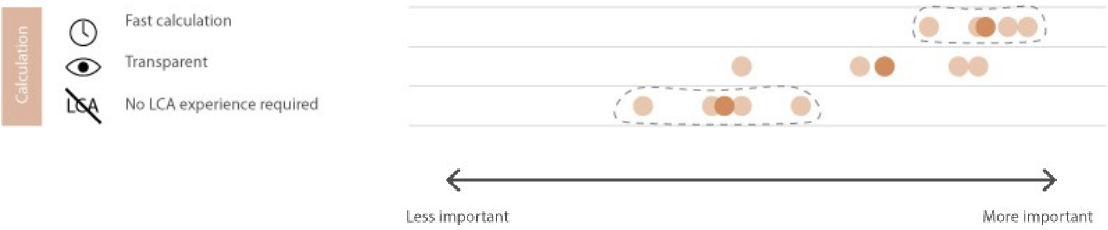


Figure 22. Priorities as stated by architects.

Opinions raised by architects around calculations and the workflow are listed below.

- The tool must give instant feedback.
- Transparency is important to most architects, as it is key to understand what might have gone wrong. An argument against transparency is that some architects do not want to be showered with technical information and numbers, but rather just trust the results.
- Deep LCA experience should not be required, however if it is an advanced tool with a lot of settings, prior knowledge of LCA is needed.

Figure 23 shows real estate developers' values regarding calculation.

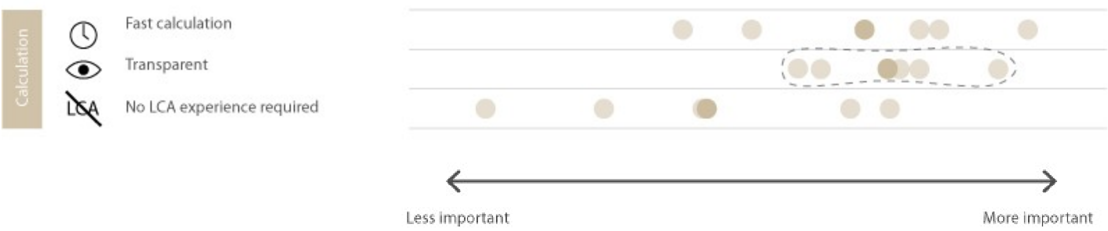


Figure 23. Priorities as stated by real estate developers.

Opinions raised by real estate developers around calculations and the workflow are listed below.

- The tool should be fast and enable quick testing of different material combinations and designs.
- Previous LCA experience is needed for the tool users.
- Keep processes simple.
- It is important that the tool is cost effective to not conduct expensive investigations in every project.
- Make it possible to follow up results along the way.

Figure 24 shows engineers' values regarding calculation.

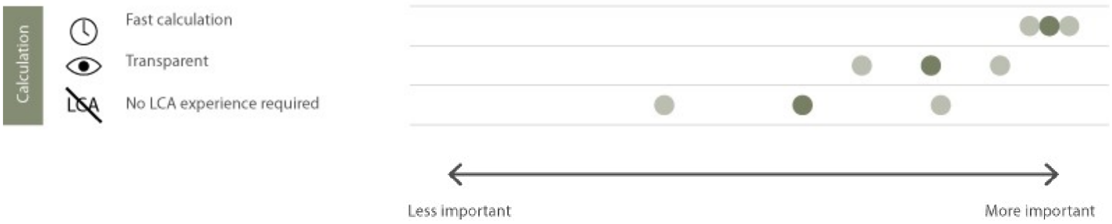


Figure 24. Priorities as stated by engineers.

Opinions raised by engineers around calculations and the workflow are listed below.

- The need for transparency depends on the user and is different depending on if it is an engineer or architect. Transparency is more important when going to later stages.
- Early-stage tools risk to focus too much on details. The tool cannot be too basic either, as it would not provide any information then.

Figure 25 shows software developers' values regarding calculation.

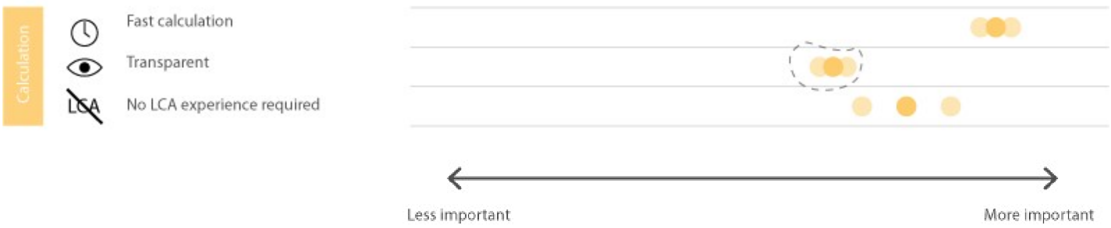


Figure 25. Priorities as stated by software developers.

Opinions raised by software developers around calculations and the workflow are listed below.

- There is a dislike of tools that are "black boxes" with no transparency, especially if the users have limited LCA experience.
- One of the software developers argued for simplicity and that it should be easy to redo the visual coding script. The same interviewee points out that using a single component to perform a lot of calculations could make it hard for someone else to understand how it works.
- From a computational viewpoint, the reliability of the tool is essential. If the tool often crashes, users will doubt other functions in the tool as well.

4.2.7 Outputs of an early-stage LCA tool

Figure 26 shows architects' values regarding outputs.

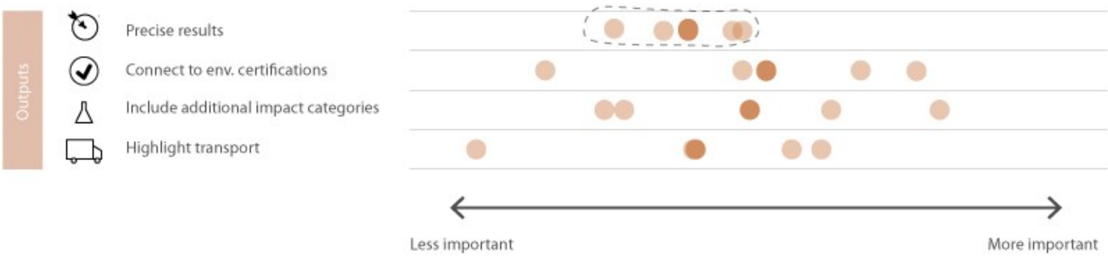


Figure 26. Priorities as stated by architects.

Opinions raised by architects around outputs are listed below.

- Precise calculations are not important in early stages.
- The connection to certifications is rather a question of formatting the results than a crucial tool development issue.
- The focus should be on global warming to begin with.
- To look into economic costs of materials in the calculation.
- Focus on analysing the load-bearing structures.
- Emphasize on communicative, pedagogical visualisations.

Figure 27 shows real estate developers' values regarding outputs.

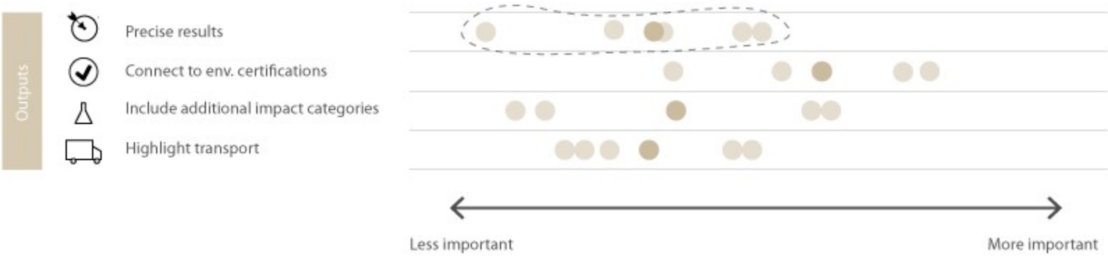


Figure 27. Priorities as stated by real estate developers.

Opinions raised by real estate developers around outputs are listed below.

- Precise results are not important, but different tools must show similar results.
- A connection to certifications could be relevant in the program stage but probably not in the detailed development plan stage.
- Regarding additional impact categories, a real estate developer stated that "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" (Brick, K., interview on February 19th, 2021).
- To compare results with legislative thresholds.
- To keep the same system boundaries as in the climate declaration.
- To look into economic costs of materials in the calculation.

Figure 28 shows engineers' values regarding outputs.

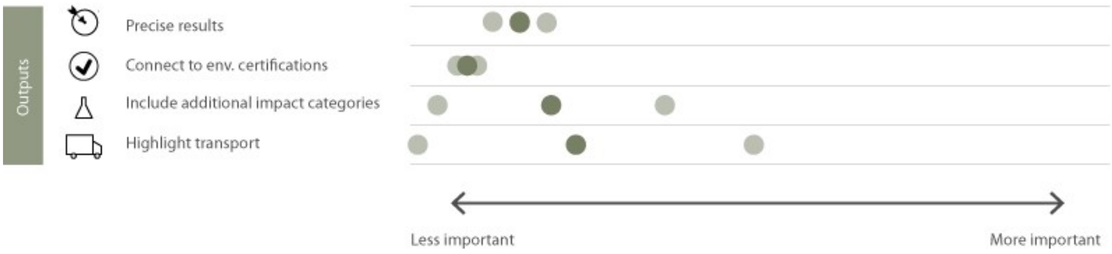


Figure 28. Priorities as stated by engineers.

Opinions raised by engineers around outputs are listed below.

- Showing transports might be misleading, as it is not the major impact.
- Regarding visualisations, it would be helpful to show a heatmap in the Rhinoceros model and a citation was that "It is good to show the result in the form of architecture!" (Richardson, B., interview on February 9th, 2021). Everything is visual at those stages and hence it is good to emphasize on visualisations.

Figure 29 shows software developers' values regarding outputs.

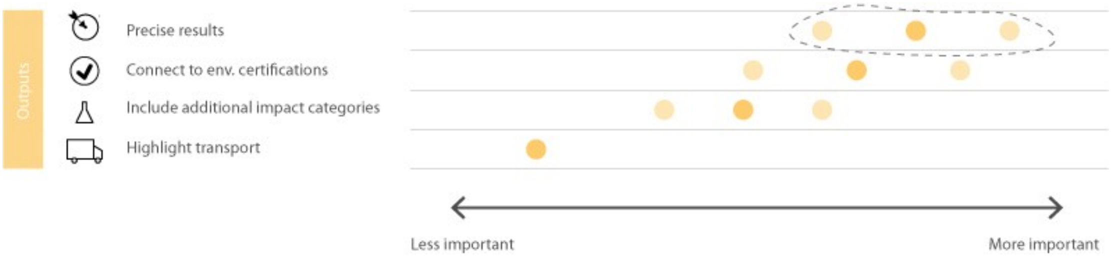


Figure 29. Priorities as stated by software developers.

Opinions raised by software developers around outputs are listed below.

- One software developer stated that precise results are more important than fast calculations. Another software developer saw it the other way around with the argument that there is no point in being fast if you are being wrong.
- The result is contingent of the user's knowledge. For the results to make sense, it is useful to compare the results to a reference value.
- Grasshopper is excellent at making visualisations and hence it should be utilised.

4.2.8 Connection to part one of the research question

The first part of the research question and the interview results related to it is presented below.

What is required…
…in terms of input data and results?
Some argue for the use of EPDs but most thought that generic, national data is of value. Regarding results, stakeholders from all professions were united around the emphasis on visual results.

…in terms of transparency?
The importance of transparency varies depending on the user and on the project stage.

…in terms of connection to a 3D model?
The connection to a 3D model is of value to most stakeholders, however a little less to real estate developers. There were different preferences on how to build the geometry and a variety of CAD software was proposed.

…in terms of calculation speed?
An early-stage tool must be fast to enable different iterations when the project team is pressed on time in early stages.

…in terms of software skills and LCA experience of the user?
There can be different branches of the tool, requiring varying LCA and modelling experience. However, a software like grasshopper is hard to learn and might not be suitable for such a tool. Architects seem to be a suitable user group as they are working with 3D models in early stages.

4.3 Tool review

A summary of properties of the studied tools is presented in Table 5.

Table 5. Scheme of tool properties.

Tools / Properties	Byggsektorns Miljöberäkningsverktyg (BM)	OneClick LCA	The Buildings and Habitats object Model (BHoM)
Connection to a 3D model	No	Yes	Yes
Functionality to add EPDs	Yes	Yes	Yes
Has data for the Swedish market	Yes	Yes	Yes
Reference study period	50 years	Varies	50 years
Additional impact categories besides Global Warming	No	Yes	Yes
Modules	A1-A5	Varies	A1-A3
Web-based tool	No	Yes	No
Desktop tool	Yes	No	No
Plug-in tool	No	Yes	Yes

4.3.1 Byggsektorns Miljöberäkningsverktyg (BM)

BM is a desktop tool provided by IVL (IVL, 2021). It holds a database with environmental data of resources representative for the Swedish market. The aim of the tool is to widen the use of LCA in the building industry, lower the climate impact and enable resource efficient construction. It can be used to calculate the embodied carbon in MB and hence make a great impact in the industry. The focus is on the modules A1-A5 and the quantities of building materials can be added to the tool via excel or manually. There is a possibility to add EPDs. The results are extracted as a report in excel with numbers and graphs (Figure 30). The tool offers subscription plans and trial periods.

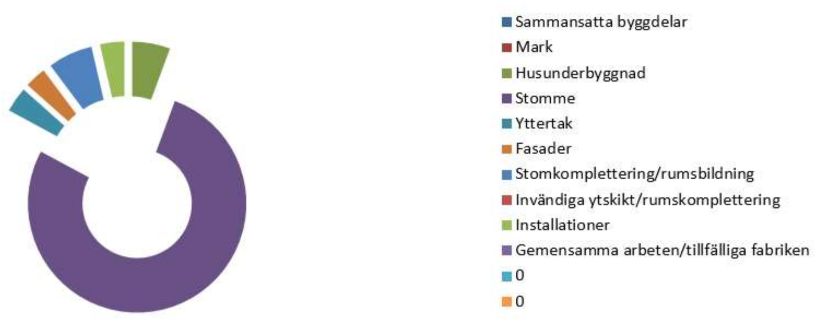


Figure 30. Result extraction from BM.

4.3.2 OneClick LCA

OneClick LCA is both a web-based tool and a plugin tool allowing connections to Rhinoceros, Revit, Excel and other software (OneClick LCA, 2021). There are subscription plans and trial periods available. The tool allows for comparing different designs of a project at different stages. It can be used for different certifications like BREEAM, LEED, MB and NollCO2. LCA phases, impact categories and the reference study period vary and depend on the project specific requirements. Quantities of building materials can be added to the tool via excel or manually. The environmental data comes from several databases and countries (Figure 31) and the result is shown in multiple ways (Figure 32 and Figure 33). Besides LCA of buildings, the software also offers LCA of infrastructure, greenhouse gas reporting and EPDs.

Figure 31. Material input to OneClick LCA.

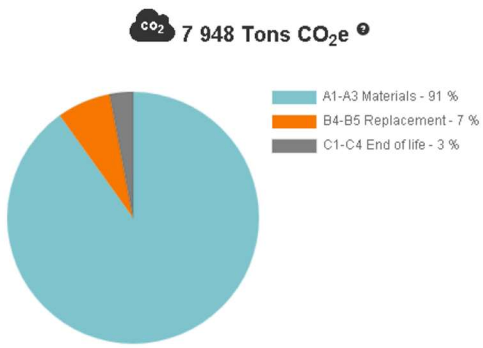


Figure 32. Result extraction from OneClick LCA.

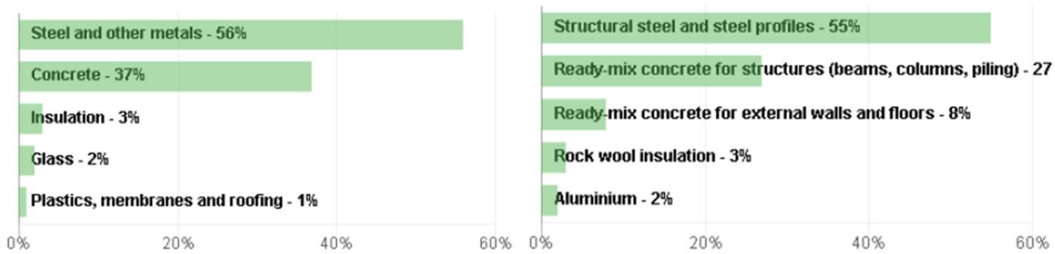


Figure 33. Detail result extraction from OneClick LCA.

4.3.3 The Buildings and Habitats object Model (BHoM)

BHoM is a computational development project that is collaborative and open source (BHoM, 2020). The project has several toolkits and since 2020 there is a LCA toolkit. The tool has user interfaces in Excel, Dynamo and Grasshopper (Figure 24). There are EPDs and databases of environmental data in the tool and a possibility to add additional data. BHoM includes data transfer between software and analysis within the tool which makes combined analysis possible.

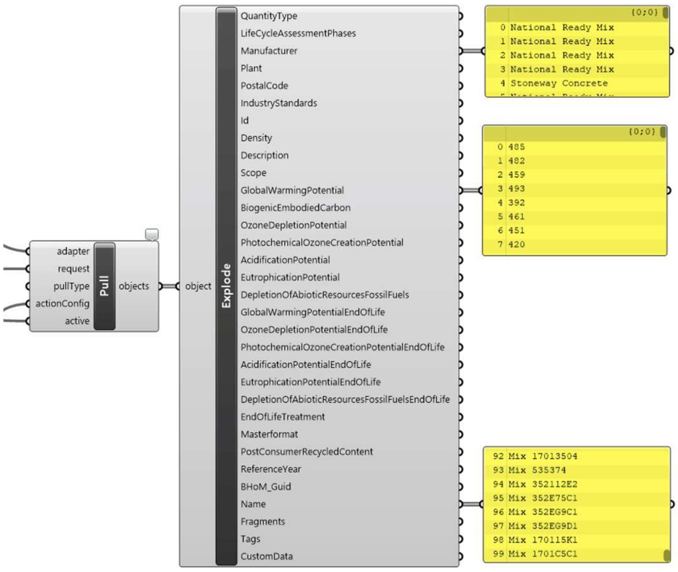


Figure 34. The BHoM workflow for LCA.

5 Method: Tool development and case studies

The methods of the tool development and the case studies are presented in this chapter.

5.1 Tool development

This chapter firstly describes the requirements brought forward from the literature review, the interviews and the tool review to the tool development. Then it presents the choices and pathways of the tool development.

5.1.1 Requirements derived from the literature review

The use of generic data and pre-set building element types was emphasized on in the tool development. The focus on climate impact was utilized. The BIM connection recommended in several papers was not included but the tool instead focused on extracting surface layers from a 3D model. Building the tool in grasshopper enabled parametric modelling. Emphasis was put on LCA phase A as recommended.

The strategies for lowered climate impact presented in 4.1.3 influenced functionalities in the tool. Reused materials and sustainable materials like climate-improved concrete was set as options in the tool. As the tool had a connection between the building shape and the material choices, materials used to a high degree could be identified and sustainable choices for those materials could be prioritised. Erlandsson et al. (2018) suggest calculating climate impact for every single project and to increase the knowledge about climate impact in the entire value-chain which was not something that could be implemented in the tool but that the tool can contribute to.

5.1.2 Requirements derived from the interviews

A conclusion from the interviews was that architects would be a suitable user group for the early-stage LCA tool if it has a connection to a 3D model. Hence, architects was chosen to be the intended user group. From the literature review and the interviews, it was found that a main purpose for architects to conduct early-stage LCAs is comparing design options in early sketching.

The tool tried to bridge the challenges “lack of time”, “lack of knowledge” and “absence of regulations” by enabling fast and informative comparisons and comparing the results to thresholds. As environmental knowledge among architects is asked for by clients, the tool strived to be educational. Figure 35 shows a summary of the interviewees’ priorities.

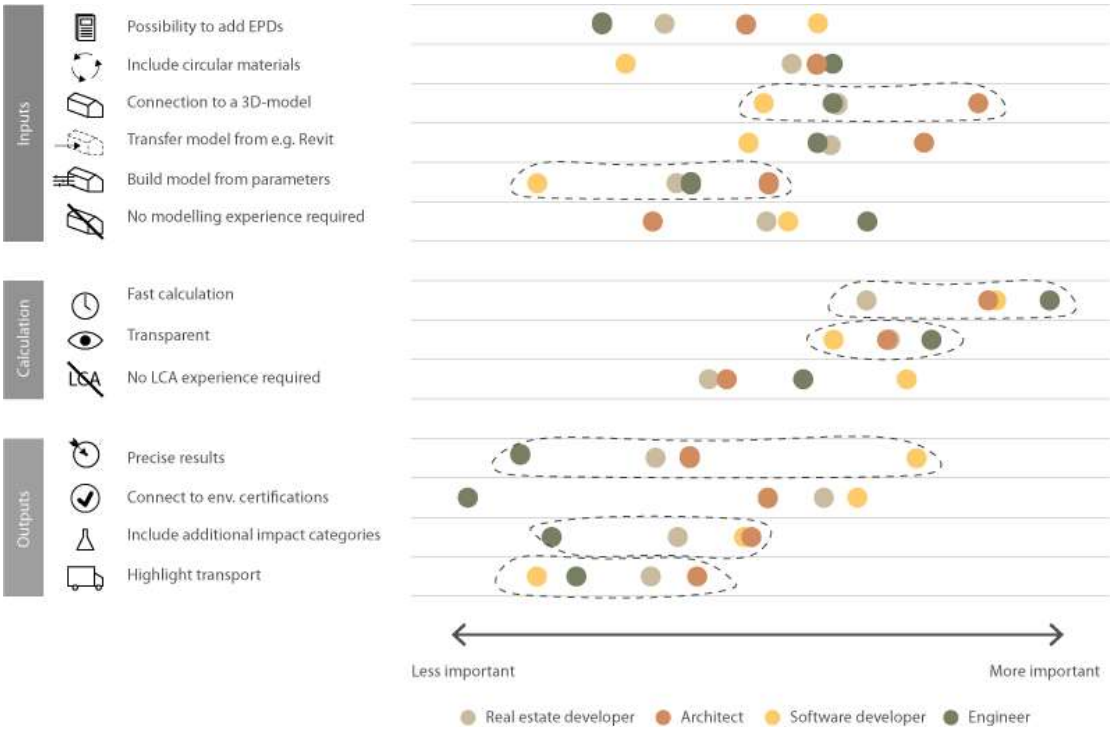


Figure 35. Mean values of priorities as stated by all interviewees.

Important features from Figure 35 and from chapter 4.2 are fast calculations, transparency and 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. Therefore, no additional impact category besides global warming was included. In Figure 35 it can be seen that the priorities of the real estate developers often are close to the other professions while the priorities of the software developers deviates from the norm.

Fast calculation was enhanced, and the accuracy of the results from the tool is highly dependent on the user's model. Transparency was valued by the interviewees, however for the tool components to be easy to update, the code was written as a plug-in to Grasshopper which made it less transparent.

As stated earlier, architects were chosen to be the user group as they are working with 3D models already in early stages, compared to real estate developers and engineers. As the analysis is on the architectural model, a drawback was that load-bearing elements are not included in the model and must be studied in the tool. As little LCA experience was required, the user was not expected to make methodological choices.

There were several reasons for using the tool mentioned by interviewees. The application areas enhanced in the tool were to create baselines, compare LCA modules A1-A5 and for learning: seeing consequences, increasing awareness, making sustainable choices and stepping away from standard materials.
The tool is thought to be useful in competitions as the result graphics can be customised and multiple design alternatives can be shown. The tool can be used in workshops or to bring forward a few solutions.

A software developer argued for simplicity in the tool and a possibility for the user to redo the visual coding script. This was enhanced in the tool and the components were made easy to connect and disconnect. The same interviewee stated that one should avoid a single component to perform multiple calculations. This was not considered in the development, to keep down the number of components.

Another software developer advised to be flexible in how the geometry is built. This was enhanced, and hence the input geometry can be built in several ways. An engineer told to not presuppose a box model, which was considered when developing the tool. The freedom of modelling enabled analysis of the current building stock as lifted by the interviewees. 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.

Interviewees discussed that a too detailed tool would not be suitable for sketching in early stages, whereas a too basic tool would not introduce learnings. The tool was developed to allow detailed modelling by customised elements and basic modelling by pre-set elements. Hence the tool used both a material and element take-off. As many interviewees thought that generic and national data was of better value in early stages than EPDs, the further was used. Similar system boundaries as for the upcoming climate declaration were enhanced.

Software developers advised to compare the results to a reference value for the numbers to make sense. This was enhanced in the tool. The powerful visualisation feature of Grasshopper mentioned by a software developer was used. An interviewee thought that a heatmap to visualise the results in a pedagogical way would be helpful, and it was enhanced in the tool. The LFM30 involvement among several interviewees led to including LFM30's thresholds in the tool. The connection to certifications was not prioritised by interviewees and hence it was left out from the development.

The possibility to make isolated LCAs on chosen building elements was enhanced. There was another idea to focus on foundation and load-bearing elements as in MB. But as it was easy to include lots of building elements, and to be in line with the upcoming climate declarations, 9 different elements were included. Another reason was that the comparison between only e. g. concrete and wood systems could introduce predictable results.

5.1.3 Requirements derived from the tool review

The tools studied are using generic data and EPDs as environmental data, and hence the tools do not perform full LCA calculations as conceptualized in Figure 1. Rather, they make sense of the data and connect it to the quantities of building materials and systems in the building project. This way of calculating was brought forward to the tool development, where no full LCA calculations are made in the tool. BM brought ideas of how to visualise results and handle data, as their database is similar to the one by Boverket (2021).

OneClick LCA inspired to the feature of comparing different designs of a project at different stages. Data handling and tool build-up was inspired by BHoM.

5.1.4 Methodological choices

The LCA calculation was set to be of an attributional type as it does not study the effect of changes in the system, but rather what impact is associated with the materials. The type is in line with the upcoming climate declarations (Boverket, 2020b). The functional unit for the tool was defined as 1m^2 Atemp of a building and year. The reference study period was set to 50 years to be in line with the upcoming climate declarations. It was a cradle to site/handover study and the LCA modules A1-A3 (the production stage), A4 (transport to site) and A5.1 (wastage, packaging and waste management) were studied as they will be included in the climate declarations 2022 (Figure 7) and as A1-A3 was often suggested in the literature review. The whole A5 module was not included as the database by Boverket only provided data for A1-A5.1. The geographical system boundary was set to Sweden and the tool was aimed to be used within the Swedish building industry. To keep the tool simple, the impact categories studied was limited to climate impact in the form of GWP with the unit of kg CO2-eq.

The building elements studied are stated below and were chosen to be in line with the climate declaration of 2022. Hence, they were limited to load-bearing elements, the building envelope and interior walls.

- Foundation
- Structure
- Ground floor
- Intermediate floors
- Roof
- Exterior walls
- Interior walls
- Windows
- Doors

From the literature review, it was clear that simplification is needed in this tool. A way of simplifying was to only use one data source and hence for conventional materials, generic environmental data from Boverket's database (2021) was used. The data is found in Appendix II- Environmental data. This was also in line with the interview results pointing at using national data. There are 170 resources in the database using the calculation standard EN 15804:A1 (Boverket, 2020b). A conservative data conversion factor is included in the database and hence the results were a bit higher than the actual impacts. The resources presented in the database are sorted into the below categories.

- Mineral materials and glass
- Energy and fuel
- Windows and doors
- Paints and sealants
- Concrete
- Insulation
- Steel and other metals

- Blocks and tiles
- Building boards
- Waterproofing
- Solid woods

5.1.5 Delimitations

A delimitation was that the functional unit did not consider e.g. insulating abilities which rather was an output of the analysis. Another delimitation was that biogenic carbon was not accounted for as it will not be included in the climate declaration until 2027. Installations were not included, even if they can have a high impact.

5.1.6 3D modelling

From the interviews, it was found that early-stage models can be built up in different ways and hence a flexibility is beneficial in an early-stage tool. When considering development paths, the author found three different alternatives of how to build up the 3D geometry. There were benefits and drawbacks of each alternative and what is the best way to go heavily relies heavily on the user preference.

One way of building the geometry was by drawing the building in Rhinoceros or importing it from another CAD software. The surfaces were then sorted into layers representing different building elements and the layers were referenced into Grasshopper. The benefits with the approach were the possibility to use an imported 3D model from e.g. Revit or Archicad and to not be limited to box models. The drawbacks were that it can be tricky to change things in the model and time consuming to draw e.g. windows and internal walls at an early stage. A challenge was to assign structural elements and foundation in early stages. This alternative was evaluated to be suitable when there is already an existing 3D model in the project or if the user wants to explore designs besides standard construction and box shapes. Figure 36 shows a model imported from Revit and makes it clear that there are no limits in how detailed the model can be with this approach.

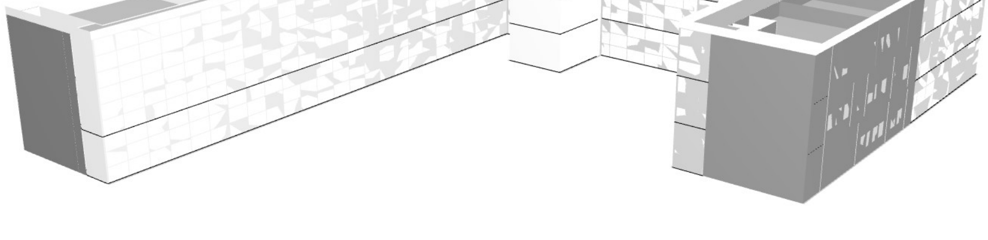


Figure 36. Geometry from a Revit model imported to Rhinoceros.

Another way of modelling the geometry was to draw it in Rhinoceros and sort the building elements in grasshopper by angle and placement. For example, horizontal surfaces at a low level would be assigned as ground floor, and vertical surfaces in the outer boundary of the model would be assigned as exterior walls. The benefits, drawbacks and challenges were the same as in the previous alternative. An additional benefit was that the user would not have to sort the building elements into layers. The areas of usage were the same as in the previous alternative.

The third way of modelling geometry explored was by using parameters in Grasshopper (Figure 37). The ground floor surface was drawn in Rhinoceros and linked to Grasshopper. Number sliders in Grasshopper defining load-bearing concept, number of levels, floor-to-ceiling height and wall-to-window ratio were used. The geometry was directly visualised and connected to the LCA calculation. The benefits were that it was easy to update the geometry by e.g. adding extra floors and that the user would not need as much 3D modelling experience as in the other proposals. The drawbacks were that there were more choices to be made by the user and that the model was disconnected from possible existing 3D models in the project. A potential area of usage was defined to be really early stages, where an existing 3D model is not in place.

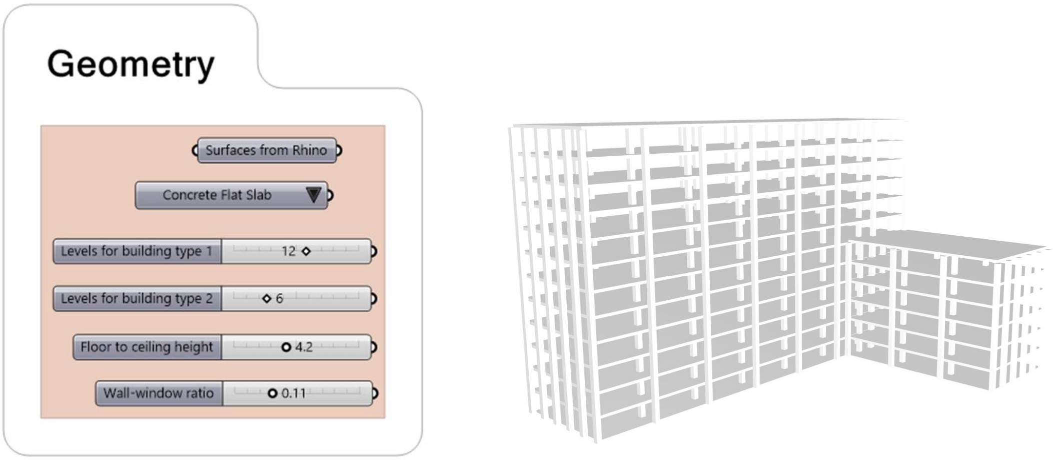


Figure 37. Geometry built in Grasshopper.

Two out of the three modelling paths were chosen, and it created two different versions of the tool. Version 1 was the development path of building up geometry by drawing in Rhinoceros and then sorting building elements manually into layers. It was chosen as it provided freedom and flexibility when shaping the building. The possible connection to other CAD modelling software was also used as an argument. Version 2 was the path of modelling geometry by using parameters in Grasshopper. It was chosen to make the modelling more parametric and to make it easier to change the design.

In the parametric model, the internal walls were assigned with factors according to Table 6. The numbers are adapted from recommendations in the paper by Hollberg (2016). The building type column in the table is added by the author.

Table 6. Internal wall factors. Adapted from Hollberg (2016).

Building type	Floor plan type	Average room size [m^2]	Factor for interior walls [length of interior walls in m/floor area of conditioned zones in m^2]
Commercial	Few walls	48	0.25
Office Service School	Moderate number of walls	20	0.4
Multi-residential building Single family building	Many walls	12	0.5

5.1.7 Environmental data assignment

The author found two different alternatives of how to assign environmental data. As with the 3D modelling, there were benefits and drawbacks of the alternatives and what is the best way to proceed relies on the user preference.

One path of assigning environmental data was to have multiple inputs to each building element. For example, to a wall there would be a choice of cladding, insulation type, building boards and so on. The thickness of each layer had to be added as well. This alternative introduced a lot of choices to be made by the user but also a freedom to control the material use in detail. Another path for assigning environmental data was to have standard choices, e.g. when choosing a standard wall it automatically assigns a certain cladding, an insulation type and building boards. This introduced less choices to be made by the user but decreased transparency.

Both development paths chosen as a possibility to use building elements with pre-set materials and thicknesses was made via an overriding connection. In this way, both alternatives of assigning climate data mentioned above were used. Hence the flexibility of building up specific constructions and the fast way of choosing between pre-set building elements were kept. The environmental data assignment partly follows the literature reviews' suggestion of extracting surface layers from the 3D model and multiplying with the thicknesses and densities. However, when creating the 3D model, some elements like columns were made as volumes instead of surfaces. In those cases, the thickness of materials was not needed 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].

5.1.8 Load-bearing structures

If building the geometry in Rhinoceros (version 1), the user had to model the load-bearing structures by drawing them. Hence, a freedom to choose between combinations of load-bearing walls, columns, beams and slabs was enhanced. If building the geometry parametrically in Grasshopper (version 2), the choice was set to use load-bearing walls or concrete, steel or wooden frames. For the latter options, the structures shown in Figure 38 were used. The structures are further described in Appendix III – Load-bearing structures. The foundation in both versions was set by stating a thickness of a ground slab. There was an ability to draw piles in version 1.

Figure 38. Load-bearing frame concepts used in the tool. Adapted from Buro Happold (2020).

5.1.9 Visualisation of results

LCA as a way of assessing environmental performance is growing and hence it is important for decision makers to understand the results (Hollberg et al., 2021). The same paper presents a review of visualising LCA results in the design process of buildings and classifies them depending on goals and amount of information displayed in the visualisation. Visualising the results in a 3D design environment is an observed trend. The visualisation types for the tool were chosen from the goal of the study. The main goal is to compare design options and hence bar charts comparing phases and building elements were chosen. To enable identification of hotspots, a pie chart comparing building elements and a heatmap colouring elements depending on their climate impact were used. To compare the results with thresholds, a benchmarking bar chart was used.

In the benchmarking bar chart, the LCA results were compared with thresholds from LFM30 and the Finnish Ministry of Environment. The thresholds have the different units of [kg CO2-eq/ m2 light BTA/year] (IVL, 2021) and [kg CO2-eq/ m2 NTA/year] (Bionova Ltd, 2021). Comparing to thresholds introduces an error as they have different units. The threshold values do not have 25% additional impact as the database by Boverket has. As mentioned in 5.1.4, the tool studied only A5.1 and not the whole A5 module, which makes it different than the thresholds. The mentioned differences were not utilized in the tool as they were not thought to have a big impact in early-stage calculations.

5.1.10 The script

The script was designed to be future proof; meaning that the code is easy to understand and possible for someone else to work on, and scalable; meaning that it can be developed to include new functionalities and easy to debug. Inputs and outputs of the components were clearly defined. Headings and informational texts were used in the script to make it user-friendly and C# coding conventions from several guides for best practice were used. Grasshopper was used as a programming environment as it is a powerful visualiser, has a direct link to a 3D model and enables a connection to other types of analysis. The additional plug-ins used were Conduit (Proving Ground, 2021) for results visualisation, Elefront (Food4Rhino, 2019) for connecting to Rhinoceros layers and BHoM (BHoM, 2020) for connecting to the JSON database from Boverket.

5.1.11 Tool concept

The concept of the tool is illustrated in Figure 39 showing version 1 and Figure 40 showing version 2. The dark green boxes highlight the user's interaction with the tool.

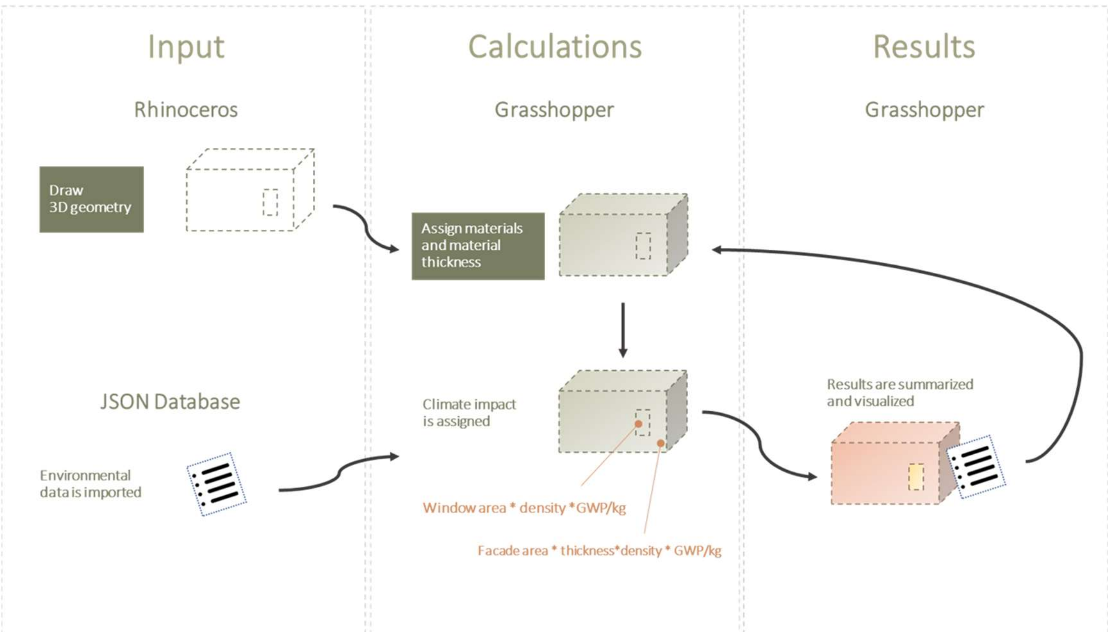


Figure 39. Illustration of the tool functionality (version 1).

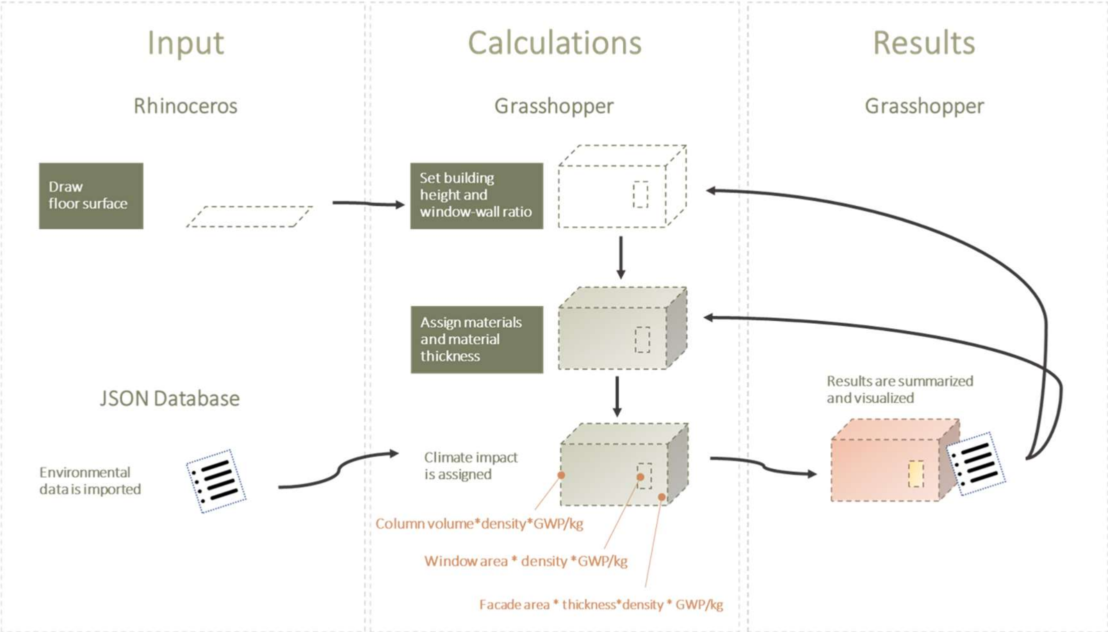


Figure 40. *Illustration of the tool functionality (version 2).*

5.2 Case studies

Two case studies were made to test the tool and they are presented below.

5.2.1 Korseberg strand

The first case study was a numerical test where a building project was modelled by the author and the results were compared to calculations in BM. The comparison was on the modules A1-A3. As the database from Boverket had a factor of 25% added to the environmental data and BM does not, the data from the tool was lowered to match the BM results.

5.2.2 User tests

The second case study included to let interviewees and employees at BDAB test the tool and give feedback. The participants in the user test were a mix of engineers, architects, a real estate developer and a software developer (Table 7). Five out of eight of the participants were interviewees in the earlier stage of the thesis. The interviewees were chosen to have all professions represented.

Table 7. *Participants in the user tests.*

Category of company	Company		Person
Engineer	Bengt Dahlgren AB	Energy and environmental engineer	Giovana Fantin Do Amaral Silva
Engineer	Bengt Dahlgren AB	Energy and environmental engineer	Gerda Ingelhag
Engineer	Bengt Dahlgren AB	Innovation leader	Linda Wäppling
Real estate developer	Catena fastigheter	Sustainability strategist	Anna Wallander
Architect	EttElva Arkitekter	Sustainability manager	Emma Östlund

Architect	EttElva Arkitekter	Architect	Erik Björnhage
Architect	Liljewall Arkitekter	Architect	Alexander Gösta
Software developer	StruSoft AB	Parametric designer	Alexander Radne

Due to the Covid-19 pandemic, the tests were conducted through online meetings and the participants tested the tool via remote control on the author's computer. Two of the interviewees, working at BDAB, tested the script on their own computers. A survey was sent out afterwards, for the participants to fill in. The questions handled usability, modelling, transparency and overall impression and they are listed below.

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

6 Results: Tool development and case studies

The results from the tool development and the case studies are presented in this chapter.

6.1 Tool development

In this section the results of the tool development are presented. The tool has two different versions as described in 5.1.11. The versions bring a flexibility in modelling and the use of the tool. In this chapter, the results refer to the versions, in the cases they differ.

6.1.1 3D modelling

In version 1 of the tool, the geometry is built in Rhinoceros or by importing it from another modelling software. All elements are modelled as flat surfaces. The building elements are manually sorted into layers with building element names, and the layers are automatically connected to the chosen materials. Version 2 uses a floor surface in Rhinoceros and then the geometry is modelled parametrically in Grasshopper. Some of the geometry is volumes, while some is surfaces. Figure 41 shows an example of a parametrically built model in the tool.

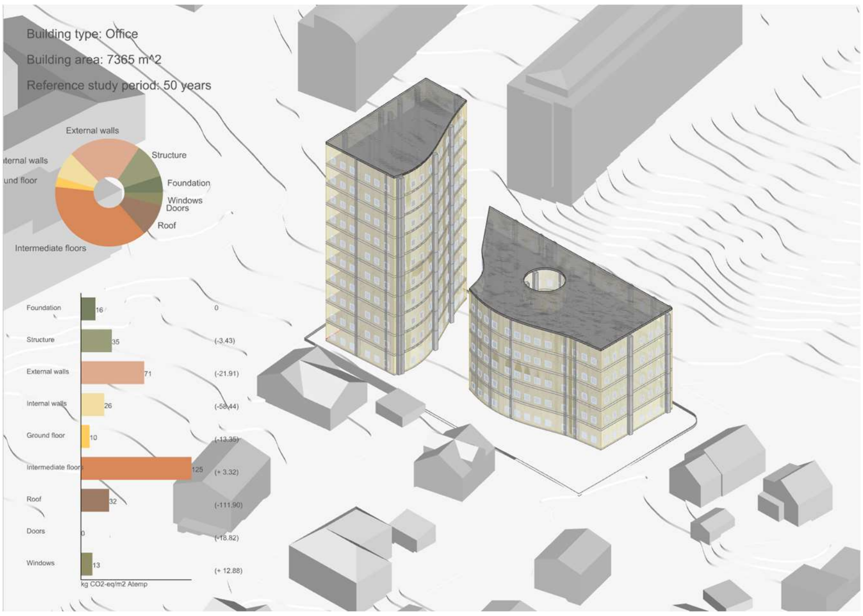


Figure 41. 3D model in the tool.

6.1.2 Environmental data assignment

The environmental data is imported from the JSON database provided by Boverket (2021). Components from the plugin BHoM are used for the data exploration. Figure 42 shows the data import and Figure 43 shows the data exploration. The building materials are divided into Boverket's pre-set categories in the database. The environmental data assignment component allows for the building element units of [kg], [m2] and [m3] as seen in Figure 44.

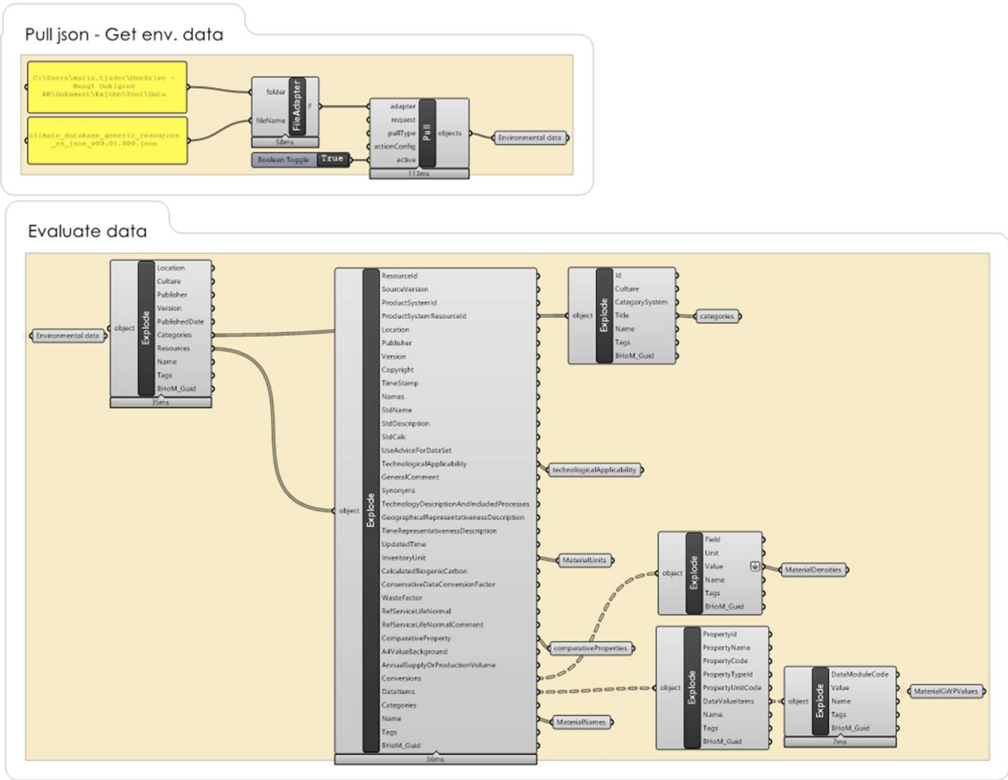


Figure 42. Functionality of importing environmental data.

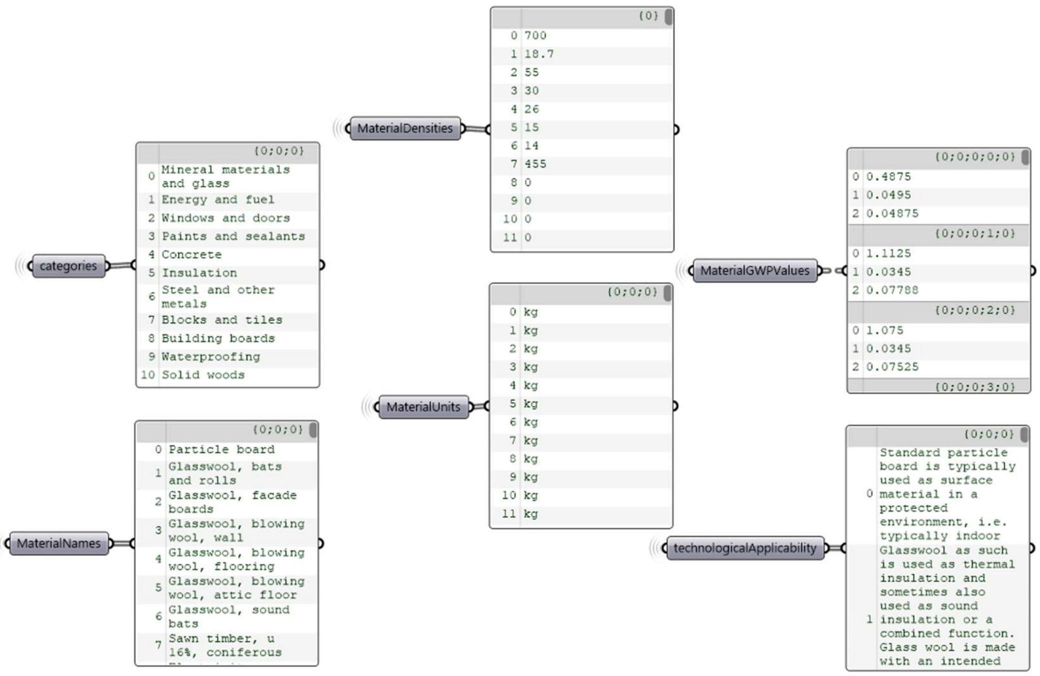


Figure 43. The environmental data explored in Grasshopper.

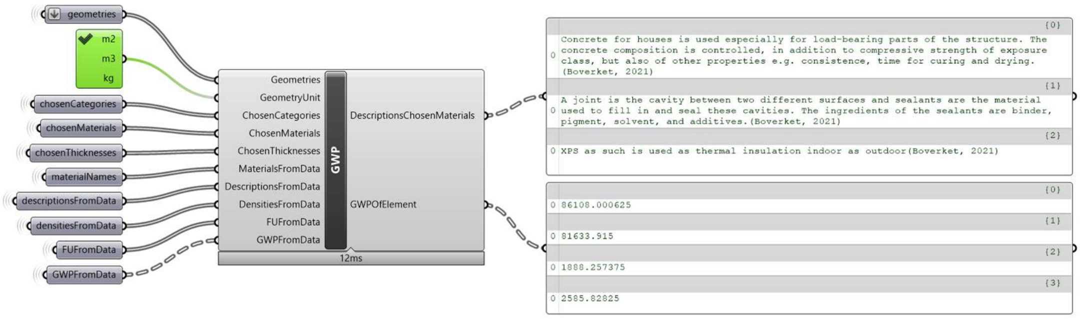


Figure 44. The choice of unit when assigning building elements.

When assigning materials to a building element, the user chooses between pre-set and custom material combinations (Figure 45). Figure 46 shows the code behind the pre-set material combinations in the building elements.

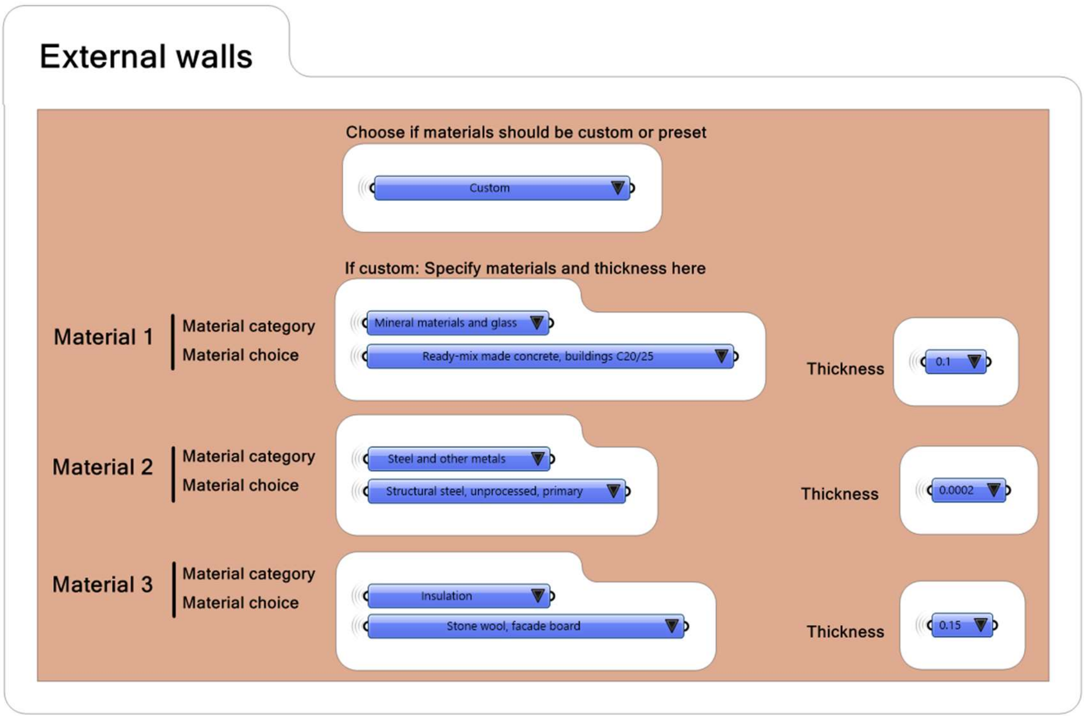


Figure 45. The choices of material category, material and thickness in the tool.

```
if (modelingChoice == "Concrete external wall")
{
    chosenMaterialsTree.Add("EPS, expanded polystyrene, pressure class 80", new GH_Path(0));
    chosenMaterialsTree.Add("Cement mortar, type A (CS IV)", new GH_Path(1));
    chosenMaterialsTree.Add("Ready-mix made concrete, buildings C30/37", new GH_Path(2));
}
```

Figure 46. Background code with material build-up of pre-set material combinations.

6.1.3 Load-bearing structures

In version 1, the load-bearing structures are drawn in Rhinoceros. In version 2, the user can choose between load-bearing walls or wooden, steel or concrete frames (Figure 47, Figure 48 and Figure 49).

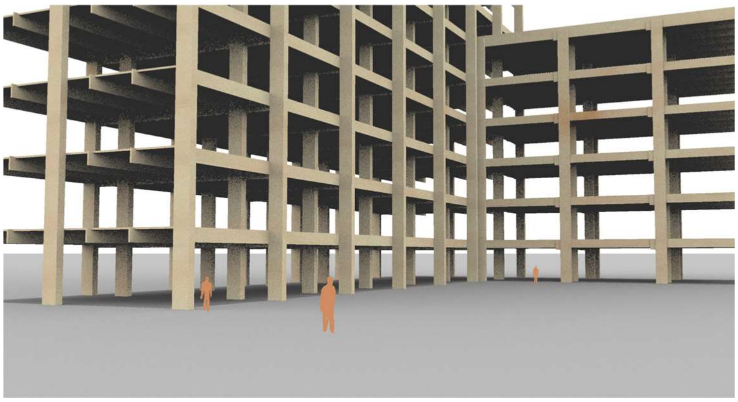


Figure 47. Wooden structure in the tool.

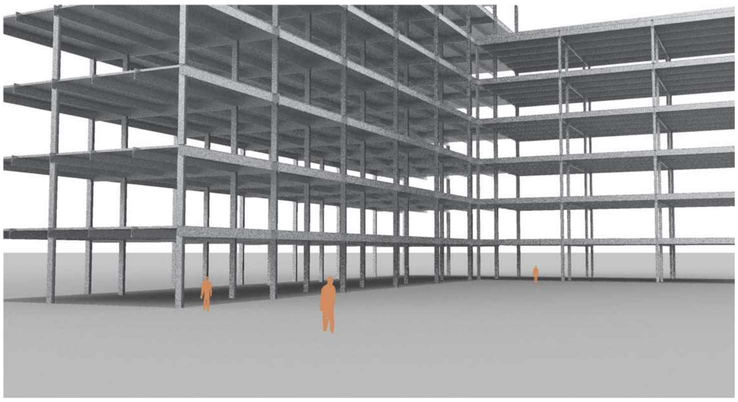


Figure 48. Steel structure in the tool.

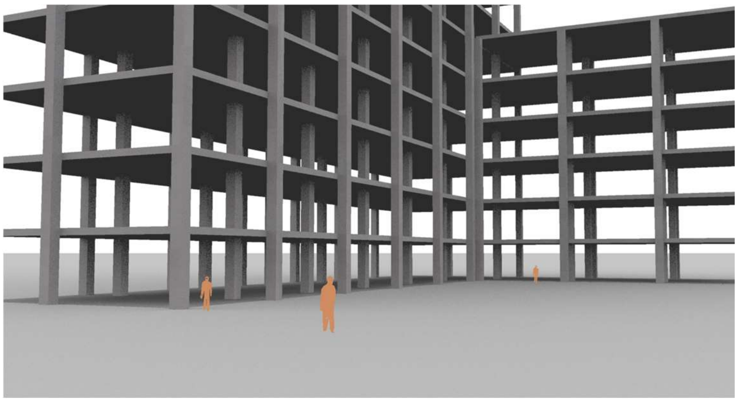


Figure 49. Concrete structure in the tool.

6.1.4 Visualisation of results

The results are shown graphically, and the user can change what bar chart results to view by using a toggle (Figure 50). The results options are comparing building elements, life cycle modules, or against threshold values like LFM30 and the Finnish Ministry of Environment (Figure 51). The threshold values are set to compare modules A1-A5. When making iterations in the tool, the previous results are shown to enable comparisons. Another way of showing results is by colouring the building elements in the model by their environmental impact (Figure 52). The heat mapping can be viewed on the whole model or on isolated elements. Rather than bringing detailed information, the graphs and heat mapping strive to highlight focus areas for lowering the embodied carbon.

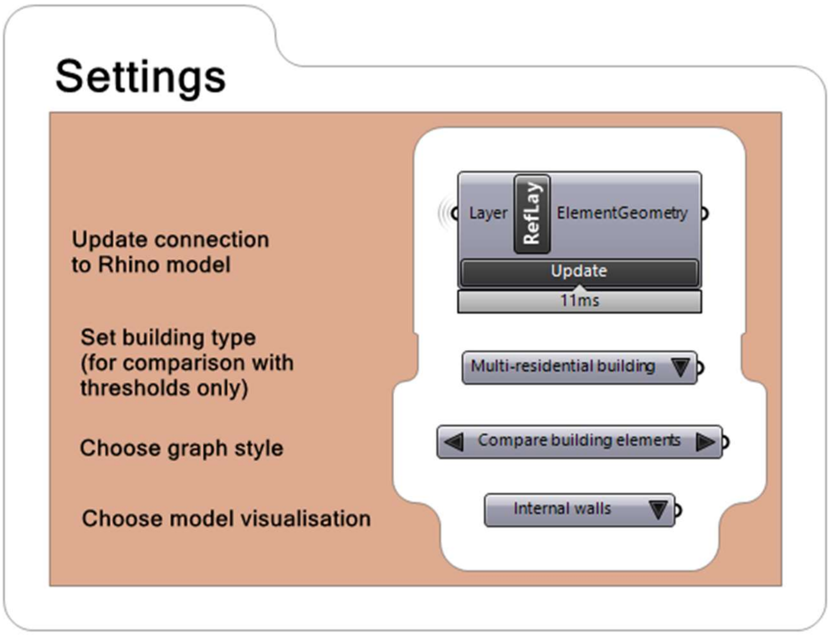


Figure 50. Toggle to set building type and make visualisation choice.

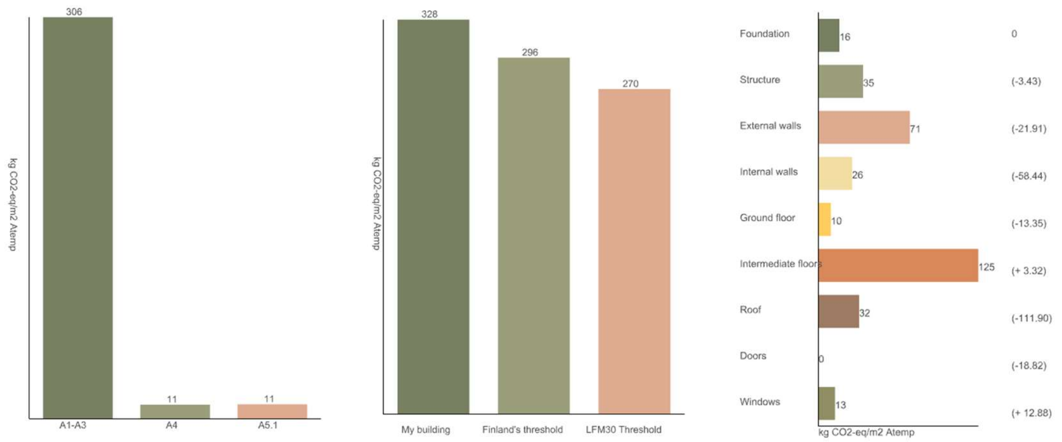


Figure 51.   Graph options in the tool.

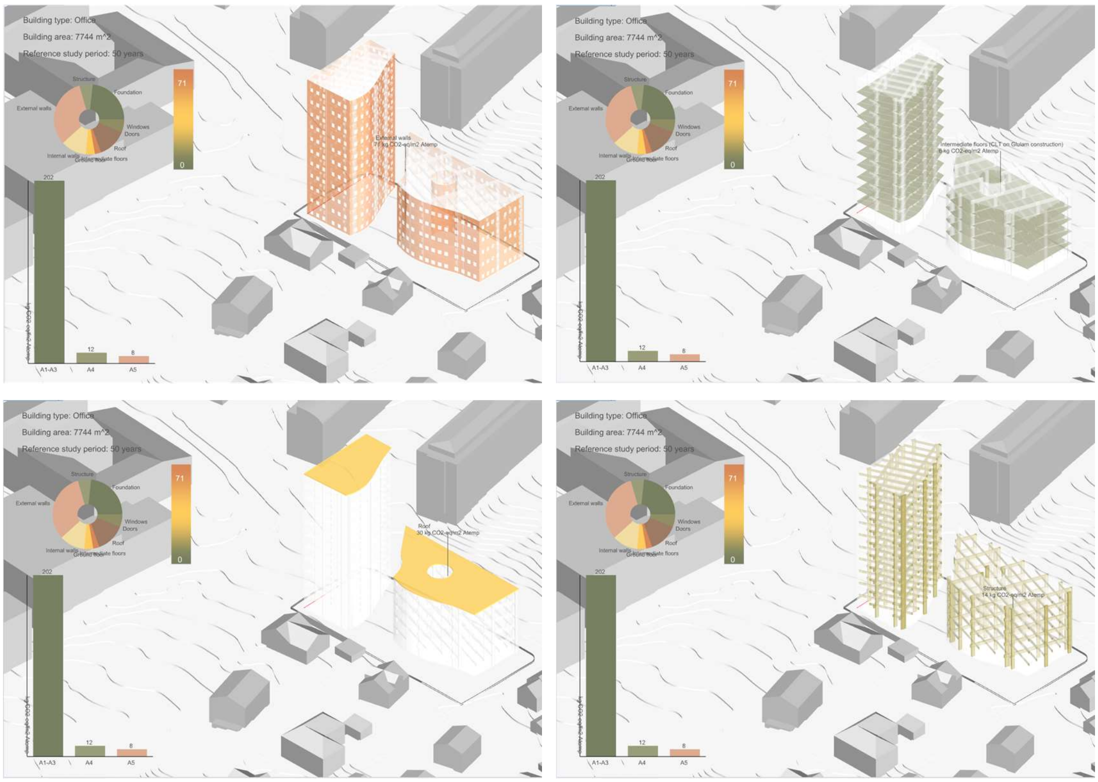


Figure 52.   Heatmap results in the Rhinoceros view.

6.1.5 The script

The script is grouped into different parts with different functionalities. There are headings with white backgrounds to ensure a quick overview of what parts there are of the script. Most groups of components are yellow, however the groups containing user input components have a red background. The inputs and outputs of every group are clearly aligned to the left and the right, respectively.

6.1.6 Areas of usage

In this section, some examples of the areas of usage are presented. A large part of the tool is about knowledge gaining, which is exemplified by the material descriptions in Figure 53. Comparing load-bearing structures is shown in Figure 54 and Figure 55. Comparing building shapes with similar floor areas but different shapes is shown in Figure 56 and Figure 57. The tool could also be used to support certifications and climate declarations by setting baselines. As the gold level of MB demands a decrease in climate impact of 10%, the tool could potentially help set the baseline.

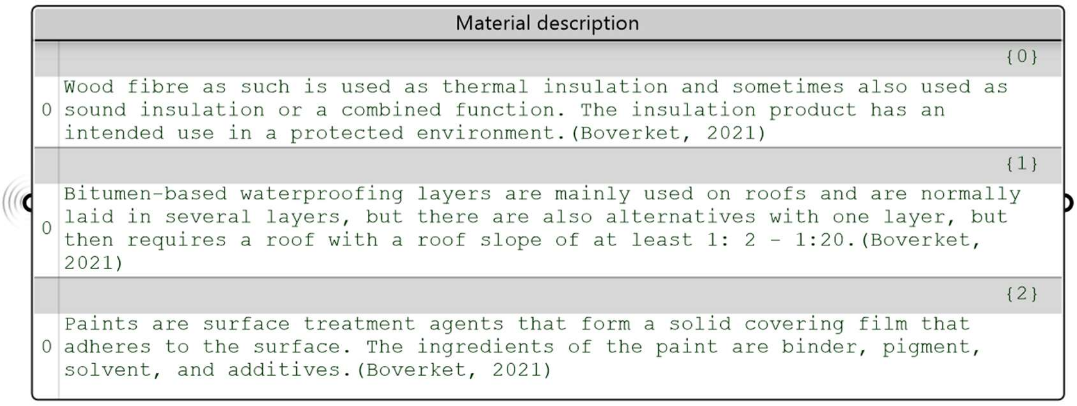

Material description
{0}
0 Wood fibre as such is used as thermal insulation and sometimes also used as sound insulation or a combined function. The insulation product has an intended use in a protected environment.(Boverket, 2021)
{1}
0 Bitumen-based waterproofing layers are mainly used on roofs and are normally laid in several layers, but there are also alternatives with one layer, but then requires a roof with a roof slope of at least 1: 2 - 1:20.(Boverket, 2021)
{2}
0 Paints are surface treatment agents that form a solid covering film that adheres to the surface. The ingredients of the paint are binder, pigment, solvent, and additives.(Boverket, 2021)

Figure 53. Descriptions of materials in the tool.

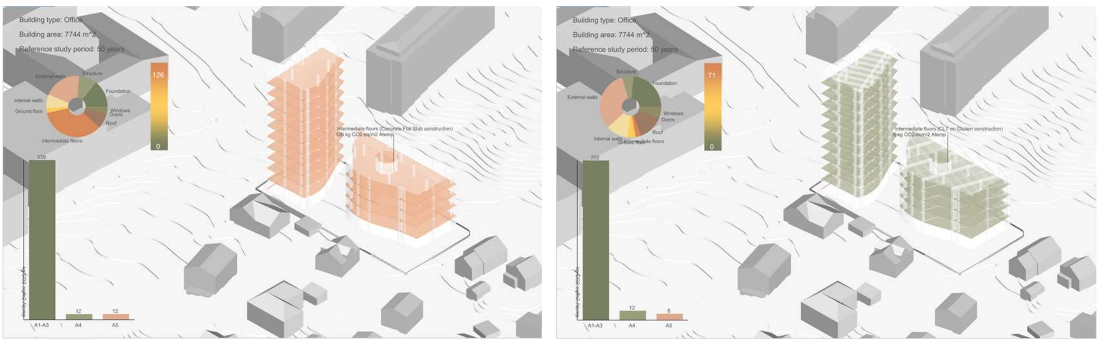


Figure 54. Comparison of concrete and wooden floor slabs.

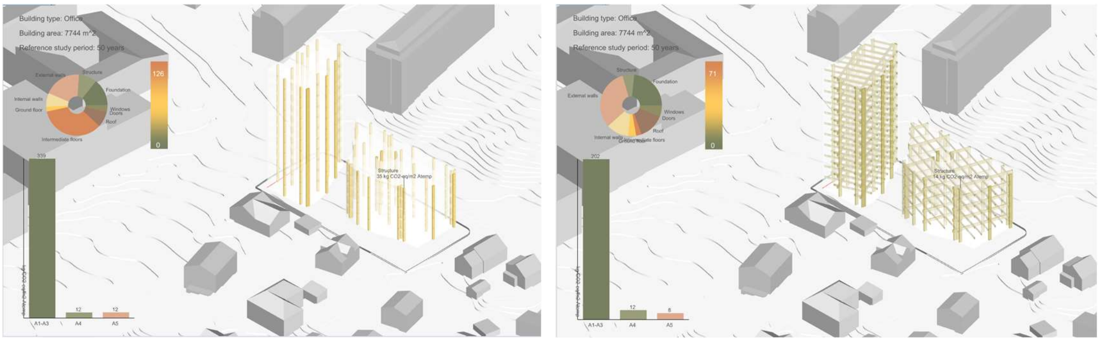


Figure 55. Comparison of concrete and wooden beams and columns.

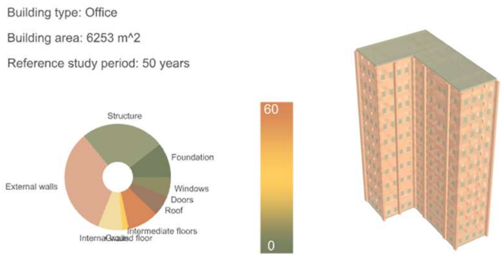


Figure 56. A building with a small ground floor area and ten levels.

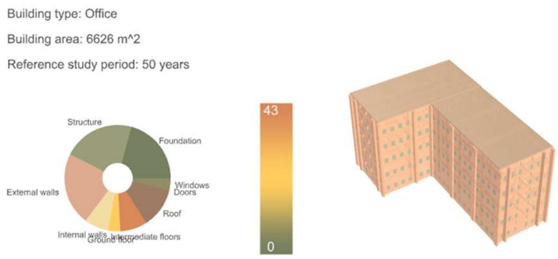


Figure 57. A building with a large ground floor area and five levels.

6.2 Case studies

The numerical case study and the user tests are presented in this section. By the end of each results part, a connection to part 3 and 2 of the research question respectively will be made.

6.2.1 Korseberg strand

The case study building is a project called Korseberg strand and it is a multi-residential building by Riksbyggen (Riksbyggen, 2020). The building hold apartments with 2-4 rooms, and the sizes of 66-91m^2. A vision image of the building is shown in Figure 58 and detail drawings are shown in Appendix IIII-Case study data.

Figure 58. *The case study building (ETTELVA Arkitekter et al., 2020, p.4).*

The case study building is built up in Rhinoceros using architectural drawings, and hence version 1 of the tool was tested. The building elements are modelled as surfaces and the concept of load-bearing walls is used. There are no columns or beams modelled. The foundation is put on the “ground floor” layer. Hence, the “structure” and the “foundation” layers are empty and the results for them are 0. The model and the results are shown in Figure 59.

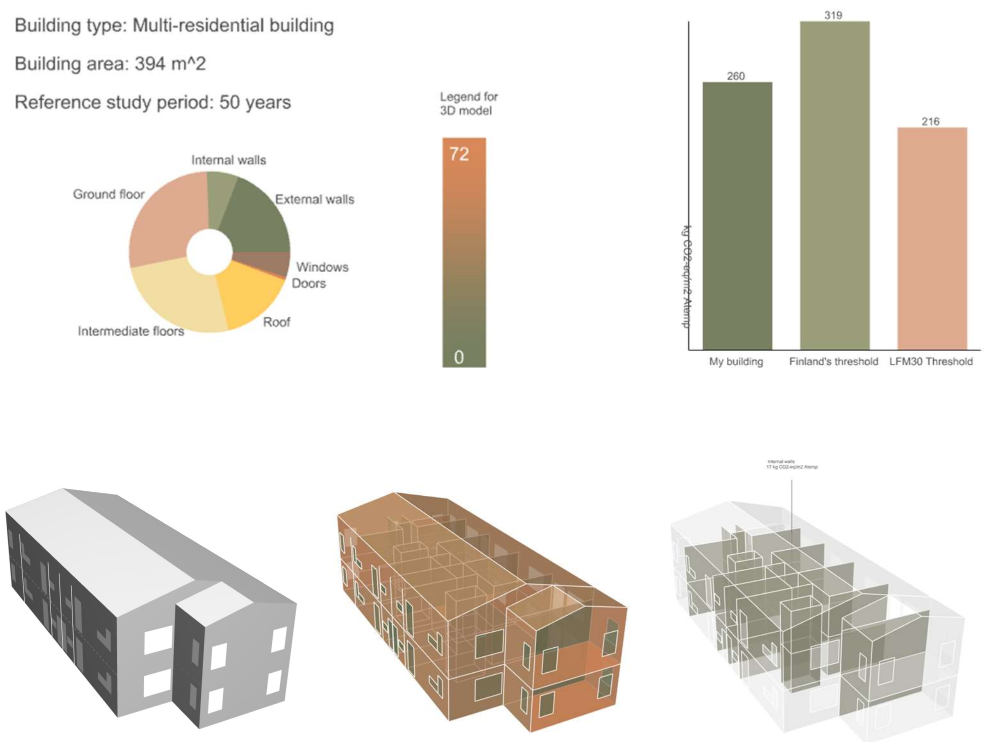


Figure 59. *The case study building and the visualised results.*

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 data, using the same building element types on e.g. all internal walls. To validate the tool, the results were compared with calculations made in BM by a sustainability engineer (Figure 60 and Figure 61). The comparison is on module A1-A3.

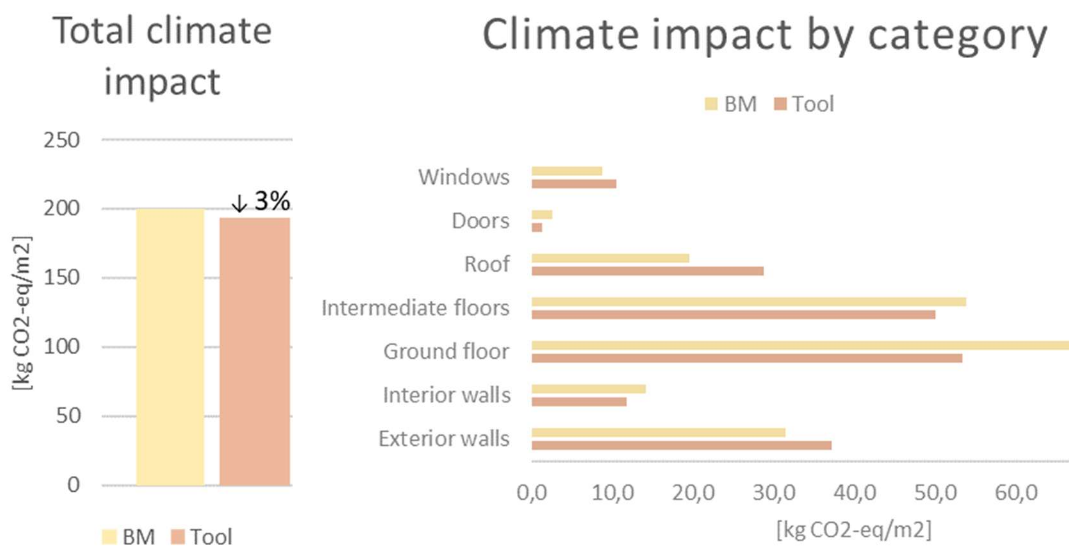


Figure 60. Comparison of the calculation in BM and in the tool.

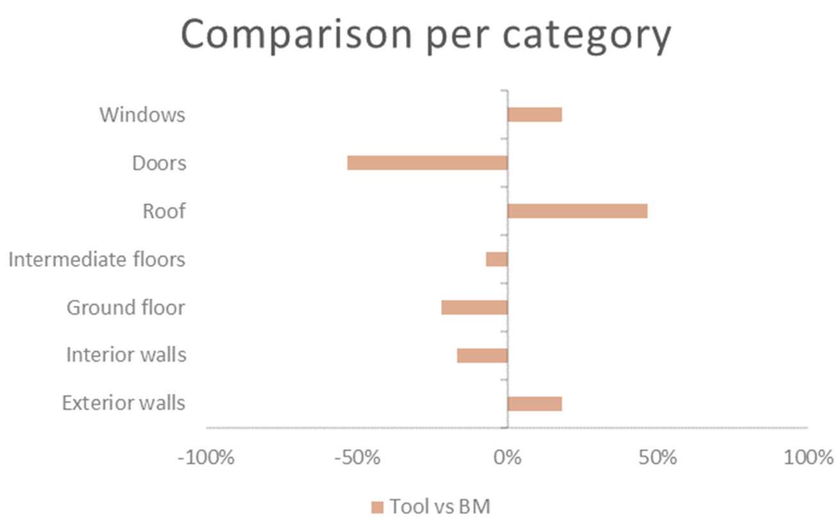


Figure 61. Percentage comparison of the results in BM and in the tool.

The categorisation of materials in BM might have errors and floor slabs are sometimes referred to as roofs and vice versa, affecting the results in Figure 60 and Figure 61 (Östlund, E., meeting on May 5th, 2021). In BM, the doors were of a heavy type which might not correspond to reality.

6.2.2 Connection to part three of the research question

The third part of the research question was "Are the LCA results from the developed tool within a 15% accuracy?". The total results differ with 3% and hence they are within a 15% accuracy. 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. The mean difference is 26%.

6.2.3 User tests

Below follows the answers from the survey sent out after the user tests.

What is your first impression of the tool?
Regarding the first impressions, the testers expressed that the visualisations and use of colours in the graphs and the model are well made. There is a clear connection to the 3D model in Rhinoceros. A comment was that the development is impressing within the short time frame and that the tool has great potential. The tool can be used to get a fast overview of climate impact. It is structured, pedagogical and user-friendly. Another comment was about an unfulfillment of the structural elements and that they need to be developed.

Would you prefer it to be more or less detailed regarding e.g. LCA phases, building elements or material choices?
The users got to rate 1-5 regarding how pleased they are with the level of detail (Figure 62). Most thought that the level of detail is too low and that they want to make more choices. The next question gives more explanations to this. Two of the interviews thought that there is a good balance of details.

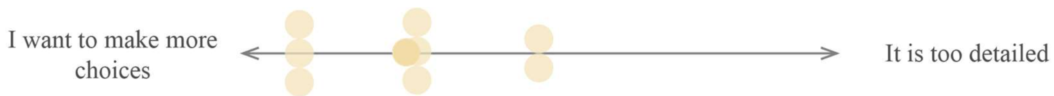


Figure 62. Users rating their preference of level of detail in the tool.

Can you update the 3D model and the material choices the way you wish to?
Five out of eight 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 in e.g. a wall. A user thought that it was hard to understand why and how it is limited to three materials. At the time of testing, there were three layers for each element. There were also discussions that it is a balancing act, and it can be hard to know the building element details in early stages. Several of the testers asked 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 suggestion was to not have the same materials on every internal wall in the model, but rather have different internal wall types. Then it would be great to mark different surfaces in Rhinoceros and apply a specific wall type.

The same tester said that some adjustments would then be needed in the Grasshopper script, but the tool today is a good starting-point. Another tester thought it would be interesting to study a direct connection to another software and to use real time data to update the model.

Is a high level of 3D modelling experience needed?
Most testers thought that some knowledge of 3D modelling is needed, but there was a spread of responses (Figure 63).

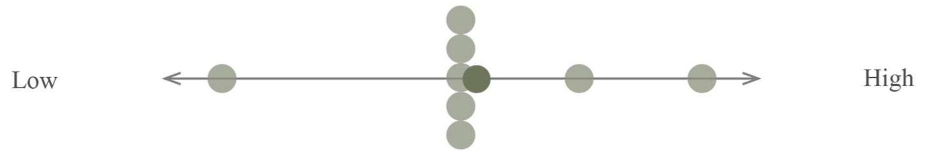


Figure 63. Users rating the level of 3D modelling knowledge needed to use the tool.

Are the results presented in a satisfying way? If not, in what ways would you like to display the results?
Seven out of eight of the users answered to the above question and most of them are satisfied with the presentation of results. The connection to initiatives like LFM30 was appreciated. A suggestion was to create a report in a PDF format or move data to excel. Providing standard values for additional LCA modules and clearly state the data source for those was another idea. There is a plug-in needed for the results visualisation, and one of the testers commented that it would be easier to use the script if one would not need to install an additional plug-in. There was a comment that the legend of the heatmap would benefit from having clearer and more varied colours.

Is the tool fast enough?
There was a spread on the perceptions of how fast the tool is as shown in Figure 64, however, most of the testers thought that it is fast enough.

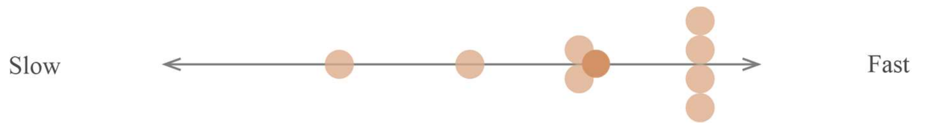


Figure 64. Users rating if the tool is fast enough.

Is the tool transparent enough? Can you understand how it works and how the calculations are made?
As seen in Figure 65, the testers thought that the transparency in the tool was on a mid-to-high level. An additional comment was that some LCA tools are not providing much information and does not enable editing. As the developed tool's calculation, based on quantities and factors, is straight forward, it is easy to double check the results.

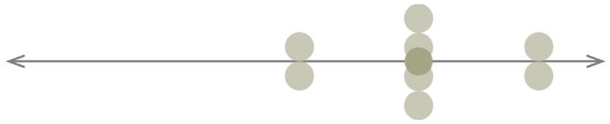


Figure 65. *Users rating if the tool is transparent enough.*

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, according to the testers (Figure 66).

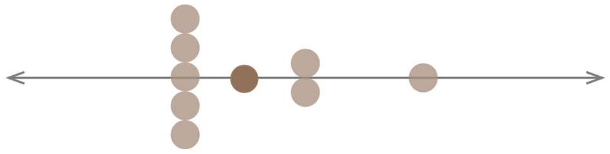


Figure 66. *Users rating the level of LCA knowledge needed to use the tool.*

Is a high level of knowledge of building materials and structures needed?
The testers thought that some knowledge around building materials and structures are needed to use the tool (Figure 67). Two of the testers perceived that a high level of knowledge in the field is needed.

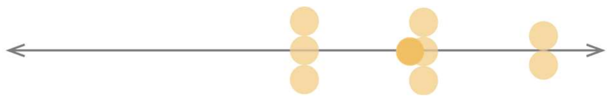


Figure 67. *Users rating the level of knowledge around building materials and structures needed to use the tool.*

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 climate impact, however it is good if the results are overestimating the impact rather than underestimating. A safety margin as in energy calculations might be needed.

The testers said that it can be useful in meetings when discussing materials, for optimizing material choices, and that it will probably also 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 for their architects to use, or that they could use it internally for an educational purpose.

If useful – how many projects a year could it be used on?
The answers regarding how many projects a year the tool could be used on varied a lot. Most of the testers stated that they could use the tool on around 10 projects a year, however an architect thought that it could be useful for around 200 projects, and another architect said that it can be useful on 50% of their projects. The software developer acknowledged that they would try and develop a similar tool for specific building elements if clients asked for it. An architect thought that the load-bearing systems might not apply to all kind of buildings but thought that taking a model from BIM would probably work.

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 thing standing in the way 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 the load-bearing elements, especially deep foundations might stand in the way of implementation. The architect might not have knowledge on the structures at an early stage, and the client do not assign structural engineers until later stages. An idea raised was that multiple users could work together in the model if possible.

A tester thought that the tool would be useful but that the costs for using the tool and the workflow is critical. It stands against other tools like Oneclick LCA which is easy to use, can be used on different scales and levels of detail, has EPDs and generic data, but is expensive. Demands from different users can vary a lot. If a user wants to follow the project from early to late stages, OneClick LCA might be preferred. Costs of using the tool and that the architect might be using another software can stand in the way. The calculations must be accurate for the contractor to not risk contractual penalty. Lack of software experience can hinder the use.

6.2.4 Connection to the second research question

The second part of the research question and the user test results related to it is presented below.

> Does the developed tool fulfil the requirements…
> …in terms of input data and results?
> The number of materials in each building element and additional pre-set building element types was asked for. The structure and layout are clear, and the results are displayed in a clear and interesting way. The testers wished for further validation of load-bearing structures.
>
> …in terms of transparency?
> The testers are generally satisfied with the transparency and some of them expressed that they could follow the calculations.
>
> …in terms of connection to a 3D model?
> There was a general appreciation of the 3D model connection, however a connection to external software was asked for.
>
> …in terms of calculation speed?
> Seven out of eight testers think that the tool is fast enough.
>
> …in terms of software skills and LCA experience of the user?
> Five out of eight testers thought that they could update the 3D model and the material choices as they wish to. What hinders them to change things is both limitations in the tool and software skills. Regarding the needed 3D modelling knowledge, answers were widespread. The testers perceived that a low-to-mid level of LCA knowledge is needed to use it.

7 Discussion

In this chapter, the results from the literature review, interviews, tool review, tool development and case studies are discussed.

7.1 Literature review

It was described in the literature review that small- to medium sized firms will probably need support in the near future, to increase knowledge on sustainable materials and to implement LCA. This was further acknowledged in the interviews, where a knowledge gap was presented. It points at a need for easier communication where the author think that simplified tools partly can fill the gap.

As mentioned in the literature review, digital tools will handle a lot of data, especially from 2027. In early stages, the author believe that tools will play a role in simplifying processes. The tools play another role at later stages, where they will be crucial to handle extensive data. The literature review suggests through several papers to connect simplified LCA to BIM modelling. However, to keep a parametric way of modelling, a BIM connection was not emphasized on in the tool development in the thesis.

7.2 Interviews

The author generally experienced a great interest from the interviewees on the subject of tool development of an early-stage LCA tool. A reason for the interest is probably the upcoming climate declarations. However, the choice of interviewees might have introduced biased results as most of them are sustainability or digitalisation experts within their organizations. The interviewees were from different countries which might affect the results in terms of statements about workflows and regulations.

Several of the interviewees discussed the challenges of wooden structures compared to concrete and steel structures. As e.g. concrete tick boxes regarding fire safety, sound insulation and mechanics, the environmental advantage of wood might be outrivalled when making structural choices.

In Figure 35, it can be seen that the software developers perceptions of what makes a good tool for early-stage LCA lies quite far from the mean values of the other professions. This points at the need of including potential users in tool development, as the developers might not know what the users need. There were different demands from interviewees: wishes to use the tool along the whole building process and to include a lot of features. The author sorted out what she considered relevant for an early-stage LCA tool. Some of the interviewees talked about the relevance of using sector EPDs in simplified tools and early stages. This was however not implemented, as the use of generic values in the national database was valued higher. As a software developer clearly stated that the strong feature of Grasshopper is visualisations, the graphics and the connection to the 3D model was emphasized on in the tool.

When talking about thresholds, the interviewees might be interested in what is applicable to their types of buildings and hence they are not always talking about the same thresholds. When discussing what is important features in an early-stage LCA tool, an architect thought that the connection to certifications is rather a question of formatting the results. Most interviewees did not put high value in connecting the tool to certifications at this stage. This shows that the connection is not something crucial to include in the initial tool development. The question about visualising 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.

The interviewees had different perceptions in their definition of early stages, and this might be affected by when they enter projects. From the literature review and the interviews, it is clear that a tool for early-stage LCA is suitable to use in the investigations and program and project definition phases. Figure 68 sums up Figure 11 and Figure 15 and points out the author's recommendation of when to use the tool.

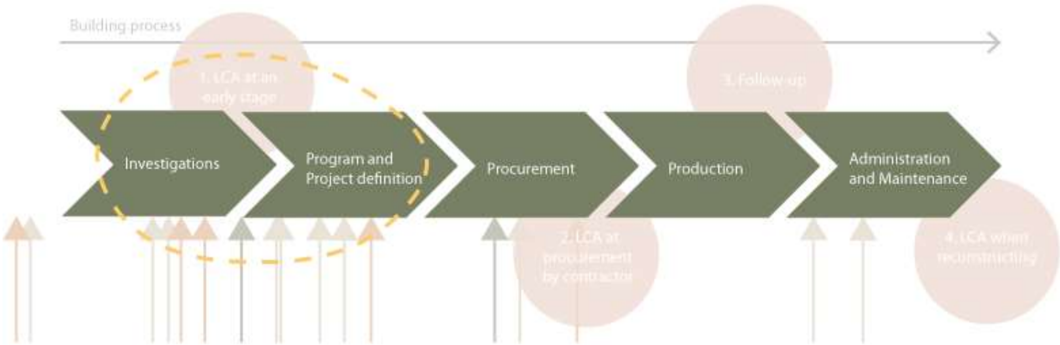


Figure 68. Author's definition of when to use an early-stage LCA tool.

7.3 Tool review

The reviewed tools are suitable for different purposes. As mentioned in the theory, literature review and interview results chapters, there will probably be a rise in tools for both simplified LCA and full LCA. Reasons are the digitalisation in the building industry, the upcoming climate declarations and not to mention the rising awareness of the emerging climate crisis.

7.4 Tool development

Regarding 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 and useful. The tool developed in the study is trying to balance this by providing the opportunity to have either pre-set or customised combinations of materials. On the same note, the geometry built in Rhinoceros can be detailed providing an accurate modelling alternative.

The geometry can also be modelled in a parametric way in Grasshopper, with less detail but with more changeability. The author thinks the versions have different areas of usage and which one to bring forward in further development depends of the user preference.

The functional unit does not consider the comparability of e.g. structural ability, thermal mass and overall U-value of the building. This makes it hard to compare design options in the tool, as the options perform different at later phases, e.g. module B6: operational energy use. Material choices also affect aesthetics which is not visualised in the tool, besides the thicknesses and structures. Neither is design for disassembly considered, which would affect the end-of-life phases.

The data in the modules A4 (transport to site) and A5.1 (wastage, 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 +25% factor in the climate database from Boverket makes it hard to compare the total results to the thresholds. Additionally, the thresholds use different areas in the units [kg CO2-eq/ m2 light BTA/year] (IVL, 2021) and [kg CO2-eq/ m2 NTA/year] (Bionova Ltd, 2021) while the unit in the tool is [kg CO2-eq /m2 Atemp/year], making the results differ.

The transparency was not prioritized in the tool development in favour of writing the code in Visual Studio. The code could have been displayed in Grasshopper instead, making it easier to get an overview of each component. The grade of transparency enhanced in the future depends on how the tool will be used, who owns the code and how it is distributed.

Communication of LCA results is enhanced through the heat map on the 3D model and hence it identifies design-specific hotspots of individual building elements, as suggested by Soust-Verdaguer et al. (2016). It tells the user about the climate impact of different elements relating to one another. However, to understand improvement potential of each element, a comparison to the "best" version of each element would bring the visualisation to the next level.

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 in the second version of the tool. The author would like to encourage further studies in the area.

OneClick LCA is an example of a tool connected to a 3D model and useful in different stages. It is hard to compare the master thesis tool to a fully developed tool, but potential selling points of the tool developed in the thesis are the connection to the needs on the Swedish market. As it is not only comparing environmental data, but uses a parametric model, it is believed to be suitable for early stages.

7.5 Case studies

Several elements of insecurity were introduced in the case study of the Korseberg strand building. The mappings in BM were at times hard to interpret. 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. Despite the challenges, the results turned out acceptable. As the case study building was built up in version 1 of the tool, it would have been interesting and useful to test version 2 as well.

The user tests brought valuable feedback regarding the applicability of the developed tool. However, to draw conclusions, additional tests need to be made as the number of testers was limited. Most of the testers had participated in the interviews earlier, but three of them did not. This can unfortunately make the results from the interviews and the user tests less comparable. A factor of how well the testers understood the tool was that the author provided supervision throughout the testing. The question of how much knowledge of 3D modelling is needed resulted in a wide spread of the responses (Figure 63). Different backgrounds of the testers might affect their apprehension of what is advanced 3D modelling.

7.6 General discussion

Boverket (2020b) stated the belief that architects will not be highly affected by the climate declarations until 2035, when the threshold limit values are sharpened. The author's belief is that architects in the Swedish context will have to adjust the design regarding material choices and building shape already today. Early-stage tools handling daylight, energy, and LCA will have a role to play in this transition, according to the author.

As written in the theory chapter, the Paris Agreement states that there is a need for negative carbon emissions, to reach the climate targets. Hence it is of value to study bio-based materials as carbon sinks and carbonation of concrete. As these processes are not accounted for neither in the Boverket database nor in the climate declarations of 2022, it was not included.

7.7 Further studies

Numerical tests of the second version of the tool are recommended as a further study. Case studies comparing the tool results to other tools than BM is suggested. Further investigations in load-bearing systems and deep foundations, like piles, are recommended.

Regarding formatting of results, the author has multiple suggestions. The coloured-by-impact model is comparing the building elements to each other, while a possible development is to put e.g. the impact of the roof on a yardstick of roofs with low and high climate impact. Other result formats include adding additional thresholds. A visualisation idea is to provide a quick detail drawing of the chosen materials, to understand the choices even more.

Another functionality would be show what materials that store CO_2-eq. The LCA phases can be extended and probably the most natural addition would be the module B6: operational energy. This is possible if connecting the BeDOT tool developed by BDAB.

The tool could be connected to Archicad, Sketchup or Revit. As multiple interviewees stated that Grasshopper is hard to learn, the tool could be extracted to another platform. As suggested by interviewees, economic costs, U-values and fire properties could be included in the tool. One could also consider how the design is constrained by the detailed development plan. A version using Swedish names and annotations could easily be developed as the climate data has a Swedish version as well.

8 Conclusion

Design-integrated early-stage tools based on LCA can be applied in several different project stages. Data is a key to make informed decisions and motivate sustainable material choices when presenting to the project group, the client, in workshops or in competitions.

By using a pedagogical, transparent interface and information on material choice consequences, an increased understanding of the climate impact from the production phase of buildings can be achieved in an early-stage LCA tool. By enabling easy and quick testing of materials, thicknesses and building shapes, such a tool can help decrease the climate impact from the production phase of buildings. Below follows a connection to the research questions.

What is required…

…in terms of input data and results?

Environmental data must be wisely chosen to make the results comparable with other studies and hence national, generic data should be used. Simplifying the workflow and reducing the amount of data for the user to handle is recommended. Results should be presented in a way that enables comparisons and a quick overview. If the user group is architects, the results benefit from being presented in a visual way, connected to the 3D-model.

…in terms of transparency?

Clear terminology helps the user understand the choices in the tool. The need of transparency in the tool depends on who is the user. The tool should not overwhelm the user with information but if one wants to look into it, it should be easy to follow.

…in terms of connection to a 3D model?

Multiple papers and interviewees suggest BIM connections to streamline processes. Some argue for parametric modelling. Connection to a 3D model is of value if the user already works with 3D modelling.

…in terms of calculation speed?

Calculation speed is highly valued and is a pre-condition for quick early-stage analysis.

…in terms of software skills and LCA experience of the user?

To conduct early-stage LCA calculations, a great experience of LCA should not be needed. If a modelling software is used, previous modelling experience is needed. The software used in the tool development, Grasshopper, is not a commonly used software and the step to learn it is high. However, findings from the development can be used to inform development of an even easier-to-use tool.

Does the developed tool fulfil the above-mentioned requirements?

The user tests brought valuable feedback and enabled a critical review of the tool. The overall impressions were positive. Regarding environmental data input, the users would like to have more pre-set material combinations to make the tool easier to use. A deeper verification of the load-bearing structures was asked for. Six out of eight testers thought the tool was transparent enough and seven out of eight were satisfied with the calculation speed.

The testers found that basic software skills and a basic knowledge of LCA would be needed to use the tool.

Are the LCA results from the developed tool within a 15% accuracy?
The average LCA results from the developed tool are within a 15% accuracy, if comparing to LCA results from a conventional tool. However, if looking at specific building elements, there are larger errors pointing at the need for additional testing. The mean value of the error if studying building elements separately is 26%.

The project has sparked interest among interviewees and people following it. The results bring new knowledge regarding user preferences of early-stage tools in general and early-stage LCA tools in particular. The outcome shows that the integration of the users' needs and expectations from the very beginning of the development of assessment tools can ensure the tools' applicability in the design process.

References

Baumann, H. & Tillman, A. (2004). *The Hitch hiker's guide to LCA: An orientation in life cycle assessment methodology and application (1. ed.).* Lund: Studentlitteratur.

Berger-Vieweg, L. (2020*). Analysing embodied and operational carbon footprint of early-stage building designs - A simplified LCA methodology and software tool.* Technical University of Denmark.

Bionova Ltd. (2021). *Carbon footprint limits for common building types.* Ministry of Environment, Finland.

BHoM. (2020). *The Buildings and Habitats object Model.* Retrieved 2021-03-11 from https://bhom.xyz/

Boverket. (n.d.). *Ordlista för energideklarationer.* Retrieved 2021-05-16 from https://www.boverket.se/sv/energideklaration/ordlista/

Boverket. (2019). *Miljöcertifieringssystem och LCA.* Retrieved 2021-01-27 from https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/livscykelanalys/miljocertifieringssystem-och-lca/

Boverket. (2020a). *LCA i byggprocessen*. Retrieved 2021-04-30 from https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/livscykelanalys/lca-i-byggprocessen/

Boverket. (2020b). *Utveckling av regler om klimatdeklaration av byggnader.* Boverket, Karlskrona. Retrieved 2021-01-27 from https://www.boverket.se/sv/om-boverket/publicerat-av-boverket/publikationer/2020/utveckling-av-regler-om-klimatdeklaration-av-byggnader/

Boverket (2021). *Öppna data - Klimatdatabas*. Retrieved 2021-03-09 from https://www.boverket.se/sv/om-boverket/publicerat-av-boverket/oppna-data/boverkets-klimatdatabas/

Bribián, I.Z., Usón, A.A. Scarpellinig, S. (2009*). Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification.* Building and Environment, 44, 2510–2520.

Collinge, W. O., Landis, A. E., Jones, A. K., Schaefer, L. A., & Bilec, M. M. (2013). *Dynamic life cycle assessment: Framework and application to an institutional building.* International Journal of Life Cycle Assessment, 18(3), 538–552.

Erlandsson, M., Malmqvist, T., Francart, N., & Kellner, J. (2018). *Minskad klimatpåverkan från nybyggda flerbostadshus. LCA av fem byggsystem, Underlagsrapport.* IVL.

ETTELVA Arkitekter, Riksbyggen, Bengt Dahlgren Göteborg AB & Lokalförvaltningen Göteborgs stad. (2020). *Slutrapport Cirkularitetsindex CIX.* Retrieved 2021-03-24 from https://www.ettelva.se/app/uploads/2020/06/Slutrapport-CIX-projektet-2020-webb.pdf

European Commission. (2014). *Communication from the commission to the European Parliament, the council, the European economic and social committee and the committee of the regions on resource efficiency opportunities in the building sector.* Brussels: European Commission.

Fan, M. & Fu, F. (2017). *Advanced High Strength Natural Fibre Composites in Construction.* Woodhead Publishing.

Fantin do Amaral Silva, G., & Bergel Gómez, R. (2018). *Energy performance modelling*. Chalmers University of Technology, Gothenburg.

Food4Rhino. (2019). Apps for Rhino and Grasshopper - Elefront. Retrieved 2021-02-01 from https://www.food4rhino.com/app/elefront.

Golsteijn, L. (2020). *LCA basics: life cycle assessment explained.* Retrieved 2021-01-28 from https://pre-sustainability.com/articles/life-cycle-assessment-lca-basics/

Graciano, A. (2020). *Considerations on Parametric Design and Generative Design.* Retrieved 2021-05-16 from https://www.researchgate.net/publication/347665683_Considerations_on_Parametric_Design_and_Generative_Design

Grasshopper3D. (2021). *About Grasshopper.* Retrieved 2021-05-16 from https://www.grasshopper3d.com/

Hedenus, F., Persson, M. & Sprei, F. (2018). *Sustainable Development: Nuances and Perspectives*. Lund: Studentlitteratur.

Hoxha, E., Passer, A., Saade, M. R. M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K. & Habert, G. (2020). *Biogenic carbon in buildings: a critical overview of LCA methods.* Buildings and Cities, 1, 504–524.

Hollberg, A., Kiss, B., Röck, M., Soust-Verdaguer, B., Houlihan Wiberg, A., Lasvaux, S., Galimshina, A. & Habert, G. (2021). *Review of visualising LCA results in the design process of buildings.* Building and Environment, 190. http://dx.doi.org/10.1016/j.buildenv.2020.107530

Hollberg, A. (2016). *Parametric Life Cycle Assessment: Introducing a time-efficient method for environmental building design optimization.* Weimar, Fakultät Architektur und Urbanistik der Bauhaus-Universität Weimar.

IVL. (2020) *Byggsektorns Miljöberäkningsverktyg.* Retrieved 2021-03-11 from https://www.ivl.se/projektwebbar/byggsektorns-miljoberakningsverktyg.html

IVL. (2021). *LFM30:s klimatbudget – Anvisningsdokument – Projektnivå - Nya byggnader. Version 1.4.* Retrieved 2021-03-29 from https://lfm30.se/wp-content/uploads/2021/02/LFM30-Anvisningar_LFM30-Metod-klimatbudget-projektniva%CC%8A-nya-byggnader_Version-1.4-AH210208.pdf

Jabi, W. (2013). *Parametric Design for Architecture.* London: Laurence King Publishing, 9-11.

Li, B. (2017). *Use of Building Energy Simulation Software in Early-Stage of Design Process.* KTH Royal Institute of Technology: Division of Building Technology.

Malmqvist, T., Nehasilova, M., Moncaster, A., Birgisdottir, H., Nygaard Rasmussen, F., Houlihan Wiberg,A. & Potting, J. (2018). *Design and construction strategies for reducing embodied impacts from buildings – Case study analysis.* Energy & Buildings, 166, 35–47.

Microsoft. (2021). *A tour of the C# language*. Retrieved 2021-05-16 from https://docs.microsoft.com/en-us/dotnet/csharp/tour-of-csharp/

Microsoft. (2019). *Welcome to the Visual Studio IDE*. Retrieved 2021-05-16 from https://docs.microsoft.com/sv-se/visualstudio/get-started/visual-studio-ide?view=vs-2019

Ministry of the Environment and Energy. (2018). *The Swedish climate policy framework.* Government Offices of Sweden.

OneClick LCA. (2021). *OneClick LCA.* Retrieved 2021-03-11 from https://www.oneclicklca.com/

Proving Ground. (2021). *Conduit.* Retrieved 2021-04-21 from https://provingground.io/2017/04/10/get-started-with-conduit/

Radziszewski, K. & Cudzik, J. (2019). *Parametric design in architectural education.* World Transactions on Engineering and Technology Education, Vol.17, No.4, 2019.

Rhino3D. (2021). *Features of Rhinoceros*. Retrieved 2021-05-16 from https://www.rhino3d.com/features/

Riksbyggen. (2020). *BRF Korseberg strand.* Retrieved 2021-03-24 from https://www.riksbyggen.se/globalassets/1-riksbyggen/bostad/1-bostadsratter/vastra-gotaland/brf-korsberg-strand/allt-om-brf-korseberg-strand.pdf

Roberts, M., Allen, S. & Coley, D. (2020). *Life cycle assessment in the building design process – A systematic literature review.* Building and Environment, 185, 107274.

Rodrigo, M., Perera, S., Senaratne, S. & Jin, X. (2019). *Embodied Carbon Mitigation Strategies in the Construction Industry*. CIB World Building Congress.

Röck, M., Hollberg, A., Habert, G. and Passer, A. (2018). *LCA and BIM: Visualisation of environmental potentials in building construction at early design stages*. Building and Environment, 140, 153–161.

Soust-Verdaguer, B., Llatas, C. & García-Martínez, A. (2016). *Simplification in life cycle assessment of single-family houses: A review of recent developments.* Building and Environment, 103, 215–227.

Svenska institutet för standarder [SIS]. (1989). *Area och volym för husbyggnader – terminologi och mätregler.* Retrieved 2021-05-16 from https://www.sis.se/api/document/preview/8245/

Svenska institutet för standarder [SIS]. (2005). *Byggstandard 2005. Ritnings- och beskrivningsstandarder / utarbetad av SIS - Swedish Standards Institute.* Stockholm: SIS Förlag AB.

Svenska institutet för standarder [SIS]. (2011). *Hållbarhet hos byggnadsverk – Värdering av byggnaders miljöprestanda – Beräkningsmetod* (Report No. SS-EN 15978:2011). Stockholm: SIS Förlag AB.

Svenska institutet för standarder [SIS]. (2006). *Miljöledning - Livscykelanalys - Principer och struktur* (ISO 14040:2006). Stockholm: SIS Förlag AB.

Su, S., Li, X., Zhu, Y. & Lin, B. (2017). *Dynamic LCA framework for environmental impact assessment of buildings.* Energy and Buildings, 149, 310–320.

Sweden Green Building Council. (2017). *Miljöbyggnad 3.0 Bedömningskriterier för nyproducerade byggnader.* Retrieved 2020-11-15 from: https://www.sgbc.se/app/uploads/2018/07/Milj%C3%B6byggnad-3.0-Nyproduktion-vers-170915.pdf

Sweden Green Building Council & BRE Global. (2018). *BREEAM-SE New Construction 2017 Technical Manual 1.1*.

Tata Steel. (2017). *ComFlor manual - Composite floor decking design and technical information*. Tata Steel UK Limited.

Trafikverket. (2019). *Åtgärder för ökad andel godstransporter på järnväg och med fartyg – redovisning av regeringsuppdrag.*

U.S Green Building Council. (2020). *LEED v4.1 Building design and construction - Getting started guide for beta participants.*

Wäppling, L. (2019). *Multi-Objective Building Performance Simulation*. Chalmers University of Technology, Gothenburg.

Appendix I- Interview material

Figure 69 and Figure 70 show the material used when making interviews. Figure 69 was not used for developers while Figure 70 was used for all interviewees.

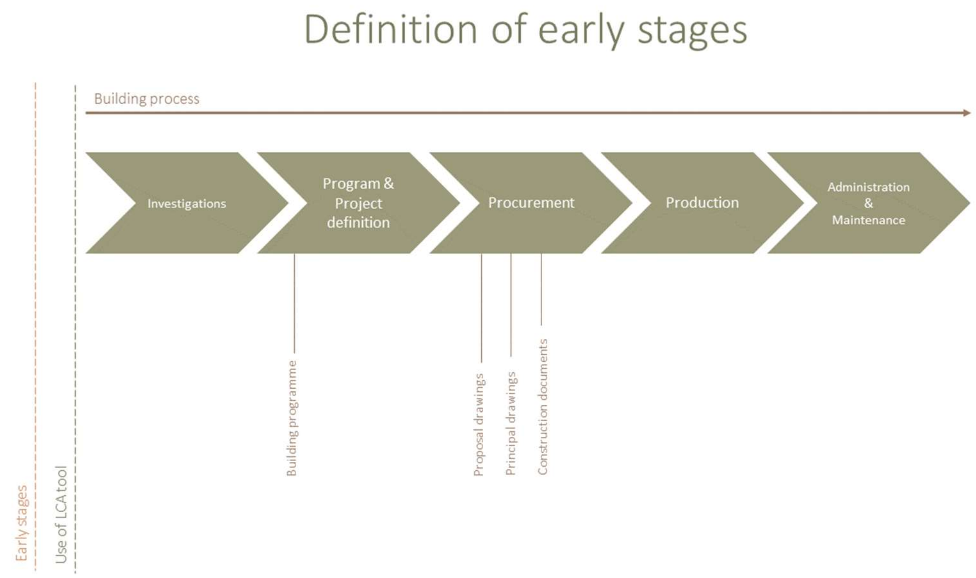


Figure 69. *Sheet for interviewee to define early stages and when is a good time to use an early-stage LCA tool.*

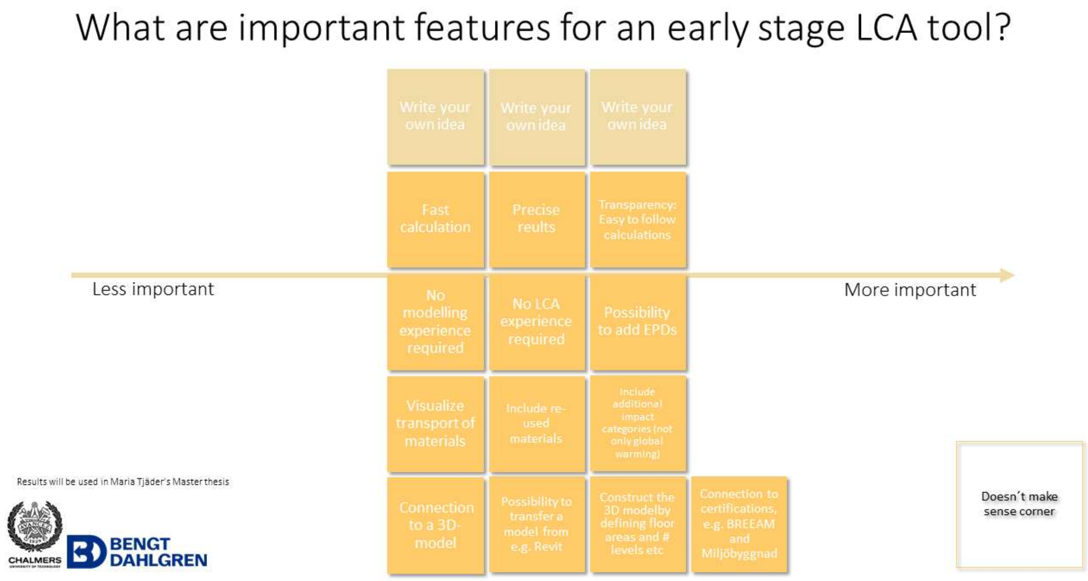


Figure 70. *Sheet for interviewee to sort statements in terms of importance for an early-stage LCA tool.*

Appendix II- Environmental data

Table 8. Selection of environmental data retrieved from Boverket (2021).

Name	Global Warming Potential [kg CO_2eq./kg]			Density		FU
	A1-A3	A4	A5.1			
Particle board	0,4875	0,0495	0,04875	700	kg/m^3	kg
Glasswool, bats and rolls	1,1125	0,0345	0,07788	18,7	kg/m^3	kg
Glasswool, facade boards	1,075	0,0345	0,07525	55	kg/m^3	kg
Glasswool, blowing wool, wall	1,2	0,0345	0,012	30	kg/m^3	kg
Glasswool, blowing wool, flooring	1,125	0,0345	0,01125	26	kg/m^3	kg
Glasswool, blowing wool, attic floor	1,125	0,0345	0,01125	15	kg/m^3	kg
Glasswool, sound bats	1,4875	0,0345	0,10413	14	kg/m^3	kg
Sawn timber, u 16%, coniferous	0,0863	0,0158	0,00863	455	kg/m^3	kg
Electricity, national mix	0,0128	0	0	-	kg/m^3	kg
Diesel, reduction obligation (2020)	0,0938	0	0	-	kg/m^3	kg
Diesel, 100% fossil	0,1188	0	0	-	kg/m^3	kg
Petrol, reduction obligation (2020)	0,1112	0	0	-	kg/m^3	kg
Petrol, 100% fossil	0,1163	0	0	-	kg/m^3	kg
District heating, national mix	0,0305	0	0	-	kg/m^3	kg
Gypsum, sheathing plasterboard	0,3325	0,0232	0,0399	760	kg/m^3	kg
Gypsum, fireboard	0,32	0,0232	0,0384	830	kg/m^3	kg
Diesel, HVO100	0,0088	0	0	-	kg/m^3	kg
Gypsum, wet room board	0,325	0,0232	0,039	760	kg/m^3	kg
Gypsum, floorboard	0,2963	0,0232	0,03556	1120	kg/m^3	kg
Gypsum, standard plasterboard	0,2838	0,0232	0,03406	710	kg/m^3	kg
Gypsum, hardboard	0,2775	0,0232	0,0333	930	kg/m^3	kg
Gypsum fibreboard with cellulose fibre	0,495	0,0795	0,0594	1180	kg/m^3	kg
Plywood (spruce)	0,4475	0,042	0,04475	460	kg/m^3	kg
OSB	0,4475	0,0645	0,04475	607	kg/m^3	kg
Ready-mix made concrete, buildings C20/25	0,1221	0,0039	0,00366	2350	kg/m^3	kg
Ready-mix made concrete, buildings climate-improved C20/25	0,0913	0,0039	0,00274	2350	kg/m^3	kg
Ready-mix made concrete, buildings climate-improved C25/30	0,0963	0,0039	0,00289	2350	kg/m^3	kg
Ready-mix made concrete, buildings C25/30	0,1289	0,0039	0,00387	2350	kg/m^3	kg
Ready-mix made concrete, buildings C28/35	0,1365	0,0039	0,0041	2350	kg/m^3	kg

Ready-mix made concrete, buildings climate-improved C28/35	0,1024	0,0039	0,00307	2350	kg/m^3	kg
Ready-mix made concrete, buildings C30/37	0,1446	0,0039	0,00434	2350	kg/m^3	kg
Ready-mix made concrete, buildings climate-improved C30/37	0,1084	0,0039	0,00325	2350	kg/m^3	kg
Ready-mix made concrete, buildings climate-improved C32/40	0,1108	0,0039	0,00332	2350	kg/m^3	kg
Ready-mix made concrete, buildings C32/40	0,1476	0,0039	0,00443	2350	kg/m^3	kg
Ready-mix made concrete, buildings C35/45	0,163	0,0039	0,00489	2350	kg/m^3	kg
Ready-mix made concrete, buildings climate-improved C35/45	0,1223	0,0039	0,00367	2350	kg/m^3	kg
Ready-mix made concrete, buildings C40/50	0,1755	0,0039	0,00527	2350	kg/m^3	kg
Ready-mix made concrete, buildings C40/50	0,1755	0,0039	0,00527	2350	kg/m^3	kg
Ready-mix made concrete, buildings climate-improved C40/50	0,1316	0,0039	0,00395	2350	kg/m^3	kg
Ready-mix made concrete, buildings climate-improved C45/55	0,142	0,0039	0,00426	2350	kg/m^3	kg
Ready-mix made concrete, buildings C45/55	0,1893	0,0039	0,00568	2350	kg/m^3	kg
Ready-mix made concrete, buildings C50/60	0,2038	0,0039	0,00611	2350	kg/m^3	kg
Ready-mix made concrete, buildings climate-improved C50/60	0,1529	0,0039	0,00459	2350	kg/m^3	kg
Ready-mix made concrete, buildings climate-improved C55/67	0,1653	0,0039	0,00496	2350	kg/m^3	kg
Ready-mix made concrete, buildings C55/67	0,2203	0,0039	0,00661	2350	kg/m^3	kg
Ready-mix made concrete, buildings C60/75	0,2294	0,0039	0,00688	2350	kg/m^3	kg
Ready-mix made concrete, buildings climate-improved C60/75	0,172	0,0039	0,00516	2350	kg/m^3	kg
TT concrete slabs, TT, TT/F and STT/F	0,2738	0,045	0	2400	kg/m^3	kg
TT concrete slabs, TT, TT/F and STT/F, climate-improved	0,2063	0,045	0	2400	kg/m^3	kg
External wall panels	0,2288	0,045	0	2400	kg/m^3	kg
External wall panels, climate-improved	0,1713	0,0324	0	2400	kg/m^3	kg

Solid interior wall panel, climate-improved	0,1463	0,045	0	2400	kg/m^3	kg
Solid interior wall panel	0,195	0,045	0	2400	kg/m^3	kg
Half-sandwich wall panels	0,3163	0,045	0	2400	kg/m^3	kg
Half-sandwich wall panels, climate-improved	0,2375	0,045	0	2400	kg/m^3	kg
Sandwich wall panels, climate-improved	0,2188	0,045	0	2400	kg/m^3	kg
Sandwich wall panels	0,2913	0,045	0	2400	kg/m^3	kg
Hollowcore floor	0,17	0,045	0	2400	kg/m^3	kg
Hollowcore floor, climate improved	0,1275	0,0324	0,01275	2400	kg/m^3	kg
Solid floor structure	0,2288	0,045	0	2400	kg/m^3	kg
Solid floor structure, climate-improved	0,1713	0,045	0	2400	kg/m^3	kg
Floor plates for floor systems	0,23	0,045	0	2400	kg/m^3	kg
Floor plates for floor systems, climate improved	0,1725	0,045	0	2400	kg/m^3	kg
Thin-shell precast panels	0,23	0,045	0	2400	kg/m^3	kg
Thin-shell precast panels, climate improved	0,1725	0,0324	0	2400	kg/m^3	kg
Columns	0,2975	0,045	0	2400	kg/m^3	kg
Columns, climate improved	0,2238	0,045	0	2400	kg/m^3	kg
Beams, slack-reinforced	0,2475	0,045	0,02475	2400	kg/m^3	kg
Beams, slack-reinforced, climate improved	0,1863	0,045	0	2400	kg/m^3	kg
Beams, prestressed	0,24	0,045	0	2400	kg/m^3	kg
Beams, prestressed, climate-improved	0,18	0,045	0	2400	kg/m^3	kg
Balconies and stairs, climate-improved	0,1963	0,045	0	2400	kg/m^3	kg
Balconies and stairs	0,2613	0,045	0	2400	kg/m^3	kg
Balcony access slab	0,2738	0,045	0	2400	kg/m^3	kg
Balcony access slab, climate improved	0,205	0,045	0	2400	kg/m^3	kg
Precast reinforced concrete, other	0,2475	0,045	0	2400	kg/m^3	kg
Precast reinforced concrete, other, climate-improved	0,1863	0,045	0	2400	kg/m^3	kg
Concrete roof tiles	0,225	0,0495	0,01125	2400	kg/m^3	kg
Concrete roof tiles, climate-improved	0,1688	0,0495	0,00844	2400	kg/m^3	kg
Clay roof tiles	0,27	0,0495	0,0135	1800	kg/m^3	kg
Bricks	0,3137	0,0495	0,01569	1800	kg/m^3	kg
Bricks, hardburned	0,5438	0,0495	0,02719	1800	kg/m^3	kg
Sand lime bricks	0,1575	0,0645	0,00788	1800	kg/m^3	kg
Expanded clay concrete block, <11% cement (650-700 kg/m3)	0,2425	0,027	0,01213	650	kg/m^3	kg

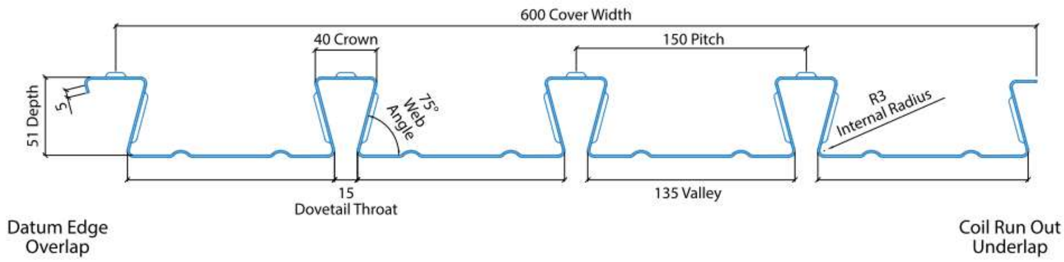
Expanded clay concrete block, 10-14 % cement (700-770 kg/m3)	0,24	0,027	0,012	750	kg/m^3	kg
Expanded clay concrete block, 15-17 % cement (700-770 kg/m3)	0,2738	0,027	0,01369	750	kg/m^3	kg
Expanded clay concrete block, 18-24 % cement (700-800 kg/m3)	0,3225	0,027	0,01613	770	kg/m^3	kg
Lightweight expanded clay clinker	0,3238	0,027	0,00648	300	kg/m^3	kg
Cement mortar, type A (CS IV)	0,2488	0,0345	0,01244	1600	kg/m^3	kg
Masonry mortar and plastering type B (CS III)	0,2088	0,0345	0,01044	1600	kg/m^3	kg
Plastering and masonry mortar type C (CS II)	0,2025	0,027	0,01013	1600	kg/m^3	kg
Plastering type C (CS II)	0,2025	0,0324	0,02025	1600	kg/m^3	kg
Plastering type D (CS I)	0,1525	0,027	0,00763	1600	kg/m^3	kg
Plastering type B (CS III), fibre reinforced two-layer treatment	0,3	0,027	0,015	1600	kg/m^3	kg
Autoclaved Aerated Concrete, (AAC)	0,5387	0,0795	0,02694	400	kg/m^3	kg
Autoclaved Aerated Concrete (AAC), reinforced element	0,6975	0,0345	0,03488	550	kg/m^3	kg
Floor screeds < 17% cement	0,195	0,027	0,00975	1750	kg/m^3	kg
Reinforced floor screeds, < 22% cement and < 4% fibres	0,2675	0,0324	0,02675	1750	kg/m^3	kg
Floor screeds, <30% cement	0,385	0,027	0,01925	1750	kg/m^3	kg
Reinforced floor screeds, < 22% cement	0,22	0,0324	0,022	1750	kg/m^3	kg
Rapid floor screeds, <60% cement	0,4363	0,027	0,02182	1750	kg/m^3	kg
Window, wood/aluminium, side hung, 3-glass	2,875	0,042	0	-	kg/m^3	kg
Window, wood, side hung, 3-glass	2,5	0,042	0	-	kg/m^3	kg
Window, wood, inward, 3-glass	2,125	0,042	0	-	kg/m^3	kg
Window, wood/aluminium, inward, 3-glass	2,5	0,042	0	-	kg/m^3	kg
Window, wood, fully reversable, 3-glass	2,625	0,042	0	-	kg/m^3	kg
Window door, wood/aluminium, fully reversable, 3-glass	2,75	0,042	0	-	kg/m^3	kg
Window, wood, fixed, 3-glass	2,125	0,042	0	-	kg/m^3	kg
Window, wood/aluminium, fixed, 3-glass	2,75	0,042	0	-	kg/m^3	kg
Window door, wood, outward patio, half glazed, triple glazed	2,375	0,042	0	-	kg/m^3	kg

Window door, wood/aluminium, half glazed, triple glazed	3,125	0,042	0	-	kg/m^3	kg
Window door, wood, outward patio, fully glazed, triple glazed	2,5	0,042	0	-	kg/m^3	kg
Window, wood/aluminium, fully glazed, triple glazed	2,75	0,042	0	-	kg/m^3	kg
Door, external, carbon steel, massive	2,5	0,042	0	-	kg/m^3	kg
Door, external, stainless steel, massive	5,6875	0,042	0	-	kg/m^3	kg
Door, indoor, carbon steel, massive	3,225	0,042	0	-	kg/m^3	kg
Door, external, wood, massive	5,6875	0,0324	0	-	kg/m^3	kg
Door, apartment door, wood, massive	1,2875	0,042	0	-	kg/m^3	kg
Door, laminated door, wood, massive, sound and fire classified	0,3875	0,042	0	-	kg/m^3	kg
Door, wooden simple or mirror type, non-classified	0,225	0,042	0	-	kg/m^3	kg
Floatglass	1,45	0,0345	0,29	1900	kg/m^3	kg
Stone wool, bats and rolls	1,6	0,0345	0,112	29	kg/m^3	kg
Stone wool, plasterboard	1,6125	0,0345	0,11288	70	kg/m^3	kg
Stone wool, facade board	1,6125	0,0345	0,11288	80	kg/m^3	kg
Stone wool, ground board	1,6	0,0345	0,112	140	kg/m^3	kg
Stone wool, roof board	1,6	0,0324	0,16	180	kg/m^3	kg
Stone wool, blowing wool, attic floor	1,6	0,0345	0,016	28	kg/m^3	kg
Stone wool, blowing wool, flooring	1,6	0,0345	0,016	65	kg/m^3	kg
Stone wool, blowing wool, wall	1,6	0,0345	0,016	65	kg/m^3	kg
EPS, expanded polystyrene, pressure class 80	4	0,0345	0,28	16	kg/m^3	kg
XPS, extruded polystyrene	4,5	0,0324	0,45	-	kg/m^3	kg
Phenolic thermal insulation	2,75	0,0345	0,1375	35	kg/m^3	kg
Cellulose fibre, blowing wool, primary raw-material	0,5	0,0345	0,005	-	kg/m^3	kg
Wood fibre insulation, blowing wool	0,2413	0,0345	0,00241	-	kg/m^3	kg
Wood fibre insulation, bats	0,3712	0,0345	0,02598	50	kg/m^3	kg
Cellulose fibre, blowing wool, recycled primary paper	0,625	0,0345	0,00625	-	kg/m^3	kg
Cellulose fibre, blowing wool, post-consumer paper	0,2	0,0345	0,002	-	kg/m^3	kg
Bitumen waterproofing membrane, top layer	0,7	0,0345	0,035	1389	kg/m^3	kg
Bitumen waterproofing membrane, bottom layer	0,85	0,0345	0,0425	1833	kg/m^3	kg
Bitumen waterproofing membrane, single layer	0,8125	0,0345	0,04063	1410	kg/m^3	kg

Bitumen waterproofing membrane, roofing shingle	0,5	0,0345	0,025	1410	kg/m^3	kg
Paint, acrylic, water-borne, interior use	2,75	0,0345	0,11	1360	kg/m^3	kg
Paint, acrylic, water-borne for exterior use	3,125	0,0345	0,125	1300	kg/m^3	kg
Paint, silicate paint	1,5	0,0345	0,06	1500	kg/m^3	kg
Paint, epoxy-based, for interior use for floors	5,125	0,0345	0,205	1600	kg/m^3	kg
Paint, Falu red	0,75	0,0345	0,03	1175	kg/m^3	kg
Sealants, silicone-based	8,85	0,0345	0,354	1150	kg/m^3	kg
Sealants, non-specified	4,0625	0,0345	0,1625	1150	kg/m^3	kg
Structural steel, unprocessed, primary	3,15	0,0795	0,1575	7850	kg/m^3	kg
Structural steel, unprocessed, scrap based	1,125	0,0795	0,05625	7850	kg/m^3	kg
Light-weight steel profile, primary	3,0125	0,027	0,06025	7850	kg/m^3	kg
Steel sheets for cladding, primary	3,2375	0,0795	0,16188	7850	kg/m^3	kg
Steel rebar, unprocessed, scrap based	0,745	0,0795	0,06705	7850	kg/m^3	kg
Steel wire, scrap based	1,25	0,0795	0,0625	7850	kg/m^3	kg
Stainless steel rebar, 72% scrap based	4,75	0,0795	0,2375	7900	kg/m^3	kg
Stainless steel water tube, 86% scrap based	4,5	0,0795	0,225	7900	kg/m^3	kg
Stainless steel sheet, 65% scrap based	4,25	0,0795	0,2125	7900	kg/m^3	kg
Aluminium profile, primary	7,5	0,0495	0,375	2700	kg/m^3	kg
Aluminium profile, 100% scrap	2,125	0,0495	0,10625	2700	kg/m^3	kg
Aluminium sheet, primary	12,5	0,0495	0,625	2700	kg/m^3	kg
Copper sheet, 51% scrap based	2,475	0,0795	0,12375	8960	kg/m^3	kg
Copper sheet, 97 % scrap based	0,625	0,0795	0,03125	8960	kg/m^3	kg
Copper pipe, 51% scrap based	2,975	0,0795	0,14875	8960	kg/m^3	kg
Copper pipe, 100% scrap based	0,8088	0,0795	0,04044	8960	kg/m^3	kg
Copper wire, primary	5,3	0,0795	0,265	8960	kg/m^3	kg
Cross laminated timber, u 12%, coniferous	0,12	0,0345	0,006	465	kg/m^3	kg
Glulam, u 12%, spruce	0,1325	0,0345	0,00663	434	kg/m^3	kg
Plywood, phenol coated	0,805	0,0645	0,0805	680	kg/m^3	kg
Bricks, second firing	0,5438	0,0495	0,02719	1800	kg/m^3	kg
Cellulose fibre, bats, recycled primary paper	0,75	0,0345	0,0075	-	kg/m^3	kg
Reused construction product	2,5	0,0045	0	-	kg/m^3	kg

Appendix III – Load-bearing structures

Figure 71. Three load-bearing structures concepts (Buro Happold, 2020, p.2).



ComFlor® 51⁺ Composite slab - volume and weight (EC values)

Slab depth (mm)	Concrete volume (m^3/m^2)	Weight of concrete (kN/m^2): Normal weight concrete		Lightweight concrete	
		Wet	Dry	Wet	Dry
101	0.091	2.27	2.18	1.82	1.73
110	0.100	2.50	2.40	2.00	1.90
120	0.110	2.75	2.64	2.20	2.09

Figure 72. Detail of the concrete in the composite slab (Tata Steel, 2017, p.15).

ComFlor® 51⁺ (S350) Section properties (per metre width)

Nominal thickness (mm)	Design thickness (mm)	Cross section area (mm^2/m)	Profile weight (kN/m^2)	Height to neutral axis (mm)	Moment of inertia (cm^4/m)		Ultimate moment capacity (kNm/m)	
					Sagging	Hogging	Sagging	Hogging
0.90	0.86	1578	0.13	15.90	60.44	42.56	5.70	6.78
1.00	0.96	1762	0.14	16.50	67.09	50.49	6.78	8.17
1.20	1.16	2137	0.17	16.80	82.60	69.00	8.94	10.96

Section properties in the above table conform to BS 5950 and Eurocode

Figure 73. Detail of the steel in the composite slab (Tata Steel, 2017, p.15).

Appendix IIII- Case study data

Table 9. Material amounts and environmental data from BM. Categories left out are marked in grey.

Name	Amount bought [kg]	GWP [kg CO2-eq/kg]	GWP [kg CO2-eq]	Category
Armering K500C- Armering, galvad (IVL LCR)	1604,79	0,92	1483,8	Bjälklag/balkar
Armeringsnät mm (IVL LCR)	1617,66	0,58	937,4	Bjälklag/balkar
Betong- Fabriksbetong-färsk betongmassa och hårdnad betong	9343,43	0,13	1205,3	Bjälklag/balkar
Trekantsläkt- Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	18,04	0,06	1,0	Bjälklag/balkar
Fabriksbetong-färsk betongmassa och hårdnad betong	136616,02	0,13	17623,5	Bjälklag/balkar
Flytspackel-Betong, anläggning C32/40	1712,55	0,17	289,4	Bjälklag/balkar
Aluminiumhandtag- Aluminiumprofil (IVL LCR)	53,55	13,55	725,4	Dörr
balksko, stos, taklucka-Rostfritt stål, ospecificerat (IVL LCR)	100,89	2,58	260,2	Dörr
Glasull isolering Isover	0,36	0,79	0,3	Dörr
K-plywood- Plywoodskivor (IVL LCR)	98,12	0,20	20,0	Dörr
Virke- Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	137,61	0,06	7,6	Dörr
Ytterdörr teak- Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	396,00	0,06	21,8	Dörr
Drevning-Glasull isolering Isover	1,49	0,79	1,2	Fönster
Droppbleck etc-Plåtdetaljer, förzinkade (IVL LCR)	37,93	2,09	79,3	Fönster
Droppbleck, fönsterbleck- Rostfritt stål, ospecificerat (IVL LCR)	113,47	2,58	292,6	Fönster
Foderbräda/smygbräda- Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	97,20	0,06	5,3	Fönster
Forderbräda/smygbrädaFuru/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	667,81	0,06	36,7	Fönster
Steni Nature facade panel	465,15	0,93	432,6	Fönster
Treglasfönster-Fönster, tre glas, trä-/aluminium (IVL LCR), ca 35 kg/m2	2402,00	1,11	2666,2	Fönster
Träram fönster-Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	314,60	0,06	17,3	Fönster
Armering K500C-T - Armering galvad (IVL LCR)	1496,99	0,92	1384,1	Grundkonstruktioner
Betong II C 25/30 i sula, plintskaft och holkar - EPD Fabriksbetong Skanska	36763,12	0,13	4742,4	Grundkonstruktioner
Cellplast, extruderad polystyrene (XPS) (IVL LCR)	207,27	3,84	795,1	Grundkonstruktioner
L-kantelement- Cellplast, expanderad polystyren (EPS) (IVL LCR)	249,90	3,90	974,6	Grundkonstruktioner
Stolpsko- stål	71,40	2,64	188,7	Grundkonstruktioner

Hängränna- Plåtdetaljer, förzinkade (IVL LCR)	98,56	2,09	205,9	Huskomplettering fasader
Härdat klarglas- Planglas (IVL LCR)	918,75	1,12	1029,0	Huskomplettering fasader
Stuprör- Rostfritt stål, ospecificerat (IVL LCR)	1051,88	2,58	2712,8	Huskomplettering fasader
Virke/trall-Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	7,51	0,06	0,4	Huskomplettering fasader
Gipsskiva	11026,26	0,23	2569,1	Innerväggar
Glasull isolering Isover	860,26	0,79	677,9	Innerväggar
Innerväggsstomme- Stålreglar (IVL LCR)	803,77	2,43	1950,7	Innerväggar
Mellanväggstomme-Stålreglar (IVL LCR)	5,94	2,43	14,4	Innerväggar
Mineritskiva- Cembrit Multi Force	113,40	0,65	74,2	Innerväggar
Plywoodskivor (IVL LCR)	1126,07	0,20	230,0	Innerväggar
Stenull-Paroc	117,60	1,21	142,6	Innerväggar
Foderlist-Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	68,75	0,06	3,8	Invändiga dörrar/glaspartier
Konstruktionsstål, galvad (IVL LCR)	820,05	1,80	1472,0	Pelare
Armering K500C-T - Armering, galvad (IVL LCR)	311,70	0,92	288,2	Platta på mark
Armeringsnät NK500AB-W - Armeringsnät mm (IVL LCR)	1180,89	0,58	684,3	Platta på mark
Betong ii C 25/30 i grundplatta - Fabriksbetong-färsk betongmassa och hårdnad betong	67714,50	0,13	8735,2	Platta på mark
Fabriksbetong-färsk betongmassa och hårdnad betong	57999,90	0,13	7482,0	Platta på mark
Flytspackel - Betong, anläggning C32/40	1759,24	0,17	297,3	Platta på mark
Isolering- Jackon Super EPS100	2489,87	0,55	1369,4	Platta på mark
Isolering- XPS- Sundolitt	91,77	3,50	321,6	Platta på mark
Plastfolier (IVL LCR)	58,80	1,81	106,4	Platta på mark
Fotplåt, stålplåt- Takplåt, förzinkad (IVL LCR)	30,58	2,09	63,9	Takfot och gavlar
Glespanel-Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	77,33	0,06	4,3	Takfot och gavlar
Hängränna, stålplåt, vindskivebeslag-Plåtdetaljer, förzinkade (IVL LCR)	138,71	2,09	289,8	Takfot och gavlar
Insektsnät- Cellplast, expanderad polystyren (EPS) (IVL LCR)	3,78	3,90	14,7	Takfot och gavlar
Mineritskiva- Cembrit Multi Force	452,76	0,65	296,1	Takfot och gavlar
Plywoodskivor (IVL LCR)	58,52	0,20	12,0	Takfot och gavlar
Räcke/snörasskydd-Plåtdetaljer, förzinkade (IVL LCR)	377,41	2,09	788,6	Takfot och gavlar
Spånskiva (IVL LCR)	71,40	0,27	19,1	Takfot och gavlar
Ståndskiva, stålplåt- Rostfritt stål, ospecificerat (IVL LCR)	5,78	2,58	14,9	Takfot och gavlar
Takbalk- Limträbalk (IVL LCR)	552,83	0,09	51,8	Takfot och gavlar
Takfotsbräda/Virke/Vindskiva-Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	758,23	0,06	41,7	Takfot och gavlar

Takfotskil- Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	117,70	0,06	6,5	Takfot och gavlar
Underlagspapp bitumen (IVL LCR)	2,77	0,65	1,8	Takfot och gavlar
Brädgång på vind-Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	37,92	0,06	2,1	Taklagskompletterin g
Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	616,00	0,06	33,9	Taklagskompletterin g
Gipsskiva	1761,48	0,23	410,4	Taklagskompletterin g
Isover Lösull	2935,80	1,00	2935,8	Taklagskompletterin g
Ångspärr	166,84	5,88	980,2	Taklagskompletterin g
Trappa- Rostfritt stål, ospecificerat (IVL LCR)	550,00	2,58	1418,5	Trappor/hiss-schakt
Virke- Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	41,03	0,06	2,3	Vitvaror
Armeringsnät mm (IVL LCR)	568,59	0,58	329,5	Väggar
Dubbelfasadspont- Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	70,40	0,06	3,9	Väggar
Fabriksbetong-färsk betongmassa och hårdnad betong	27272,70	0,13	3518,2	Väggar
Fiberriktad Spånskiva (IVL LCR)	166,32	0,27	44,4	Väggar
Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	14332,62	0,06	788,3	Väggar
Gipsskiva	3088,05	0,23	719,5	Väggar
Glasull fasadskiva	914,03	1,15	1051,1	Väggar
Glasull isolering Isover	914,03	0,79	720,3	Väggar
Isolering regelskiva-Stenull (IVL RR)	1575,42	1,19	1874,7	Väggar
Plastfolier (IVL LCR)	50,19	1,81	90,8	Väggar
Plastfolier (IVL LCR)	0,84	1,81	1,5	Väggar
Stenull-Paroc	1631,39	1,21	1978,9	Väggar
Eklamellparkett- Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	2478,30	0,06	136,3	Ytskikt golv/trappor
Mosa Tiles	949,94	0,42	396,1	Ytskikt golv/trappor
Sockellist av ek-Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	150,92	0,06	8,3	Ytskikt golv/trappor
Våtrumsspackel-Cement, standard portlandscement (torrbruk) (IVL LCR)	945,00	0,82	773,6	Ytskikt golv/trappor
Höganäs kakel	1488,69	0,44	653,5	Ytskikt vägg
Betongtakpanna-Fabriksbetong-färsk betongmassa och hårdnad betong	8753,22	0,13	1129,2	Yttertak sammansatta
Inbrädning/ Bärlläkt/ströläkt för takpannor-Furu/gran, hyvlad & sågad, 473 kg/m3 u=16% (IVL LCR)	6189,26	0,06	340,4	Yttertak sammansatta
VU typ 111-underlagspappUnderlagspapp bitumen (IVL LCR)	650,26	0,65	419,7	Yttertak sammansatta

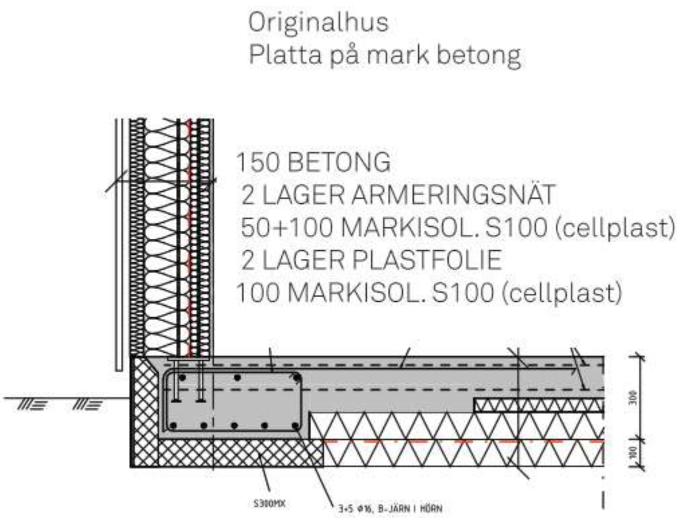


Figure 74. *Detail of ground-to-wall connection by Integra engineering AB (ETTELVA Arkitekter et al., 2020, p.21).*

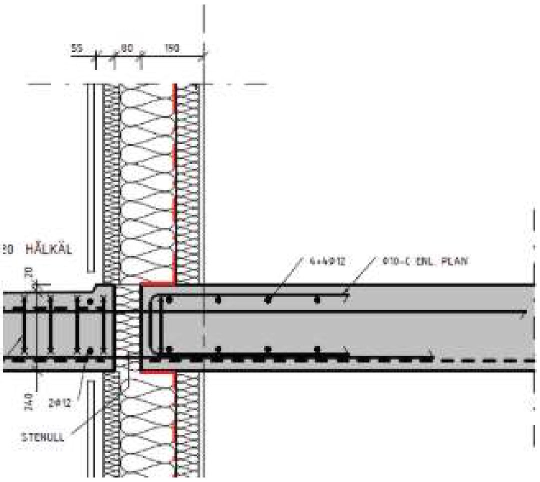


Figure 75. *Detail of intermediate floor-to-wall connection by Integra engineering AB (ETTELVA Arkitekter et al., 2020, p.24).*

Figure 76. *Detail of interior wall construction by Integra engineering AB (ETTELVA Arkitekter et al., 2020, p.28).*

Table 10. Material choices and thicknesses in the Grasshopper tool.

Building element	Material	Thickness [m]
Exterior walls	Ready-mix made concrete, buildings C20/25	0.1
	Structural steel, unprocessed, primary	0.0002
	Stone wool, facade board	0.15
Interior walls	Gypsum, standard plasterboard	0.025
	Structural steel, unprocessed, primary	0.0003
	Glasswool, sound bats	0.07
Ground floor	Ready-mix made concrete, buildings C25/30	0.35
	Structural steel, unprocessed, primary	0.05
	EPS, expanded polystyrene, pressure class 80	0.25
Intermediate floors	Ready-mix made concrete, buildings C25/30	0.25
	Structural steel, unprocessed, primary	0.002
Roof	Concrete roof tiles	0.02
	Ready-mix made concrete, buildings C25/30	0.1
	Stone wool, roof board	0.1
Doors	Door, apartment door, wood, massive	-
Windows	Window, wood/aluminium, fully glazed, triple glazed	-

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
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