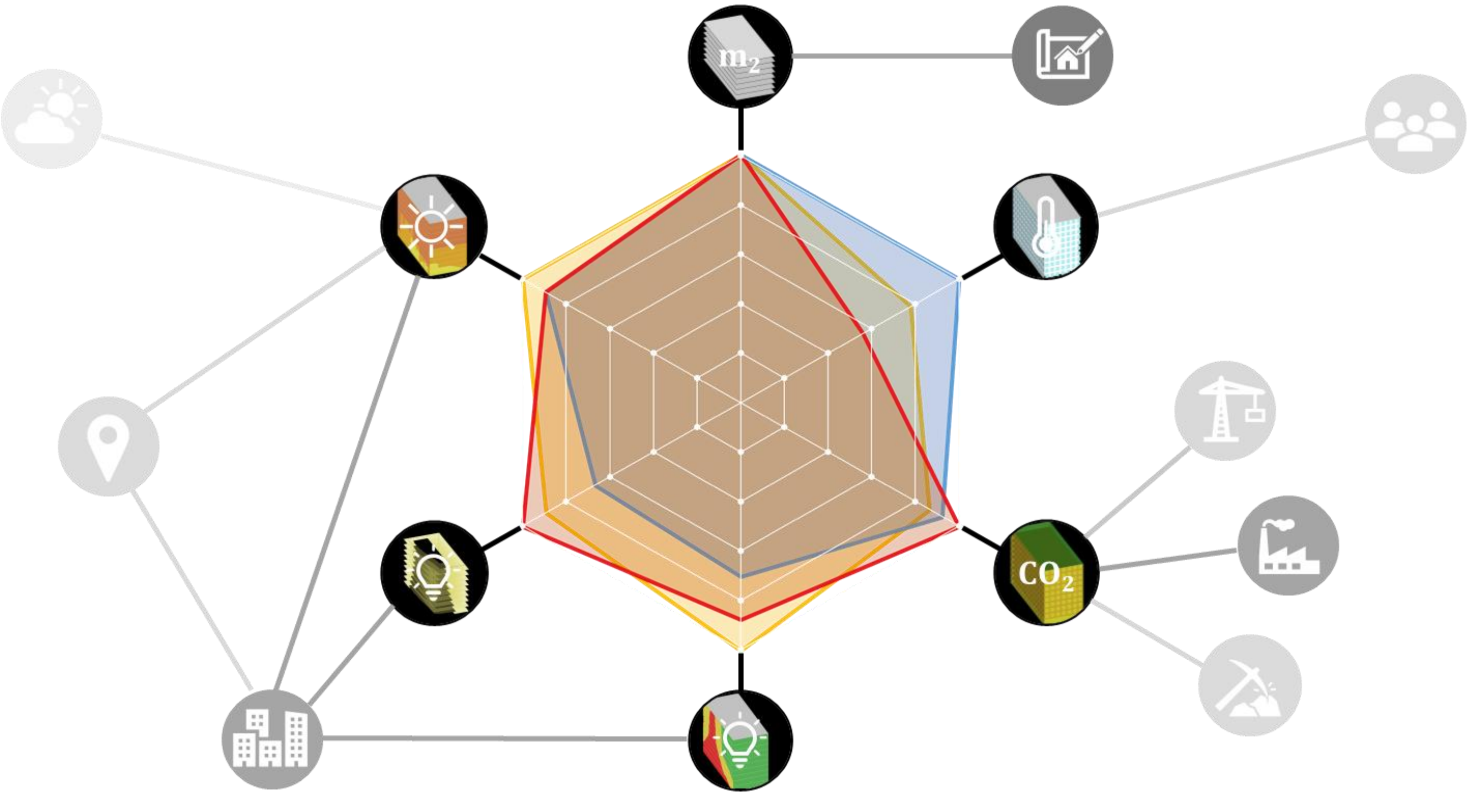

Combining building performance and life cycle assessment in early design stages

Developing a tool for parametric building sustainability assessment

Master's thesis in Structural Engineering and Building Technology

EMIL MAGNUSSON

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF BUILDING TECHNOLOGY

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
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MASTER'S THESIS ACEX30

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Examensarbete ACEX30
Institutionen för arkitektur och samhällsbyggnadsteknik
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Cover:
Conceptual illustration of the developed tool.
Department of Architecture and Civil Engineering
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ABSTRACT

Life Cycle Assessments (LCA) and Building Performance Assessments (BPA) are today mainly introduced in the late stages of building design, although decisions with the largest influence on both building performance and environmental impact are taken already in the early design stages. Implementation of both LCA and BPA from the beginning of the design process allows for consideration of the multifaceted influence of architectural design decisions in the stages when they are the most effective.

The present study aimed to identify the requirements for, and develop, a framework that integrates LCA and BPA for application early in the architectural design process. The thesis covers the requirement-based development of a parametric tool through the application of an incremental prototyping method.

First, a literature and a tool review were conducted to identify and compile the barriers for the implementation of LCA and BPA in early design stages and the potential conflicts between the respective workflows. The barriers and conflicts were converted into tool requirements divided into four themes: required knowledge, design supportiveness, relevance to architects, and applicability in early design stages.

The incremental prototyping method demonstrated useful potential through the parallel development of several prototypes, which allowed for isolated implementation of the requirements and a quick iterative development process for each prototype. However, further iterations are required for a more profound evaluation of the method.

The resulting tool is a proof-of-concept integrating performance indicators quantifying embodied carbon, energy performance, daylight, and sunlight conditions into a common framework. Evaluated through a tool demonstration and a survey, with potential users, the tool was found to be promising for application in early stages. The evaluation showed agreement that the scope of the tool was suitable for independent use by architects to guide the design development based on several LCA and BPA indicators.

Keywords: Life cycle assessment, building performance, early design stages, sustainable building design, incremental prototyping

Kombination av byggnadsprestanda och livscykelanalys i tidiga skeden

Utveckling av ett parametriskt verktyg för hållbarhetsanalys av byggnader

Examensarbete inom Konstruktionsteknik och Byggnadsteknologi

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SAMMANDRAG

Livscykelanalys (LCA) och byggnadsprestandaanalys (BPA) används idag främst i sena skeden i byggprocessen. Detta trots att besluten med störst påverkan för byggnaders prestanda och miljöpåverkan tas i tidiga gestaltningsskeden. Genom att implementera både LCA och BPA från början av designprocessen ges möjligheten att ta hänsyn till den mångfacetterade inverkan av designbeslut i skedet när de är som mest avgörande.

Målet med studien var att identifiera kraven för, och utveckla, ett ramverk som integrerar både LCA och BPA för användning i arkitekturprocessens tidiga skeden. Arbetet täcker utvecklingen av ett parametriskt verktyg genom en metod baserad på inkrementell prototyputveckling.

Först genomfördes en litteratur- och verktygsstudie för att identifiera barriärerna som hindrar implementeringen av LCA och BPA i tidiga skeden, samt potentiella konflikter mellan respektive arbetsflöde. Dessa omsattes sedan till en kravspecificering för verktygsutvecklingen utifrån fyra teman: krav på förkunskap, designstöd, relevans för arkitekter och användbarhet i tidiga skeden.

Inkrementell prototyputveckling visade god potential som metod genom parallell utveckling av flera prototyper. Det möjliggjorde för separat implementering av kraven och en snabb iterativ process för varje individuell prototyp. Dock vore fler iterationer av utvecklingen fördelaktigt för att ge en djupare utvärdering av den använda metoden.

Det utvecklade verktyget är ett koncept för integrering av indikatorer för inbäddad koldioxid, energiprestanda, dagsljus och solljusförhållanden. Utvärderingen av verktyget gjordes genom demonstrationer för potentiella användare och en efterföljande enkät. Utvärderingen visade samstämmiga resultat om att verktygets omfång lämpar sig för att arkitekter självständigt ska kunna använda det i tidiga skeden för att stödja designprocessen baserat på LCA- och BPA-indikatorer.

Nyckelord: Livscykelanalys, byggnadsprestandaanalys, tidiga skeden, hållbar byggnadsgestaltning, inkrementell prototyputveckling

Contents

Preface

This report is the result of a Master's thesis of 30 ECTS in the Master's Programme Structural Engineering and Building Technology at Chalmers University of Technology. In this study, the integration of Life Cycle Assessment (LCA) and Building Performance Assessment (BPA) in the early design stages has been investigated through the development of a parametric tool.

The thesis has been conducted at the Department of Architecture and Civil Engineering, Division of Building Technology, at Chalmers University of Technology in Gothenburg, Sweden, in collaboration with Arkitekterna Krook & Tjäder AB, Gothenburg, Sweden. The work has been carried out from January to June 2022.

I would like to express my gratitude to both of my supervisors for this thesis. Ph. D. Candidate Toivo Säwén for the guidance and inspiring discussions during the exploration of the subject. I am looking forward to taking part of your upcoming research. Maria Tjäder, Sustainability Engineer at Arkitekterna Krook & Tjäder AB, for the continuous support providing your expertise and sharing your network in the industry. Your contribution has been fundamental. Also, I would like to thank my examiner Professor Holger Wallbaum for his valuable feedback.

In addition, I would like to thank the employees at Arkitekterna Krook & Tjäder AB for the warm welcoming to the office and their sharing of knowledge and experience from the industry. Also, a special thanks to all of those who participated in the interviews and provided their thoughts and perspectives on the work.

Finally, to my family, thank you for your endless support and encouragement during my years at Chalmers University of Technology. It would not have been possible without you!

Göteborg, June 2022

Emil Magnusson

Abbreviations and Nomenclature

Abbreviations

BBR	Boverkets byggregler (the Swedish building regulations)
BPA	Building Performance Assessment
BPE	Building performance Evaluation
BPS	Building Performance Simulation
BTA	Gross floor area [m^2]
CAD	Computer-Aided Design
CIE	International Commission on Illumination
CFP	Carbon Footprint [kg CO2-e]
DF	Daylight factor [%]
DSH	Direct sunlight hours [h]
ECA	Embodied Carbon Assessment
EPD	Environmental Product Declaration
EPW	EnergyPlus Weather file
FF	Form Factor ($A_{envelope}$/ A_{floor}) [m^2/m^2]
GWP	Global Warming Potential [CO_2-eq]
HBD	Holistic Building Design
HUD	Heads-Up-Display
IDP	Integrated Design Process
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MRD	Maximum Room Depth [m]
RD	Room Depth [m]
RH	Room Height [m]
SF	Shape Factor ($A_{envelope}$/ $V_{building}$) [m^2/m^3]
SHL	Solar Heat Load
VSC	Vertical Sky Component [%]
WFR	Window to Floor area Ratio [-] [%]
WWR	Window to Wall area Ratio [-] [%]

Nomenclature

$A_{envelope}$	Building envelope area [m^2]
A_{floor}	Floor area [m^2]
A_{glass}	Window glass area [m^2]
A_{room}	Room floor area [m^2]
A_{temp}	Heated floor area [m^2]
CO_2-e	Carbon dioxide equivalents [kg]
I_{sol}	Solar irradiance [W/m^2]
l	Length of linear thermal bridge [m]
g_{sys}	solar shading factor [-]
U_m	Mean U-value [W/m^2K]
$V_{building}$	Building volume [m^3]
ψ	Heat transfer coefficient for linear thermal bridges [W/mK]
χ	Heat transfer coefficient for point thermal bridges [W/K]

Figures and tables

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1 Introduction

The construction and real estate sector was responsible for 34 % of the total energy consumption in Sweden in 2019. In addition, during the same year, the sector caused 21 % of the greenhouse gas emissions (Boverket, 2022d). Despite the considerable decrease of emissions related to the heating of buildings: 90 % since 1990, there is still a significant environmental impact from the production of materials and the construction process. This proportion has increased along with improved energy production and increased thermal efficiency of buildings (Boverket, 2021f). Hence considering the life cycle perspective of buildings is important to reduce the total environmental impact of society (Boverket, 2021a).

Furthermore, people spend about 90 % of their time indoors (Kelly & Fussell, 2019), making the quality of the indoor environment essential for human well-being. An example of this is the proven relation between indoor daylight conditions and human health (Christoffersen, 2011). Altogether, building design needs to balance numerous aspects in order to achieve a well-performing building.

Building performance is a concept of describing how well a building is fulfilling its intended functions (de Wilde, 2017) and covers the extensive areas of functionality, safety, health and well-being, and sustainability (Becker, 2008). To evaluate and predict the performance of building designs, Building Performance Assessment (BPA) tools have been developed to assess energy performance and indoor environment (Spitler, 2006). Meanwhile the methodological framework of Life Cycle Assessment (LCA) is widely recognized and applied to evaluate the environmental impact of buildings (Schlanbusch et al., 2016).

To address the extent and importance of these issues in building design several demands have been implemented in the building industry. National regulations, like the Swedish building regulations, BBR, and certification schemes like BREEAM, LEED and Miljöbyggnad aim to provide requirements ensuring the desired quality of buildings through the evaluation against numerous building performance indicators covering environmental impact, energy performance and quality of the indoor environment.

Decisions made early in the architectural design process are the most influential and decisive regarding building performance (AIA, 2019) and environmental impact (Hollberg & Ruth, 2016). Therefore, architects working in early design stages have a large influence and an important position in the design process. It is therefore crucial to enable building designers to consider the consequences of different design options from the earliest design stages (Bragança et al., 2014).

Design decisions characteristic for early stages, like massing, building orientation, façade design and selection of construction types, have a direct impact on energy performance, daylight, and sunlight conditions (AIA, 2019), as well as environmental impact (Hollberg & Ruth, 2016). Thus, this thesis advocates the integrated and simultaneous assessment of several indicators to capture the multifaceted influence of design decisions. Thereby a more comprehensive evaluation is provided showing both conformity and eventual trade-offs between different performance aspects.

1.1 Background

To face the full complexity of building design methods like Holistic Building Design (HBD) and Integrated Design Process (IDP) have been developed and are characterized by multidisciplinary collaboration utilizing the combination of engineering and architecture expertise (Kamari & Kirkegaard, 2020).

IDP has increased in relevance along with the growing focus on sustainability in the building industry (Reed, 2009) and increases the potential to reach a sustainable design (Deutsch, 2011). It is driven by interdisciplinary collaboration of all consultants from early design stages and evaluation of design alternatives through the use of simulation tools. A consequence is the central role of the architect in projects (Löhnert et al., 2005). Nevertheless, architects often work alone in the early design stages with limited presence of engineers (Petersen et al., 2014) and environmental consultants (Lamé et al., 2017).

Even though there is an understanding among building designers about the importance of including sustainability principles (Feria & Amado, 2019) and the advantages of implementing LCA and BPA in early design stages, it is not fully reflected in practice. There is a discrepancy between the enthusiasm among architects and engineers, and the application in early-stage design, both for LCA (Jusselme et al., 2020) and BPA (Mahmoud et al., 2020).

Instead, the common application of LCA and BPA is as reactive, post-design, evaluation methods for compliance with demands and regulations (AIA, 2019; Basic et al., 2019a; Lamé et al., 2017). Hence a large part of the optimization potential is lost in the early stages.

In place of a widespread use, the uptake of performance assessment in the design process is often on an individual level, mainly centered to those who are 'self-motivated' (Mahmoud et al., 2020). However, involving architects in the assessment itself can provide a more promising approach to the implementation of evaluation results in design practice (Petersen, 2011).

According to Purup and Petersen (2020) the underlying barrier for this situation is sufficiently covered by previous studies. Therefore, emphasis in research should be on bridging these barriers to enable a broader integration into design practice. Purup and Petersen defines the topic of integrating performance assessments in building design as the overlap between design practice and building performance simulation development, shown in Figure 1.

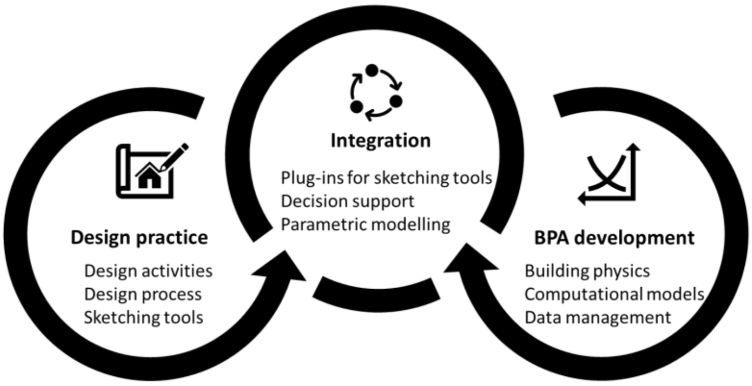


Figure 1 *The overlap between design practice and BPA development. Based on the definition by Purup and Petersen (2020).*

The application of parametric tools has been identified as having high potential to fulfil this purpose due to allowing the quick evaluation of several solutions, the automated handling of large data amounts, complex calculations, and standardized methods, but architects will only employ the tools if they are adapted to fit the design process (Purup & Petersen, 2020).

The advantages of integrating early-stage analysis in the architects' design tools through parametric modelling have been investigated for both BPA (Aksamija & Brown, 2018; Negendahl, 2015) and LCA (Hollberg, 2016; Negendahl et al., 2016), among others. Promising conclusions have been drawn, highlighting the advantages of a direct link to a design tool. It provides an intuitive and flexible workflow (Negendahl, 2015) and lets architects focus on building design (Hollberg, 2016).

However, the combination of LCA and BPA has mainly been focusing on the inclusion of energy performance in the LCA framework. This leaves room for expansion in the number of parameters to capture the trade-off between additional performance aspects beyond operational and embodied carbon.

1.2 Area of research

This project investigates the integration of combined LCA and BPA in design practice, as shown in Figure 2. The focus is on combining embodied carbon, energy, daylight, and sunlight assessments in a framework targeting the early architectural design stages. Emphasis is put on the applicability for architects working in these stages. The thesis covers the development of a parametric tool that incorporates both LCA and BPA workflows into a common interface. The tool is developed and implemented in Grasshopper®, a visual programming language (VPL) add-on to the 3D-modelling Computer-aided design (CAD) software Rhinoceros®.

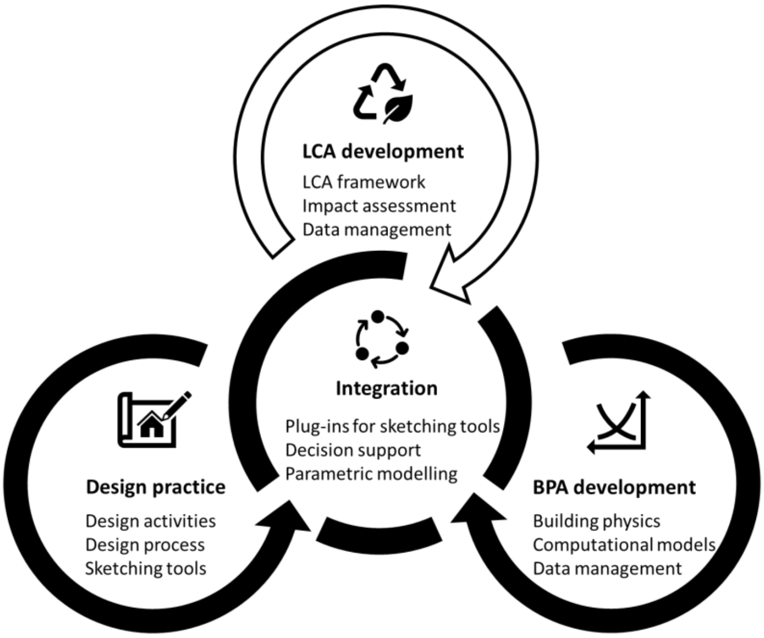


Figure 2 Expansion of the integration described by Purup and Petersen (2020) by the addition of LCA development.

1.3 Aim

The aim of the thesis is, firstly, to identify the requirements for a framework that integrates Life Cycle Assessment (LCA) and Building Performance Assessment (BPA) in early architectural design stages, and, secondly, to investigate incremental prototyping as a method of determining the relevance of these requirements through the development of such a framework, conceptualized as a parametric tool.

1.4 Research questions

The research questions are formulated as follows:

a) What are the barriers limiting, or preventing, the integration of LCA and BPA in early architectural design stages?

b) What potential conflicts are there between the workflows of existing LCA and BPA tools targeted at early design stages?

c) What are the requirements when developing tools for integrating LCA and BPA in the early design process?

d) How can incremental prototyping be used as a method to identify and develop requirements for a combined LCA, and BPA tool targeted at early design stages?

e) Does the tool bridge the barriers for integrating LCA and BPA in early design stages?

1.5 Delimitations

The project is delimited to study the integration of LCA and BPA from architects' point of view, hence other stakeholders are left out. The primary focus is on architects' use of tools early in the design process and not on methodologies for collaboration between professions. The considered BPA aspects are delimited to energy, daylight, and sunlight. The work is also done in, and with focus on, the Swedish industry and context.

The project is delimited to only consider individual buildings and not urban planning. The developed tool is a proof-of-concept and has not yet been validated for accuracy. Hence, the results presented in this report are not verified and only for demonstrative purposes.

Further delimitations on the literature review, tool review and tool development, are described in the detailed method descriptions for each phase of the project.

1.6 Intended audience

The intended audience of this thesis and the developed tool is primarily architects, but also engineers involved in the early design of buildings. Contractors and real estate developers may also find it interesting and useful.

1.7 Overview of methodology

The project was carried out in four phases which outline the methodology. The connection to the research questions (a)-(e) is described in Figure 3.

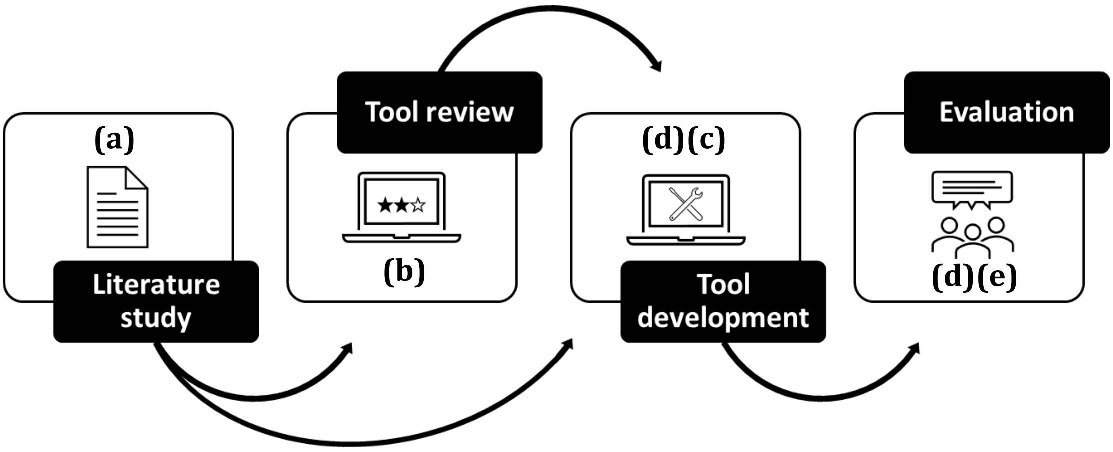


Figure 3 Overview of the method and the connection to the research questions.

First, a literature review was conducted regarding barriers limiting, or preventing, the application of LCA and BPS in the architectural practice. The barriers identified were mapped to tool requirements.

Second, a tool review was carried out to evaluate existing LCA and BPA tools in the software Grasshopper ®. The focus was on identifying potential conflicts in the integration of workflows for LCA and BPA in a parametric environment.

Third, a proof-of-concept tool was developed through an incremental prototyping method informed by the takeaways from the literature and tool reviews.

Fourth, the developed tool was evaluated against the requirements formulated for the tool development. It was done by a tool demonstration for architects working in early design stages.

Detailed descriptions of the methods can be found in the respective chapter:
2.4 Literature Review, 3 Tool Review, 4 Tool Development, and 5 Tool Evaluation.

The master's thesis project lasted for six months, from January to June 2022. Figure 4 shows the phases of the project in relation to the project timeline.

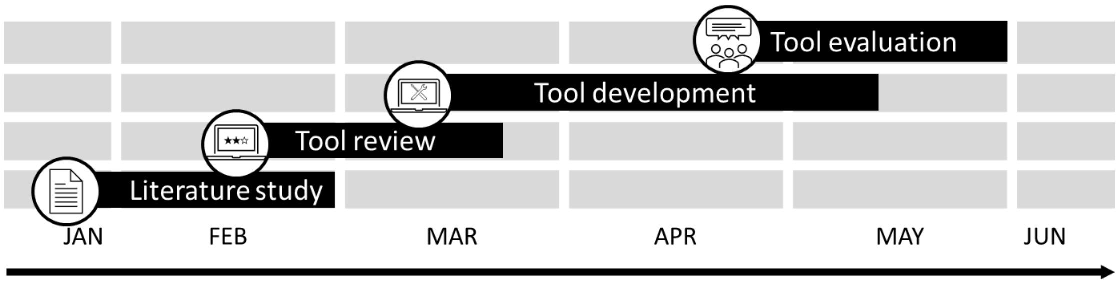


Figure 4 Overview of the project timeline.

1.8 Outline of thesis

The thesis contains seven chapters.

CHAPTER 1. **Introduction**

Introduces the topic and the importance of the subject in relation to the current situation in the building industry. It also includes aim, research questions, delimitations, and an overview of the methodology of the project.

CHAPTER 2. **Overview of area**

Establishes the underlying theory, principles, definitions of LCA, BPA and parametric design, and the relation to early design stages. Also includes the method and results from the literature review.

CHAPTER 3. **Tool Review**

Presents method and results from the tool review.

CHAPTER 4. **Tool Development**

Describes the method used in the tool development and presents results from the process, such as feedback from professionals in the industry. The developed tool is presented and demonstrated.

CHAPTER 5. **Tool Evaluation**

Describes the method used in the evaluation of the tool and summarizes the results.

CHAPTER 6. **Discussion**

Discusses the results from each phase of the project in relation to the research questions and evaluates the methods used in the project. Also presents ideas for further development of the project.

CHAPTER 7. **Conclusion**

Presents the conclusions drawn from the project.

2 Overview of area

This chapter covers the principles of building design process, life cycle assessment (LCA) and building performance assessment (BPA). Hence, a background to the three main areas treated in this thesis is provided.

2.1 Early design stages

The building design process is characterized by a series of stages that guides the design development. The stages are described in different terms across the industry which makes it difficult to specify a definition but in general they consist of the same activities and goals. Bragança et al. (2014) summarizes six phases which should be included in a building design process, shown in Figure 5.

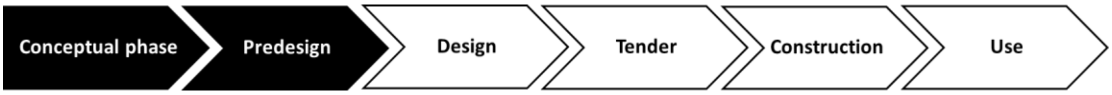


Figure 5 Phases in the building design process with the early design stages highlighted. Adapted from Bragança et al. (2014).

It is difficult to define a distinctive limit between the early stages and detailed design stages since the design development is a continuous refinement of the concept. However, Bragança et al. (2014) defines the early stages as the conceptual and predesign phases and emphasizes their importance on the development of sustainable buildings. These are the two stages where the client and the design team define the objectives and develop a preliminary design of the overall system of the building. Typical products from these stages are project requirements, sketches, and schematic drawings. The level of design at these stages involves building shape, orientation, principal structure, and construction types. The activities and decisions characteristic for the early stages are summarized in Table 1.

Table 1 Activities and decisions made in early stages.

Activities in early stages	Decisions in early stages
Meeting with clients, defining project requirements Sketch studies Creating alternative proposals and evaluate against requirements Validating/adjusting requirements	Volume/massing Orientation Façade design Selection of structural system Selection of materials

2.1.1 Architectural optimization

The importance of the early stages in building design is frequently addressed in literature (AIA, 2007; Bragança et al., 2014; Hollberg, 2016). The basic notion is in its fundamental sense that the effort of changes increases, while their effect decreases along the design process, Figure 6 (AIA, 2007).

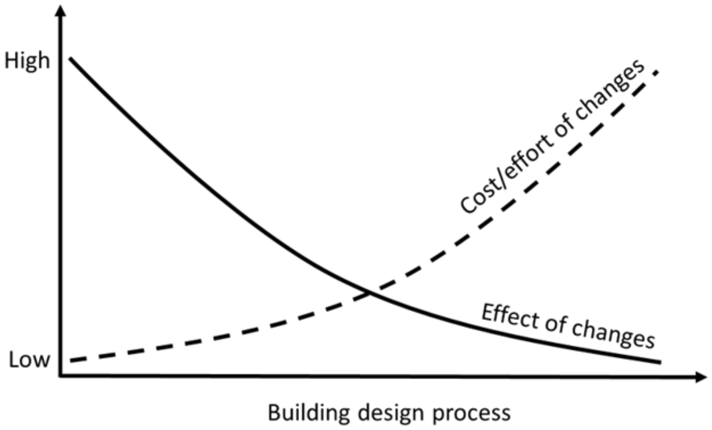


Figure 6 Cost/effort and effect of changes along the building design process. Adapted from AIA (2017).

This is said to be true for design decisions both relating to building performance (AIA, 2019) and environmental impact (Roberts et al., 2020). Bragança et al. (2014) address the importance of enabling the consideration of the impact of different design decisions from the earliest design stages. However, the dilemma of the early design stages is that the most decisive decisions need to be taken when detailed information about the building is scarce (AIA, 2019; Hollberg & Ruth, 2016).

This reasoning means that the early design stages hold the largest optimization potential in architectural design. The design process requires iterative development, evaluation, and comparison of alternative designs to improve the performance of design solutions (ASHRAE Press, 2006; Hollberg, 2016). Hollberg (2016) identifies two main types of parameters for architects to work with in the optimization of design: geometric parameters, including the shape, orientation, and fenestration of the building, and non-geometric parameters such as materials and technical systems.

Architectural optimization is, due to the unique context of each building, based on an exploration of the design space to reach a sufficient solution. Hollberg (2016) refers to three design exploration approaches described by Rittel (1970) and shown in Figure 7: a linear process approach, an approach with design alternatives and a decisions tree approach.

The linear approach limits the design development to one design version that is refined along design. In the approach using design alternatives various solutions are evaluated and compared and the best one is brought into further development. The decision tree approach has similarities to the design alternatives approach but does not abandon solutions in each step since these can be the basis for the best solutions in the coming steps.

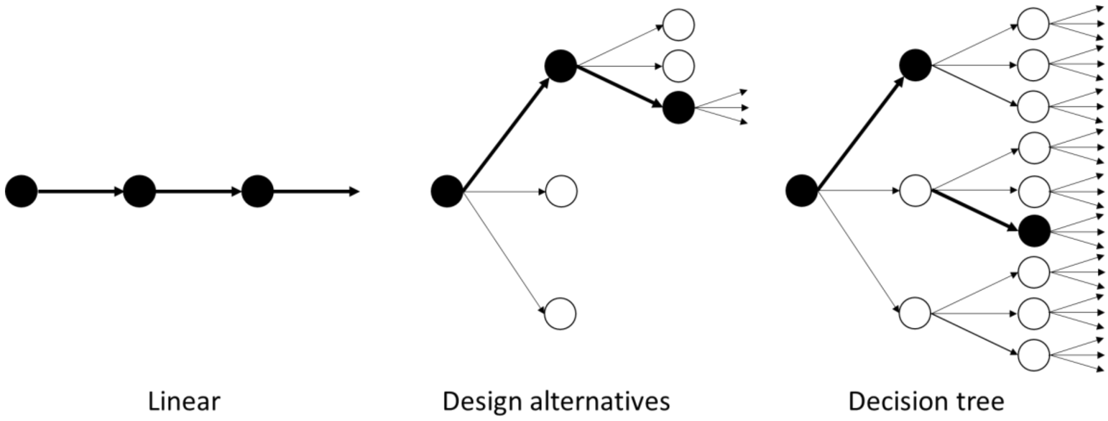


Figure 7 Design exploration approaches. Adapted from Hollberg (2016)

Still, iterative and explorative approaches are often restricted by limited time and economy, forcing the omission of evaluation of alternative solutions (ASHRAE Press, 2006). Therefore, the early stages require methods and tools for quick and intuitive assessment of several alternative designs.

2.1.2 Parametric modelling

Parametric modelling is based on the concept of describing design properties by different parameters. These parameters are connected, creating dependencies, which delineate the design space. By changing the parameters, various design alternatives can be generated within the domains of the defined parameters.

Once a parametric model has been defined it allows for the rapid production and evaluation of design alternatives which is enabling architectural design optimization and lets the architects focus on their principal task of building design (Hollberg, 2016).

In relation to the design process parametric design improves the cost-to-effect ratio of changes by applying two strategic approaches described by Hollberg (2016), shown in Figure 8. It has the potential to shift the decision-making into early stages through an earlier analysis of design alternatives, illustrated by the MacLeamy curve in Figure 8 a), and to alter the effort-to-impact ratio along the design process, illustrated by the Davis curve in Figure 8 b). Both approaches have the aim of increasing the influence of changes and decreasing their respective cost.

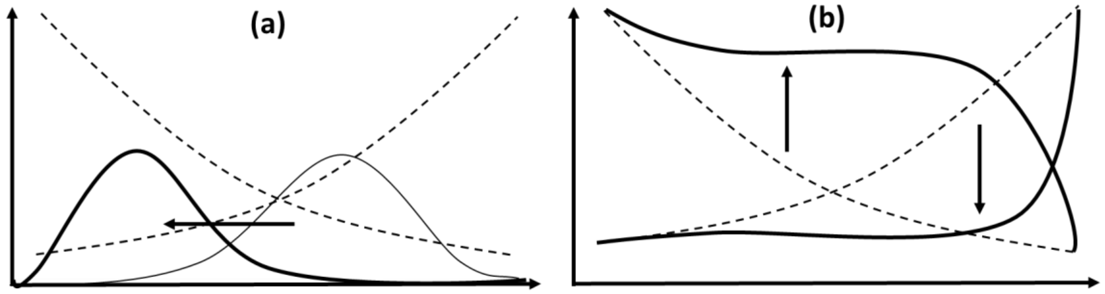


Figure 8 Potential of parametric modelling a) Shift of the design effort towards early stages. b) Change of cost and effect of changes further into the design process. Adapted from Hollberg (2016).

Parametric modelling is often discussed in relation to Building Information Modelling (BIM). BIM integrated analysis is limited by the fact that a BIM model is usually not established from the beginning of design (Roberts et al., 2020). The distinction in practice is that parametric modelling is mainly utilized in early conceptual stages, considered suitable in the intuitive exploration of alternative designs, while BIM is used foremost in the detailed design stages for the delivery of projects and for interdisciplinary coordination (Holzer, 2015).

Parametric modelling has enabled direct connection between design and analysis tools which has increased the awareness of building performance early in the design process (Oxman, 2008). The integration of analysis and design tools through a parametric model is, according to Negendahl (2015), providing a flexibility and tool diversity superior to BIM based tools. But it is limited by the lack of standardized formats for application in varying projects.

Drawbacks discussed in literature regarding parametric modelling treats the additional effort for creating a model (Woodbury & Aish, 2005). It is also likely that the model does not capture all parameters required by the designer (Holzer et al., 2007), and that major changes in projects often requires complete remodelling (Burry, 2007; Gerber, 2007).

2.2 Building performance assessment

Building performance is a concept describing how well a building is fulfilling its intended functions. In general, it is done by quantification of the performance by the means of physical measurements, simulations, user evaluations or expert judgements (de Wilde, 2017). De Wilde (2017) highlights the fact that the definition of building performance is rather vague and in large parts undefined. He emphasizes that it should cover several perspectives such as the engineering, as well as the artistic and humanistic aspects of architecture.

As shown in Figure 9, Becker (2008) presents a categorization of common performance attributes, related to the users' needs, into four categories: functionality, safety, health and well-being and sustainability.

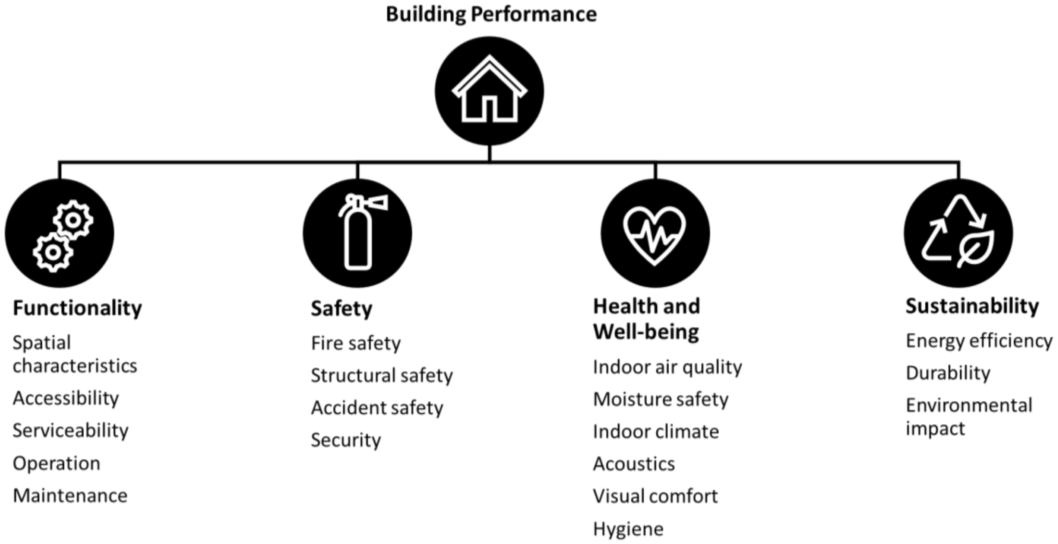


Figure 9 Common building performance categories. Based on Becker (2008).

Typically, the demands (from the client and regulations) on buildings are converted into physical terms describing the performance requirements in a qualitative way. These are accompanied by performance criteria that by physical factors, referred to as performance indicators, offer a quantitative measure to evaluate the performance (Becker, 2008), see Figure 10.

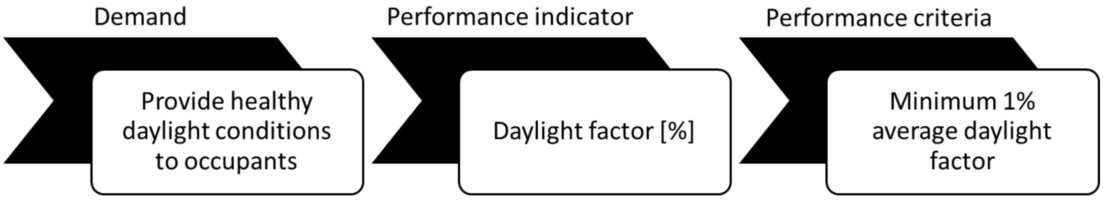


Figure 10 Example of connecting a demand to a quantitative criterion based on a performance indicator.

There are two primary approaches towards the assessment of building performance, either pre- or post-evaluation methods.

Building Performance Evaluation

Building performance evaluation (BPE) is an assessment approach where the building performance is measured in the post-design stage. In that way the real performance during occupancy can be monitored. Hence the focus is on optimizing the operation of the building. The evaluation can be done through measurements, questionnaires and interviews with occupants, expert consultation, and technical surveying visits (Sotsek et al., 2018).

Building Performance Simulation

Predicting the building performance in advance is recognized as a far more efficient approach than adjusting the building post-design (Hensen & Lamberts, 2011).

Building performance simulations (BPS) has its cradle in the 1960s, focusing on energy modelling. Since then, the domain of aspects included in building performance simulations has increased to include daylight, thermal comfort, and air quality, among others (Spitler, 2006). Today, BPS is built upon a foundation of a set of diverse disciplines like mathematics, physics, environmental sciences, and human behavioral science. This makes it a complex and extensive type of analysis aiming at predicting the building performance (Hensen & Lamberts, 2019).

2.2.1 BPA in demands and regulations

In Sweden, the minimum demands on buildings from the authority regulations are described in Boverkets byggregler (BBR). It covers areas such as accessibility, fire safety, energy use and indoor climate (Boverket, 2018a). In addition to the demands in BBR, commercial environmental certification systems are often used in the Swedish building industry, even though they are not governmental requirements.

The most frequently used systems in Sweden are Miljöbyggnad, LEED and BREEAM (Bengt Dahlgren AB, 2019). They cover multiple aspects of building performance through the grading of specific indicators, shown in Table 2. GreenBuilding is also common but only considers the energy performance of buildings.

Table 2 Performance aspects covered in the certification systems Miljöbyggnad, LEED, and BREEAM.

Miljöbyggnad 3.1	LEED v4.1	BREEAM-SE
Energy	Location and transportation	Management
Indoor environment	Sustainable cities	Health and well-being
Material	Water efficiency	Energy
	Energy and atmosphere	Transport
	Materials and resources	Water
	Indoor environment quality	Materials
	Innovation	Waste
		Land use and ecology
		Pollution
		Innovation
(16 indicators)	(50 indicators)	(80 indicators)

2.2.2 BPA in early design stages

It is common that the architect performs stand-alone work in the early stages in the design process. Collaboration with engineers is only brief, with input based on experience rather than analysis (Petersen et al., 2014). In general, building performance assessments are introduced in the projects at a late stage, often for the purpose of documentation for compliance with regulations. Therefore, the potential of BPA in early stages is unexploited, even though the decisions made in the architectural design process have a direct influence on related building performance parameters (AIA, 2019), which is exemplified in Table 3.

Table 3 Typical design decisions made by architects and their connection to building performance.

Design decision	Performance design decisions
Form and orientation	Solar geometry, Daylight
Structural system	Thermal mass
Wall design	Thermal mass, Heat transfer
Window design	Window-to-wall area ratio, Daylight

2.2.2.1 Energy performance

In 2019, the construction and real estate sector accounted for 34 % of the total energy use in Sweden, whereof 70 % was for the heating of buildings (Boverket, 2021c). This makes the thermal and energy efficiency of buildings essential from a societal perspective.

The prediction of the energy demand of buildings involves balancing of heat losses and heat gains, where the thermal envelope of the building is the boundary. The difference of the losses and gains is summarized into heating and cooling demands for the building and can be calculated based on dynamic, quasi-steady-state or steady-state calculation models. However, in early design stages, several factors influencing the heat losses and gains are unknown and complex to estimate. These factors are, for instance, the air leakage through the envelope, the efficiency of technical installations and internal heat gains from users and appliances.

An alternative to the extensive calculations and simulations trying to predict the actual energy use for the building is the use of indicators capturing important characteristics of the building related to the energy performance.

Danielski (2014) discusses the benefit of assessing the energy performance of buildings with heating demand, through indicators based on "intrinsic" properties rather than trying to predict the energy demand. In the design phase parameters related to the performance of installed systems, user behaviour and the quality of construction work are unknown, but yet too significant to ignore. Instead, they need to be predicted based on assumptions making the calculations subjective to the one who conducts the calculation.

Danielski elaborates on the advantages of evaluating the thermal performance based on properties such as the mean heat transfer coefficient of the thermal envelope, and the building form factor. In that way the indicator is easily obtained from building drawings in early stages and independent of the user behaviour and technical installations in the building.

The influence of the form factor varies with climate and thermal envelope properties: the colder the climate, and the poorer the thermal performance of the envelope, the higher is the influence of the form factor. For form factors between 1 and 1,7 a difference of 10-20% in final energy demand was found (Danielski et al., 2012).

Shape and form factor

The shape and form factors are measures of a building's compactness. The shape factor describes the ratio between the area of the thermal envelope and the building volume, see Equation (1), while the form factor is the area ratio between the envelope and total floor area in the building, see Equation (2). Essentially, they are describing the size of the thermal envelope in relation to the internal space in the building. This is of special interest since the thermal envelope is the boundary between the interior and exterior climates and a large part of the building energy, in cold climates, is lost due to transmission through the envelope. Figure 11 illustrates the geometrical properties included in the shape and form factor.

Shape factor:
$$SF = \frac{A_{envelope}}{V_{building}}, [m^2/m^3] \tag{1}$$

Form factor:
$$FF = \frac{A_{envelope}}{A_{floor}}, [m^2/m^2] \tag{2}$$

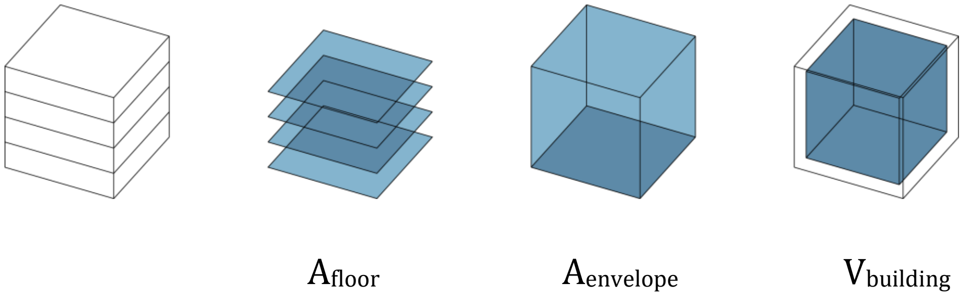


Figure 11 Definition of the geometrical properties floor area (A_{floor}), thermal envelope area, ($A_{envelope}$) and building volume ($V_{building}$).

The disadvantage of the shape factor is that it does not consider the floor height. Hence an increased floor height would result in a lower shape factor, even though in reality it would imply a larger thermal envelope and a bigger volume to heat. The form factor is more accurate since it is containing the relation to the floor area which is common functional unit in energy requirements and more relevant for architects.

Mean U-value

The mean heat transfer coefficient value of a building, U_m, is calculated according to Equation (3) (Boverket, 2021b). It is the area weighted heat transfer coefficient for all elements in the thermal envelope including ground slab, external walls, windows, and roof. In addition, linear and point thermal bridges are accounted for by adding the respective terms.

$$U_m = \frac{\sum U \times A + \sum l \times \psi \, + \sum \chi}{A_{envelope}}, [W/m^2K] \qquad (3)$$

$U = element\ heat\ transfer\ coefficient\ [W/m^2K]$
$A = element\ area\ [m^2]$
$l = lenght\ of\ linear\ thermal\ bridge\ \ [m]$
$\psi = heat\ transfer\ coefficient\ of\ the\ linear\ thermal\ bridge\ [W/mK]$
$\chi = heat\ transfer\ coefficient\ of\ the\ point\ thermal\ bridge\ [W/K]$
$A_{envelope} = total\ area\ of\ the\ thermal\ envelope\ [m^2]$

The Swedish Building Regulations (Boverket, 2021b) contains a limit for the mean heat transfer coefficient for residential buildings of 0,4 W/m^{2}K, including thermal bridges. In addition, recommended values are provided for the thermal envelope's constituent elements, see Table 4.

Table 4 Recommended U-value for the elements of the thermal envelope (Boverket, 2021b).

Building element	U-value [W/m²K]
Roof	0,13
Wall	0,18
Floor	0,15
Window	1,2
Door	1,2

Energy performance indicator

The indicator for energy performance used in this thesis is the product of the mean heat transfer coefficient and the form factor, the two indicators discussed by Danielski (2014), see Equation (4). It describes the total heat loss through the building envelope per degree Kelvin temperature difference, normalised by the floor area of the building. In that way the insulating and the geometrical properties of the building envelope are combined and related to the functional unit of floor area. The lower the value, the better the thermal efficiency of the buildings' thermal envelope.

$$U_m \; x \; FF \;, [\frac{W}{K * m^2}] \tag{4}$$

2.2.2.2 Daylight conditions

Daylight conditions have been shown to influence various aspects of human health and well-being (Christoffersen, 2011). Insufficient lighting conditions affects the circadian rhythm and human performance, and can among other effects lead to headache, fatigue, and seasonal affective disorder, also known as winter depression.

The Swedish Building Regulations, (Boverket, 2021b), express that rooms or spaces with more than temporary use should be designed in such a way that good access to direct daylight is provided. A complementary recommended guideline is to provide 10 % window-to-floor area. However, the guideline is based on a set of simplifications that in practice mean that the most common way to show compliance with the regulations is through calculation of the Daylight Factor (DF). The Daylight Factor is a ratio between the illuminance indoors and outdoors under the standard overcast sky. It is a common metric in daylight analysis and is present for example in the requirements in Miljöbyggnad and BREEAM.

The normal application of daylight analysis is the calculation of Daylight Factor in late stages of the building design, focusing on the individual rooms with the most critical conditions. At that stage, the possibility to adjust the main parameters that affect the daylight levels, such as building placement, room geometry and windows specifications, is limited (Gjestvang & Rogers, 2020).

Vertical sky component

A daylight analysis using the daylight factor requires knowledge about the interior plan layout, material reflectances, and the transmittance of the window glazing.

But before the interior design is considered, a supplementary daylight analysis that can be used in those early stages is the Vertical Sky Component (VSC).

VSC is defined by the Building Research Establishment (BRE) as the ratio between the illuminance that a point on a vertical plane is receiving from a CIE standard overcast sky and the illuminance an unobstructed point on a horizontal plane is receiving, for the very same sky (Littlefair, 2011). Hence it is a metric that describes the access of daylight on surfaces, for instance facades or specific windows. Figure 12 illustrates the definition of the vertical sky component. The sky model used in the definition have a varying distribution of illuminance which is three times larger at the zenith than at the horizon.

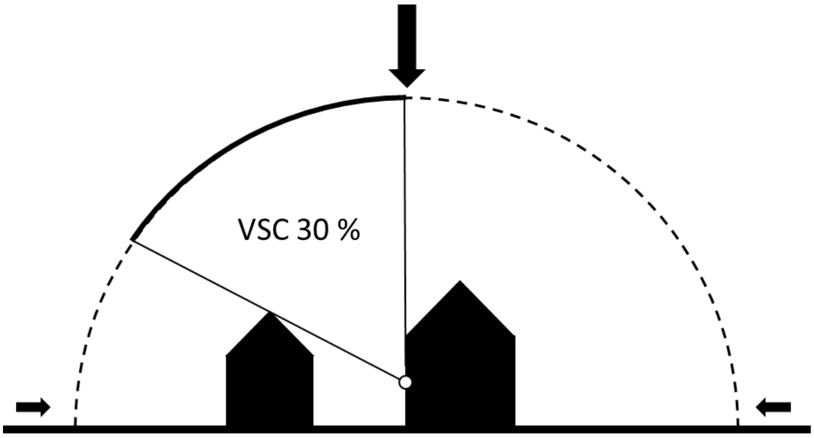


Figure 12 *Illustration of the vertical sky component. The arrows represent the sky illuminance.*

The calculation of VSC omits reflections between facades making it a quick calculation and the only information needed is the geometry of the measure plane and the shading geometry. It is useful in urban planning, but also has a large potential in early stage building design to assess the daylighting conditions already during the massing design of the building geometry to identify critical issues even before the façade design and internal layout is determined and the daylight factor can be calculated.

Several studies have been made regarding the relation between VSC and DF to establish guidelines and limiting values. The guidelines *Site layout planning for daylight and sunlight* from the British Building Research Establishment (BRE) (Littlefair, 2011) provides values on VSC targeting for 2% DF while the daylight regulations in Sweden are typically targeting 1 %. An example of the application of this type of guidelines is the recommended intervals for residential buildings from the City of Gothenburg (Göteborgs Stad, 2020), see Table 5, indicating different conditions to meet the requirements of 1 % DF.

Table 5 *VSC guidelines for compliance with 1% DF* (Göteborgs Stad, 2020).

VSC	Access to daylight	Description
> 25 %	Good	Normally no adjustments needed.
15 % - 25 %	Limited	A more detailed investigation and some adjustments needed.
< 15 %	Insufficient	Large risk to not reach 1 % DF, major changes needed.

An important note is that the intervals in Table 5 are only guidelines and not evidence of the interior conditions. VSC is only an analysis of the conditions on the facades, the interior conditions then need to be evaluated in detail with the specific window properties and floor layout.

Advanced VSC method

In addition to the relation between VSC and daylight factors, studies have been made to link the VSC to maximum room depth, which allows it to guide the organization of the internal layout of the building.

The report *Advanced VSC – an Early-Stage Method to predict compliance with the Swedish Daylight Standard* (Pacheco et al., 2021) describes the method called Advanced VSC developed in collaboration between White arkitekter AB and Lund University. The Advanced VSC method predicts the maximum room depth possible to meet the Swedish regulations on daylight based on VSC, window-to-wall area ratio and room height. The method is therefore possible to apply already during the massing stage of the building design and is suitable for application by designers without daylight expertise. The model was found to have an accuracy for 80% of the test cases within 0,5 m of the actual room depth. Thus, it shows a great potential for the early design stages.

However, the method is only validated and developed considering rectangular rooms, without shading balconies and only with windows on one side with a frame factor 0.17-0.39 and a light transmittance of 70 % for the glazing. Therefore, the method is not proven for irregular room and window geometry and the developers identify that it may overrate the room depth for cases with high window-to-wall ratio. The geometrical conditions used when applying the formula in the present study are defined in Figure 13.

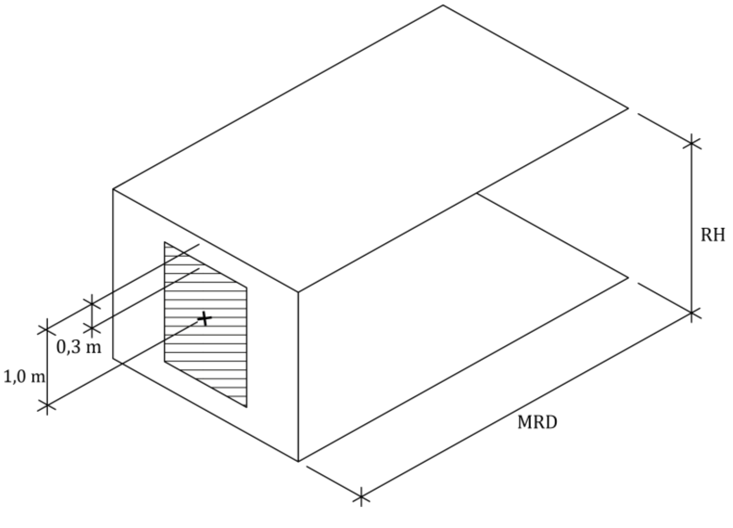


Figure 13 Geometrical definitions of the Advanced VSC method (Pacheco et al., 2021).

The room height, RH, is the vertical distance between the floor surface and the ceiling surface. The top of the window is assumed to be on the height 0,3 m below the ceiling and the VSC measure point is 1,0 m below the ceiling surface as illustrated in Figure 13. The window-to-wall area ratio is calculated from the interior. The established model that estimates the maximum room depth is described in Equation (5) (Pacheco et al., 2021).

$$MRD = \frac{0.2 \times (VSC \times RH \times WWR)}{(WWR + 0.7)} \tag{5}$$

$MRD = maximum\ room\ depth\ [m]$
$VSC = vertical\ sky\ component\ on\ window\ [m]$
$RH = room\ height\ [m]$
$WWR = window\ to\ wall\ area\ ratio$

2.2.2.3 Sunlight conditions

Sunlight is an important factor in building design since it has both positive and negative influences on the building performance. The access to sunlight is considered a quality and is a requirement by BBR. It states, specifically for residential buildings, that any room with more than temporary occupancy should have access to direct sunlight (Boverket, 2021b). Meanwhile conflicting aspects related to sunlight conditions, are the requirements on good thermal comfort and low cooling demands.

Solar heat load

Beyond the positive effects of access to sunlight, namely free heat and light, the aforementioned requirements capture the complexity of solar radiation in building design. It is a valuable quality but also a source of discomfort in the shape of glare and high operative temperatures resulting in increased cooling demands to ensure a good level of thermal comfort. The extra heat coming from the sun can both be a benefit decreasing the heating demand and an extra load increasing the cooling demand. It is intricately related to window and shading properties, internal layout, orientation as well as the schedule of occupancy behaviour and internal loads. Therefore, the consideration of the energy and comfort aspects of sunlight requires sophisticated input data and simulations.

A simplified model calculating the solar heat load (SHL), described in Equations (6) and (7), is implemented in Miljöbyggnad 3.1 (SGBC, 2020). Equation (6) should be applied for rooms with windows facing one direction. For a room with windows facing two directions the maximum of Equation (6) and Equation (7) should be used. Only facades oriented between 90° and 270° are considered in the model.

$$SHL = 800 * g_{sys} * \frac{A_{glass}}{A_{room}} \tag{6}$$

$$SHL = 560 * g_{sys} * \frac{A_{glass1}}{A_{room}} + 560 * g_{sys} * \frac{A_{glass2}}{A_{room}} \tag{7}$$

$SHL = solar\ heat\ load\ [W/m^2]$
$g_{sys} = combined\ shading\ factor\ of\ glass\ and\ solar\ shading\ [-]$
$A_{glass} = window\ glass\ area\ [m^2]$
$A_{floor} = room\ floor\ area\ [m^2]$

The solar irradiance of 800 W/m^2 and 560 W/m^2 can be adjusted by simulating the maximum irradiance between the vernal equinoxes.

Direct sunlight hours

Direct sunlight hours (DSH) evaluation is a quick analysis to determine access to direct sunlight on the surfaces, for example facades. It is calculated for a specific position of the sun, according to a given time and location, by evaluating if a vector reaches the evaluation point on the analysis surface without being obstructed by shading geometry, Figure 14.

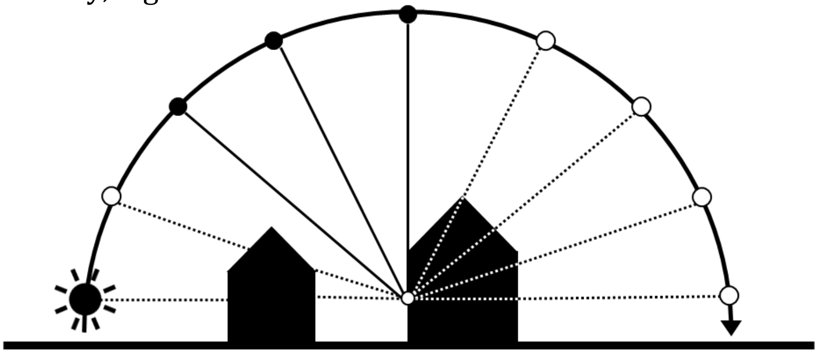


Figure 14 *Illustration of direct sunlight hours. It is aggregated for each position of the sun with consideration of shading objects.*

It is considered as a useful and crucial indicator in early stages since it is the building geometry in relation to surrounding shading buildings that determines the access to sunlight. Hence the possibility to influence the conditions is very small later in the design process, eventually only dependent on the façade design and window placement.

By considering the DSH from the beginning of the design process one can establish an understanding of the predefined conditions on site ensure sufficient access to sunlight. As previously mentioned, there are several measures to limit the access to sunlight later in design but probably small possibilities to increase the access when the overall building geometry has been decided.

2.3 Life Cycle Assessment

Life cycle assessment (LCA) is a methodological framework to assess potential environmental impact of product and service systems by compilation of inputs and outputs throughout its life cycle (ISO, 2006).

The intended applications of an LCA are for instance for: product development, communication (consumer information and marketing) or policy making (Grahl & Klöpffer, 2014). The framework is defined by the international standards ISO 14040 and 14044, where the former standard describes the outline and main structure of LCA, and the latter is oriented towards the usage and implementation of the framework.

The LCA methodology is structured into four phases according to the international standard ISO 14040, see Figure 15. These are goal and scope definition, inventory analysis, impact assessment and interpretation.

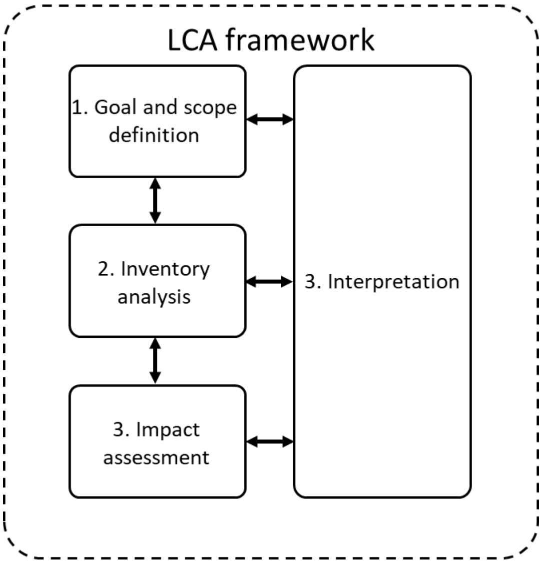


Figure 15 The framework of LCA including the four phases in ISO 14040.

The goal and scope definition establishes the purpose of the assessment. Inventory analysis is the compilation of the utilized resources in the studied system. The impact assessment is then conducted by converting the resources into potential environmental impacts. The interpretation of the results is then done in accordance with the defined purpose of the study.

As can be seen in Figure 15 there is a two-way relation between the phases which is indicating the iterative nature of the LCA methodology. The process of conducting an LCA is knowledge-building and the results of one phase may result in a change of another phase as knowledge of the studied system is gained (Grahl & Klöpffer, 2014).

2.3.1 LCA of buildings

The increased thermal and energy efficiency of buildings have led to an increased proportion of the environmental impact of buildings coming from the production phase, which can be seen in Figure 16. It is therefore important to assess the life cycle of buildings to capture their environmental impact (Boverket, 2021f).

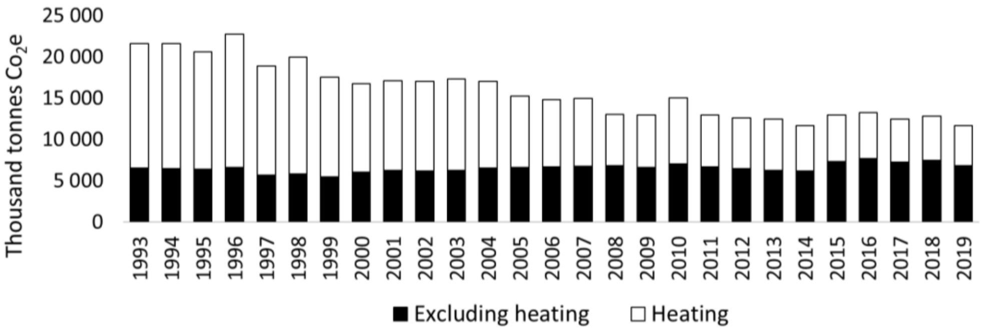


Figure 16 Greenhouse gas emissions from the Swedish building and real estate sector with separated contribution from heating (Boverket, 2021e).

The framework and guidelines for implementation of LCA in the building industry are described by the European standards EN15978:2011 and EN15801:2011. The former treats the building level and contains the structure of the LCA modules related to life cycle stages as presented in Figure 17, while the latter describes the product level of LCA in the building industry with the principles of environmental product declaration (EPD).

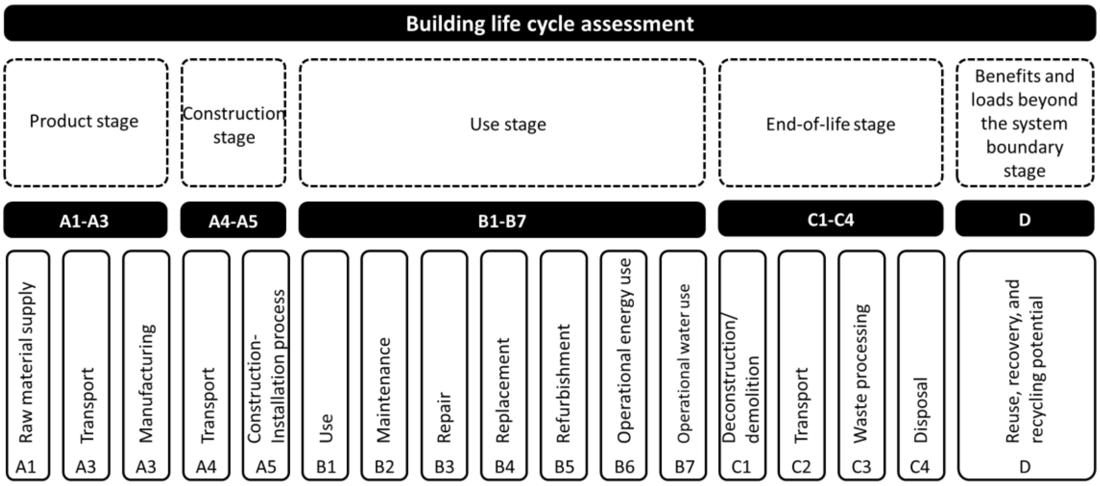


Figure 17 The life cycle stages and modules as structured in EN15978:2011.

As Figure 17 shows, the life cycle of buildings is divided into five stages: product stage, construction stage, use stage, end-of-life stage, and benefits and loads beyond the system boundary stage. Everything is covered by the 17 modules A1-A3, A4-A5, B1-B7, C1-C4 and D. These modules are illustrated in the life cycle of buildings shown in Figure 18, which also shows common system boundaries of LCA: Cradle to gate (A1-A5), Cradle to grave (A1-C4) or Cradle to cradle (A1-D).

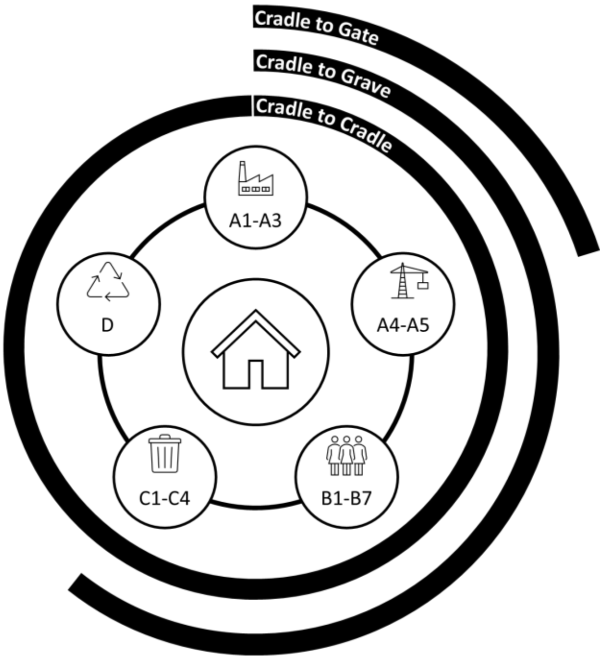


Figure 18 Life cycle of a building. Related to the stages in EN15978:2011.

The National Board of Housing, Building and Planning, Boverket, describes four phases of the building process where LCA is of value, presented in Figure 19. These are in the early stage, at procurement of contractor, at follow-up, and at reconstruction (Boverket, 2022b).

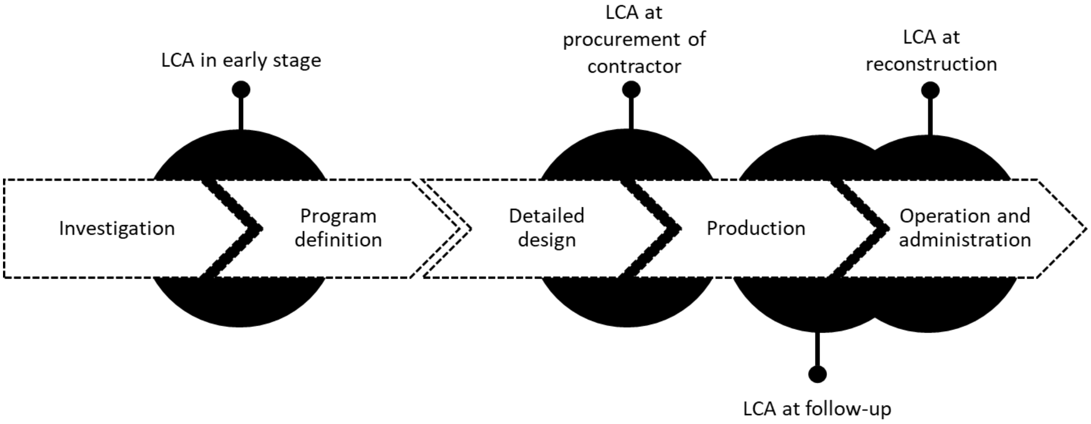


Figure 19 Recommendation on when it is valuable to perform LCA in the building process. Adapted from Boverket (2022b).

There are three alternative principal goals with LCA of buildings: to identify the main contributors to environmental impact (hotspot analysis), to improve the environmental impact of the building based on the main contributors, or to make comparative studies with other buildings (Boverket, 2022b).

2.3.2 LCA in demands and regulations

Since January 1, 2022, BBR includes a requirement on performing climate declarations, outlined in Table 6. The regulations require a climate declaration for new buildings in Sweden covering the modules A1-A3 (product stage), A4 (transport to site) and A5 (waste and energy in the installation process). Elements considered are the building envelope, the structural system, and internal walls. These elements cover about 80 – 90 % of the environmental impact for the LCA modules A1-A3 (Boverket, 2018b), which is responsible for about 80 % of the impact from A1-A5 (Malmqvist et al., 2021). The impact category studied is global warming potential, excluding consideration of biogenic uptake of CO_2.

Table 6 Current regulations and the proposed extension of scope in the climate declaration from 2027.

	2022	2027
LCA modules	A1-A5	A1-A5, B2, B4, B6, C1-4
Impact category	GWP	GWP
Considered elements	Structural system Building envelope Interior walls	Structural system Building envelope Interior walls Installations Internal surface finishes Moldings, linings etc.
Reference study period	-	50 years
Limiting value	None	Covering modules A1-A5

Table 6 also presents the proposal for further extensions of the declaration from 2027. The suggestion is the inclusion of the modules B2, B4, B6 and C1-4, additional building components, as well as a reference study period of 50 years. Complemented with limiting values for modules A1-A5 (Boverket, 2019a).

Boverket also provides a material database with generic data for the use in the climate declaration, including data for the LCA modules A1-A3, A4 (transport to site) and A5 (waste of material) (Boverket, 2022a).

Miljöbyggnad, BREEAM and LEED do all include some sort of LCA indicator. The current state of the certification systems is targeting different aspects of the work with environmental impact. BREEAM and LEED stress the use of LCA in early stages to inform the design decisions, while Miljöbyggnad stimulates the use of EPDs in the building industry. An overview of the scope of assessment in the certifications is compiled in Table 7.

Table 7 Scope of LCA in Miljöbyggnad, BREEAM, and LEED.

	Miljöbyggnad 3.1	**LEED v4.1**	**BREEAM-SE**
LCA modules	A1-A3, (A4)	A1-A4, B1-B5, C1-C4	A1-A3 minimum
Impact categories	GWP	6 different (incl. GWP)	At least 3 different (incl. GWP)
Considered elements	Structural system Foundation	Structural system Foundation Building envelope	Roof, Windows, External walls, Upper floor slabs
Reference study period	-	60 years	60 years

2.3.3 LCA in early design stages

The uncertainties of the building design in early stages entails limited information about the inventory data both for quantities and type of materials. Even though the LCA needs to be built upon assumptions it can still be a powerful method to support design decisions. It could be used to investigate what a reasonable environmental requirement could be for the specific project or to support architects and engineers in choices of building components, structural systems, and materials (Boverket, 2022c).

However, Hollberg and Ruth (2016), are pointing at the fact that a LCA, in itself, does not improve the design from an environmental point of view. It is when it is applied it can be a powerful tool, but the most common application today is to achieve a certification at the end of the project, that is, when the potential improvement for the considered building barely exists.

Hollberg and Ruth further connect LCA to the architectural design process and elaborate on the challenges related to it. It is during the development of the architectural concept where LCA first can be applied to support decisions. It is the stage where decisions defining the project are taken and then continuously refined to achieve final geometry, structural system and building components. But it is not until the detailed design is conducted that the specific inventory data of the building is known. Instead LCA in the early design stages is characterized by simplifications.

2.3.3.1 Simplified LCA

A wide variety of strategies are applied in practice to deal with the complex task of conducting an LCA. Beemsterboer et al. (2020) identify and categorize these into five simplifying logics: exclusion, inventory data substitution, qualitative expert judgement, standardisation, and automation. Exclusion and inventory data substitution are explained as the most common simplifications, both addressing the extensive data collection required in an LCA.

Beemsterboer et al. further discuss the standardisation and automation simplifications in relation to LCA tools. Standardization is based on the idea of establishing a structure to frame the LCA methodology and calculation. It is seen in the development of many tools built on a predefined structure for a specific purpose of application. Meanwhile, automation has been introduced with computational LCA tools characterized by data integration, for instance through the direct connection to CAD software reducing the time investment in both modelling and calculation.

Beemsterboer et al. concludes that it is close to inevitable not to introduce simplifications when conducting any form of LCA. The importance of transparency and critical interpretation of the result is therefore emphasized as the influence of the final result may vary (Beemsterboer et al., 2020).

The EeBGuide (Wittstock et al., 2012), which is the result of the research project, 'EeBGuide – Operational guidance for Life Cycle Assessment Studies of Energy-Efficient Buildings Initiative', funded by the European Commission, proposes two types of simplified application of LCA in early design stages: screening and simplified LCA. The characteristic of these types of LCA is the limited scope of the assessment, the exclusion of inventory data, and the use of generic data, to suit assessments in the early stage of building design.

Screening LCA is defined to be used in the earliest stages while the simplified LCA is an intermediate type of assessment between the screening and a complete LCA. The application of screening LCA is, due to the non-detailed results, limited to internal comparisons. It is suitable for assessing early architecture sketches to identify optimization potentials and support the documentation for architecture competitions. Simplified LCA, on the other hand, is the type of assessment commonly seen in certification systems and can be used by architects and engineers to get more detailed and specific information about their building.

Wittstock et al. further explains that the simplification strategy is to maintain precision in the assessment as far as possible by focusing on the main contributors. Thereby the exclusion of modules, elements and impact indicators is motivated by their insignificance. While screening LCA is purely based on generic data and to a wide extent delimited in its scope, the simplified LCA aims to replace generic data with specific data, and to include more modules and indicators even though they may be based on reference values. An overview of the scope of screening LCA and simplified LCA is provided in Table 8.

Table 8 Minimum scope of screening and simplified LCA as defined by EeBGuide (Wittstock et al., 2012).

	Screening LCA	**Simplified LCA**
Life cycle modules	A1-A3, B6, B7	A1-A3, B4, B6, B7, C3, C4, D
Impact categories	One (or more)	Several
Operational energy demand estimation	Expected performance (e.g., target in certification scheme)	Dynamic simulation National calculation method
Considered building elements	Roof, load-bearing structure, exterior and basement walls, windows, floor slabs, foundation, floor finishes/coverings	Roof, load-bearing structure, exterior and basement walls, windows, floor slabs, foundation, floor finishes/coverings
Data	Generic	Generic or Specific

2.3.3.2 Embodied carbon assessment

Global warming potential is by many considered as the most urgent climate threat and therefore a common delimitation in LCA of buildings is to only consider GWP as impact category (Boverket, 2019b).

Addressing the attention on carbon emissions in society, carbon assessments is an environmental assessment method aiming at calculating the carbon footprint (CFP) of buildings. It is built upon the principles of the LCA methodology but due to the limitation to only one impact category it is not conforming with the holistic aim of the LCA framework.

Carbon assessments can vary in scope. From whole building assessments including life cycle stages A1-A5, B4 and B6, preferably A-D, to embodied impact assessments delimited to stages A1-A5. Including more life cycle modules is considered best practice and captures burden shifting between life cycle stages. However, the importance to consider embodied impact from stages A1-A5 is emphasized since the mitigation of environmental impact in the short term is crucial. In addition, these stages include the most certain data (Gibbons & Orr, 2020).

A criticism against this type of assessment is the fact that it is not capturing a comprehensive prediction of the environmental impact, compromising the holistic purpose of LCA. Reducing the assessment only to carbon footprint as a proxy indicator for the environmental impact introduces risk for suboptimization due to burden shifting to other impact categories (Laurent et al., 2012).

Nevertheless, the reduction of impact categories is used to simplify the interpretation and communication of results for non-experts, supporting decision making (Beemsterboer et al., 2020).

2.4 Literature review

A review of previous studies was performed regarding the integration and combination of LCA and BPA in early design stages. A special focus was on the integration and use of simulation tools in the architects' design process. The review covered the following two topics:

- Barriers for the integration of LCA and BPA in early design stages
- Requirements on tools applicable in the early design stages

Due to the rapid development in the field and the development of simulation tools, special attention was put on the temporal aspects of the reviewed literature. Hence new studies were prioritized to older ones. However, some older papers were reviewed since they contributed with valuable insights about aspects considered to be consistent on long-term.

Since this project is conducted within the Swedish context the goal was to find literature relevant to the Swedish industry. However, studies on the national situation in Sweden were lacking hence the author suggests this as a subject for further studies. The literature was mainly retrieved from ResearchGate, ScienceDirect and Web of Science and the typical search blocks used in the search are presented in Table 9.

Table 9 Combinations of the search blocks A-C were used in the search.

A	B	C
LCA	Building design	Barriers
BPS	Early-stage design	Challenges
BPA	Conceptual design	Limitations

In this review, the identified barriers have been categorized into the four areas of origin: user, resource, methodology and demand barriers, according to the structure in Table 10.

Table 10 Method for categorizing the identified barriers

Structure of categorizing barriers	Example
Origin	User
Category	Knowledge
Barrier	Difficult interpretation

The search for barriers was limited to surveys and interviews with architects as respondents and focus on the architectural design process. This was done to capture the perspective of a large set of practicing architects to provide an overall picture beyond the individual differences between architects.

2.4.1 Barriers for application of LCA and BPA in early stages

In summary the following barriers, compiled in Table 11, have been identified in the studies.

Table 11 Barriers identified in the review.

Origin	Category	Barrier
User	Knowledge	Lack of knowledge how to perform LCA/BPA
		Lack of knowledge of how to use tools
		Lack of awareness regarding LCA/BPA
		Absence of LCA/BPA expertise in early stages
		Difficulty to interpret results
		Difficulty to turn results into design decisions
		Lack of information about the building
		Lack of data regarding LCA/BPA
	Attitude	Limited motivation of using LCA/BPA
		Results not allowed to influence design
		Concerns it will compromise architectural quality
Resources	Time	Limited time allocated to early stages
		Time for use of tools
	Cost	Limited economy allocated to early stages
		Financial uncertainty in early stages
		Cost of tools
		Cost for use of tools
Methodology	Responsibility	Distribution to other disciplines
		Distribution to later stage of design
		Not considered in domain of architects
	Workflow	Discrepancy between design process and LCA/BPA workflow
		No common praxis of how/when to integrate LCA/BPA
		Tools not compliant with the design process
		Inconsistent workflows between architects and engineers
	Communication	Deficient communication between architects and engineers/ consultants
Demands	Client	Lack of client demands
		Lack of awareness/ knowledge of clients
	Regulations/ Certifications	Lack of demands
		Demands not stressing early stages
		Lack of reference values

The references reviewed are compiled in Table 12.

Table 12 References included in the review.

Reference	Topic	Study	Respondents	Region
Jusselme et al. 2020	LCA	S	495	Europe
Lamé et al. 2017	LCA*	I	30	France
Mahmoud et al. 2020	BPS	I+ S	6+418	UK
Petersen et al. 2014	BPS	I	5	Denmark
Weytjens & Verbeeck 2010	BPS	I + S	9+629	Belgium

I= Interview, S=Survey, *eco-design

Table 13 provides an overview of the categories of barriers covered by the reviewed studies presented in Table 12. User barriers are related to the professionals involved in the early design stages, mainly architects, while resources cover the available budget and access to adequate tools. The methodology category includes the workflow and collaboration between disciplines. Finally, demand barriers are related to the requirements from the industry and market. This structure is used to support the identification of barriers and the comparison between LCA and BPA.

Table 13 Overview of barriers in the studied references.

		(Jusselme et al., 2020)	(Lamé et al., 2017)	(Mahmoud et al., 2020)	(Petersen et al., 2014)	(Weytjens & Verbeeck, 2010)
Origin	**Category**	**LCA**	**LCA**	**BPS**	**BPS**	**BPS**
User	Knowledge	X	X	X		X
	Attitude			X	X	
Resources	Time	X	X		X	X
	Cost		X		X	
	Tools	X	X	X	X	X
Methodology	Responsibility	X		X		X
	Workflow	X	X		X	X
	Communication	X			X	
Demands	Client	X	X	X		
	Regulations/Certifications	X	X	X		X

Barriers related to LCA application

Jusselme et al. (2020) performed a survey with 495 respondents, mainly architects. The focus was on the use of LCA tools in early design stages from a user centered perspective. It was found that the cost of use of the tools is a larger barrier than the cost of the tool itself. In general, tools involve high effort for input data and provides low design support. This limits the use, especially in the early stages, where projects are financially uncertain.

The survey also highlighted a lack of requirements from the clients which is reflected in a low market demand. It is a contrast to the scientific society and the engineers' and architects' general attitude towards this subject.

Lastly, Jusselme et al. identified issues in the collaboration between architects and engineers that is reducing the uptake of LCA methods in early stages. There is an inconsistency in the respective work methodology. It is common for architects to work on their own in early stages and when engineers are involved, they are struggling with implementing their knowledge in the design process. Rather than evaluating the design, the assessments need to contribute to the exploration of the design space, support the design and be understandable for the designers.

Lamé et al. (2017) studied the use of eco-design tools, tools to evaluate environmental impact, in the French building industry, focusing on the design of buildings. Through 30 interviews they formulated seven main issues for practicing eco-design, two of which were a low level of both environmental and technical data known for the building. The major issues were, however, related to the interpretation of the results which includes difficulties to detect whether the performance is good or bad, how to compare environmental performance with other building criteria, and difficulties to capture and compare the effect of different design choices.

Lamé et al. further describe a situation where there is a shortage of environmental consultancy, or expertise, involved the early design stages. In addition, the rigid and sequenced structure of the building design process, with specific deliveries for each phase, is hindering the implementation of integrated design and the development of parallel solutions. The building industry is also depicted as having a reactive rather than a proactive culture, as the assessments are mainly done in the late stages, when the design cannot be influenced. The effort invested in the use of expensive tools is instead limited to meeting the minimum requirements from legal and client demands. The study concluded that the main problem is not to get even more detailed tools with even higher capacity, instead it is rather to turn the results of the assessments into design decisions.

Barriers related to BPA application

Mahmoud et al. (2020) performed a large-scale survey with 418 respondent architects and conducted six interviews with representatives from renowned architecture companies. The aim was to identify limitations for the implementation of BPS tools in early stages in the UK practice, focusing on energy simulations. The study found limited knowledge among architects on the topic and that the current building regulations do not stimulate a wider and deeper interest in applying BPS in early design stages among architects. Instead, the entire responsibility is allocated to the building services engineer.

Another barrier found was the absence of demands and investments from the clients. However, Mahmoud et al. describe this as a consequence of insufficient knowledge from the designer. While lack of knowledge, described on various levels above, was considered the largest barrier, Mahmoud et al. discovered that the cost of using the tools is the second largest. BPS tools, still today, are described to suffer from poor user interfaces, data handling and difficulties to interpret the results.

In interviews with five representatives from architecture companies in Denmark Petersen et al. (2014) explored the collaboration between architects and engineers and the use of BPS tools in early design stages. Barriers like the limited budget allocated for the early stages of design and a lack of suitable tools were identified. The interviews also revealed that some performance issues (indoor climate) are considered irrelevant in this stage of design as the issues are in the responsibility of building service engineers.

Petersen et al. also found a concern that measurable engineering issues are valued higher than the softer, often non-measurable architectural design features. Finally, a large limiting factor is the mismatch between the engineering and the architectural approach. The engineering work process is perceived as slow due to detailed calculation in comparison to the architectural design process with quick judgment and exploration.

Weytjens and Verbeeck (2010) investigated the requirements on applicability of energy simulation tools in early design stages. A survey with 629 respondents and an interview with nine architects revealed that energy simulation tools mainly was used to meet the legal demands and that the use was primarily in the detailed design stage. The main reasons for not using energy evaluation tools were found to be lack of time and that it was not considered to be within the domain of the architect profession.

In essence, Weytjens and Verbeeck (2010) found a discrepancy between and the architectural design process and tools which generally required too detailed input data for application during design. They derive common tool properties typical for good applicability in the early design stages, such as: interpretable output, easy input, simple operation, fast calculations, and use of default values among others.

2.4.2 Tool requirements

Digital tools are developed to simplify the application of LCA and BPA in building design. However, sometimes barriers exist within the tools themselves when they are insufficient to address the intended aspects (Lamé et al., 2017).

To guide the development of tools suitable for the architectural design process the conversion of barriers into a specification of requirements can be done. Based on interviews and a survey Weytjens and Verbeeck (2010) created a framework covering aspects that makes BPS tools suitable for architects. The aspects were divided into five categories: data input, data output, interface, usability in design process, and general tool properties. Meex et al. (2017) started from the framework developed by Weytjens and Verbeeck and, through a large-scale survey, interviews, and a focus group, adapted the framework to suit environmental impact assessment tools in early design. The main aspects covered in the five categories in the frameworks are summarized in .

Table 14.

Table 14 Summarized requirements for tools applicable in the design process (Meex et al., 2017; Weytjens & Verbeeck, 2010)

	Requirements
Data input	• Intuitive, quick, and limited data input in the same level of detail as the design stage. The input should also be properties known by and relevant for the architect • Default values and settings provided. Library with materials and building components • Quick creation of different design options • Connection to the architect's 3D model
Interface	• Intuitive and flexible • Simplicity, only a limited set of functions provided
Data output	• Easy interpretation of results. Simplified, clear and limited output • Design supportive, indication of problem areas • Graphical/visual presentation of results connected to parameters related to the architect • Comparison of different designs, show influence of design choices • Comparison with reference values.
Usability in the design process	• Minimal interruption of the design process, input consistent with the design stage • Quick operation of the tool to create and compare alternative solutions • Guide the further design work
General	• Easy to learn and use after a long-time non-use • Transparency of the tool towards the user • Adaptable default values

3 Tool Review

This chapter explains the method of the tool review and the corresponding results. In part, the tool review has previously been described by Säwén et al. (2022a, 2022b).

3.1 Method

The tool review included the study of existing tools within the repositories of Grasshopper3D libraries targeted for early design stages. This delimitation was made since Grasshopper offers the benefit of a direct connection to a modelling environment. The review evaluated existing workflows and approaches in a parametric environment for LCA and BPA appropriate to implement in the tool development. The aim was to identify differences in the approaches between LCA and BPA which is needed to be considered when integrating them into a common interface. Ultimately the conflicting aspects identified in the review formulated a set of main takeaways brought into the tool development. The review included the compilation of a tool inventory and detailed tool review.

Tool inventory
A search for existing LCA and BPA plug-ins was done, and the results compiled into a tool inventory. Additionally, the tools were categorized according to the approach for integrating LCA and BPA in the design tool.

The categorization was based on the proposed scheme including five integration approaches of LCA and BIM tools by Wastiels and Decuypere (2019). In this review, three types of approaches were identified, shown in Figure 20, covering the context of parametric design and plug-ins for integration of LCA and BPA in a design tool.

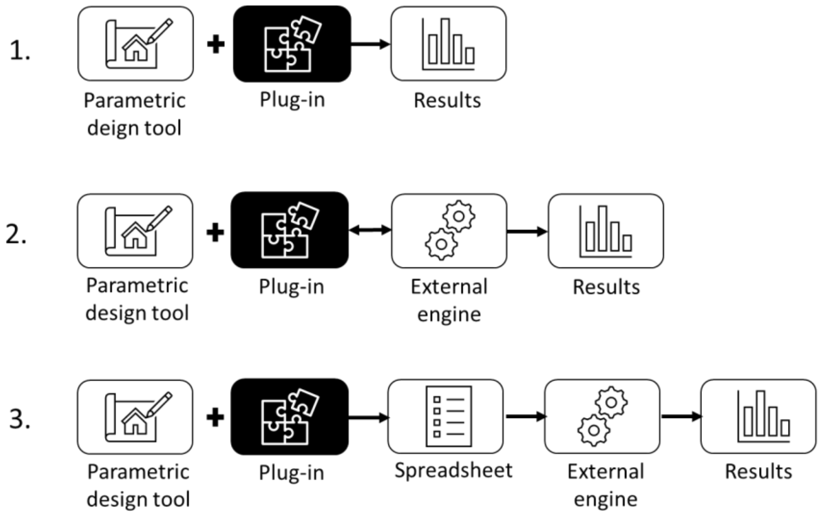


Figure 20 Approaches for plug-ins implementing LCA and BPA calculations in parametric modelling. Inspired by Wastiels & Decuypere (2019).

In the first approach calculations are integrated within parametric environment and no export of data is needed. In the second one, the plug-in is designed to connect to an external engine for analysis. Approach number three is similar to the second but with the intermediate step where the building information is exported to a spreadsheet format and then further processed in a designated engine.

The main source to find the tools was the plug-in community food4Rhino, which is a service provided by McNeel, the developer of Rhino. It is the location containing the latest plug-ins and add-ons for Rhino and Grasshopper (Food4Rhino, 2022b).

Detailed review

The purpose of the detailed review was to study plug-ins in detail regarding their approach towards parametric integration of LCA and BPA. Focus was on workflow, adaptability and required knowledge from the perspective of early architectural design stages and use by non-experts.

A test case was used to examine the principal workflow and functionality of the plug-ins. It was done for a simplified case based on a box with one window which was predefined and modelled with surfaces in Rhino. The geometry was then referred into Grasshopper and each of the plug-ins from the detailed review were explored based on the test case. The resulting scripts can be found Appendix A.

The detailed tool review followed the approach presented by Bach and Hildebrand (2018) regarding comparison of LCA software through a characterization based on several categories. Bach and Hildebrand specify eight categories: origin, data source, required user knowledge, accessibility, entry format, level, default settings, and LCA phases. By evaluating the software for each category, a comprehensive comparison of the tools is established.

However, the categories evaluated in this thesis were adapted to suit the purpose of the tool review and capture the main characteristics of the plug-ins regarding their integration in the architect's workflow. For this, eight categories were formulated and divided into two parts: workflow, and scope of LCA/BPA. The categories and their explanations are compiled in Table 15.

Table 15 Categories used to review the tools.

Category		Classification	Explanation
WORKFLOW	**Required knowledge**	Low Moderate High	Low: materials/component types Medium: material/ component properties High: calculation/ methodology principles
	Geometry input	Surfaces Volumes Curves	Type of Rhino/Grasshopper geometry accepted by the plug-in.
	Adaptability	Low Moderate High	Low: adaptable input/default values. Medium: adaptable analysis settings High: adaptable scope of analysis
	Modelling level	Material level Component level Building level	Level of input specification of the analysis settings.
SCOPE OF LCA	**Intended application**	Education Early design stages Complete assessment	Purpose of development and use of the tool.
	Data source	Material database	Specify the database that is used and eventual possibility to use other databases or import own materials and components.
	LCA modules	A1-A3; A4-A5; B1-B7; C1-C4; D	Included LCA modules from EN15804
	Impact categories in addition to GWP	Yes / No	Impact categories included in the plug-in in addition to GWP
SCOPE OF BPA	**Intended application**	Education Early design stages Complete assessment	Purpose of development and use of the tool.
	Building performance analysis	Daylight Sunlight Energy	Type of analysis
	Complexity of input	Low Moderate High	Low: material, type of building, location Moderate: material/ building properties High: load/user schedule, technical systems
	Type of simulation	Steady state Quasi-steady state Dynamic	Static calculations Monthly timesteps Timesteps of 1 hour or less

3.2 LCA tool review results

This chapter covers the review of LCA tools.

3.2.1 Tool inventory

The LCA plug-ins found relevant for the scope of this thesis are compiled in Table 16. Each tool is categorized according to one of the three types of approaches presented in Figure 20.

There is a distinction made between embodied carbon assessment (ECA) tools and LCA tools in this review. ECA tools only consider the life cycle stages A1-A3 and exclusively evaluates the global warming impact, whereas tools classified with LCA scope consider a more complete life cycle of the building and/or several impact categories.

Table 16 LCA tool inventory, with plug-ins brought into the detailed review highlighted.

Tool	Developer	Scope	Type
BHoM LCA toolkit	**Buro Happold**	**LCA**	**1**
Bombyx	**ETH Zürich**	**LCA**	**1**
CAALA**	CAALA GmbH, Alexander Hollberg	LCA	2
Cardinal LCA	**Chen J., Kharbanda K., Loganathan H.**	**ECA**	**1**
COVE	cove.tool	LCA	3
E2B2 LCA tool*	IVL Svenska Miljöinstitutet AB	ECA	3
IDGB	Department of Civil Engineering, DTU	LCA	1
One Click LCA**	Bollinger+Grohmann, One Click LCA	ECA	1
Tortuga	**Maximilian Thumfart**	**ECA**	**1**
ZEB-tool**	Norwegian ZEB research centre	LCA	3

*Currently in development
**Grasshopper plug-in integration to existing LCA software

The most common approach identified in the tool inventory shown in Table 16 is type 1, that is, the implementation of the calculations within the Grasshopper environment. It utilizes the benefit of Grasshopper enabling the assembly of all analyses within the same workspace.

3.2.2 Detailed tool review

In this section, the BHoM LCA toolkit, Bombyx, Cardinal LCA and Tortuga are further reviewed focusing on workflow and connection to early-stage design. These were selected since the calculations are integrated within the parametric environment but offer alternative workflows.

A summarized comparison of the tools is presented in Table 17, based on the categories in Table 15, covering the workflow characteristics and scope of the LCA in the tools.

Table 17 Overall comparison of characteristics of the LCA tools.

	Category	BHoM toolkit	Bombyx	Cardinal LCA	Tortuga
WORKFLOW	**Required knowledge**	Moderate High	Low Moderate	Low	Low Moderate
	Geometry input	Surface, Curves, Volumes, Points etcetera	Surfaces	Surfaces Volumes	Surfaces, Volumes Curves,
	Adaptability	High	Moderate	Low	Low
	Modelling level	Material	Material; Component Building	Material	Material
SCOPE OF LCA	**Intended application**	Design evaluation	Education Design evaluation	Design evaluation	Design evaluation
	Data source	Quartz, ICE,EC3, Boverket, Ökobaudat,EPiC	KBOB EcoKomposit Bauteilkatalog	EC3 ICE V3.0	Ökobau.dat Quartz
	LCA modules	All modules available	A1-A3; A4-A5; B4; B6; C1-C4	A1-A3	A1-A3; C3; D
	Impact categories in addition to GWP	Yes	Yes	No	Yes

3.2.2.1 BHoM LCA toolkit

The Buildings and Habitats object Model (BHoM) is an open-source project developed by BuroHappold to improve collaboration in computational development across disciplines in the built environment (Fisher, 2020).

The LCA toolkit was added to its repository in 2020. The intention was to provide a tool for building designers to quantify the environmental impact, mainly embodied carbon, of the designs in a transparent way throughout the entire design process (AIA, 2020).

Workflow

The overall workflow of the BHoM LCA toolkit is built upon a hierarchy of the four levels Scope, Objects, Materials and Datasets. The modelling of the LCA starts with specifying the scope in which the outline of the assessment is defined. Thereby the life cycle stages, impact categories and building elements included are stipulated. In this way a consistency in the assessment is achieved. Objects are then connected to the scope from the model and assigned a material from the datasets included in the toolkit (Hoehn, 2021).

Adaptability

The adaptability of the BHoM LCA toolkit is high, primarily due to the scope objects where one can define the entire scope of the LCA and thereby increase the extent of the assessment or narrow it down. The vast number of options by the inclusion of several databases, impact categories and LCA modules makes it a versatile tool throughout the entire design process.

Required knowledge
The high adaptability and its optional settings demand knowledge from the user mainly regarding the scope definition of the assessment. This is required to achieve a consistency between the results of the LCA and its application to the design process. Nevertheless, it still has the capability to be used as a simplified assessment suitable for early stages.

3.2.2.2 Bombyx

Bombyx was created for implementation in the architecture and engineering education at ETH in Zürich and is heavily Swiss oriented (Basic et al., 2019b). The plug-in consists of 24 components sorted into five panels. The reviewed version is Bombyx 2.0.8.

Workflow
The LCA procedure in Bombyx is structured into two approaches, bottom-up and top-down, and the integration of predefined materials, components and building typologies allows for modelling on several level of details.

The top-down approach allows for analysis on a building level. The workflow starts with specifying parameters such as building size, intended use, the energy performance standard, and main structural material. These four specifications together with the building geometry organized into building elements is all information needed to perform the analysis.

The bottom-up approach is based on the conventional methodology and requires more information about the building but is offering a more detailed assessment and transparency. In this approach the workflow starts with assigning material properties to the layers and thereby building up the inventory of materials in the building whose impact is summarized for the entire building. The result in this approach is divided into embedded impact, replacements, and end-of-life, and thereby it captures the life cycle stages of the building materials.

Both approaches include operational energy calculations that are presented separately with monthly results on energy demand and total impact (Basic et al., 2019b). Calculations of impact from transport of material and people, as well as impacts from building services are also included.

Adaptability
Altogether, the combination of the two approaches extends the applicability of the tool in the design process, from the earliest stages where comparison of the main features and system of the building is done, such as structural concept and building geometry, until the assessment on material level. Thereby the potential use of the tool is extended from quick simple assessments into more detailed calculations. This makes it possible to adapt the tool after the available time and, known information and purpose of the assessment.

Required knowledge
For the top-down application of the project there is a low level of knowledge required to be able to use the tool, as most of the assumptions and limitations are built into the components. However, special attention is needed in the interpretation to be aware of the implied assumptions. For the bottom-up method

the detail of the analysis is increased, demanding more technical knowledge. The user is then required to specify, among other factors, type of material, thickness, service life, thermal properties, transport distances, energy and building services.

3.2.2.3 Cardinal LCA

Cardinal LCA is a plug-in created for early-stage assessment of environmental impact of buildings. It is intended to be used by non-LCA-experts, to make conscious decisions in the concept stage of building design (Chen et al., 2021). It is developed by Jessica Chen, Kritika Kharbanda and Hariprasath Loganathan. The reviewed version is Cardinal LCA v0.01 from 2021.

Workflow
The plug-in consists of eleven components sorted into four categories: import, material selection, compilation, and output. These categories define the workflow provided by the tool and are easily overviewed. It follows a bottom-up approach where the geometry in separate in layers are assigned material and then summarized into the total building impact.

Adaptability
Overall, Cardinal provides a predefined standardisation of the LCA methodology, and the functionality is therefore limited to its specific scope, only including modules A1-A3 and calculation of GWP.

The tool allows for material data from both ICE database and EC3 database with either specific manufacturer data or average data. There is also an option to customize your own material by providing a material name, material category and specify density and global warming potential.

Required knowledge
Due to its streamlined approach Cardinal LCA is easily overviewed and there is a visual and coherent relation between the inputs and the results through hotspot visualization. Hence the effect of design changes is easily observed in early stages.

3.2.2.4 Tortuga

Tortuga was developed in 2015 by the software developer Maximilian Thumfart. The intended application of the tool is to assess the environmental impact of materials used in construction of buildings focusing on global warming potential (Thumfart, 2016). The plug-in is built up by 14 components divided into four panels.

Workflow
Tortuga is based on a LCA modelled from the material level. Materials are selected from the database and assigned to corresponding geometry (volumes, surfaces, lines). The LCA results are then calculated by summation of all included materials and given as total values separated into six impact categories, including GWP.

Adaptability
The functionality of the plug-in offers the choice of which of the LCA modules to include in the assessment as well as results separated into several impact

categories. In that way the scope of the LCA can be altered to some extent. There is also a possibility to import a database in CSV format.

Moreover, Tortuga allows for several types of geometries as input. Such as surfaces, volumes and curves making it possible to use for a more intricate 3D model.

Required knowledge
In its fundamental sense Tortuga is to large extent offering similar functionality as Cardinal LCA. Nevertheless, the experience is that it demands more of the user. There are no default settings or predefinitions except the included databases that simplifies the procedure.

3.2.3 Summary and comparison

To summarize the main characteristics of the reviewed LCA tools, the most defining feature is the amount of LCA expertise integrated within the tools and how much responsibility that is left for the user. It can be described as the degree of standardization of the LCA framework. The consequence of predefining and structuring the methodology is a narrowed scope of assessment in the tools. Subsequently, the flexibility is reduced.

This was exemplified in the review as the BHoM toolkit and Bombyx were considered to possess high adaptability and potential to be applied further along the design process, whereas Cardinal LCA and Tortuga had a clearer purpose of application and an obvious relation between input and results.

The general approach in the tools is to assign material to the organized geometry. Either material by material or component by component and the conversion of input to output is logical to follow.

The top-down procedure in Bombyx on the other hand expands few simple inputs into more comprehensive results based on the built-in assumptions and expertise. However, this holds only true to some level, in the earliest design stages until the assumptions are overruled by detailed specifications. This forms the discussion about the role of assumptions in early stages. They are necessary for being able to perform assessments and guide the design but at same time introduces hypotheses that may not be valid in the next stages of design.

3.3 BPA tool review results

This section contains the outcome of the tool review of BPA plug-ins for Grasshopper.

3.3.1 Tool inventory

The BPA tools identified in the inventory are compiled in Table 18. There are many tools related to the field of energy, daylight and sunlight and various types of analysis. Therefore, the inventory is limited to tools relevant for this project.

Table 18 BPA tools found in the inventory. The plug-ins written in bold style were brought into the detailed review.

Tool	Developer	Scope	Type
BeDOT	**Bengt Dahlgren AB**	**Energy**	**2**
ClimateStudio	**Solemma**	**Daylight, Solar, Energy**	**2**
Daylight_VK-01	Vandkunsten	Daylight, Sunlight	2
GECO (Ecotect)	Uto, Ursula Frick and Thomas Grabner	Daylight, Solar, Energy	2
ICEbear v. 01.00.00	**Aarhus University (AU)**	**Energy (Daylight)**	2
Ladybug + Honeybee	**Ladybug Tools LLC, Mostapha Sadeghipour Roudsari**	**Daylight, Solar, Energy**	**2**
TRNLizard	TRANSSOLAR	Daylight, Energy, Solar	2

3.3.2 Detailed tool review

In this section, BeDOT, ClimateStudio, ICEbear and the Ladybug + Honeybee are further reviewed, focusing on workflow and connection to early-stage design. Ladybug + Honeybee and ClimateStudio were selected due to their rich variety of analysis types, and BeDOT and ICEbear for their alternative workflows.

A summarized comparison of the tools is presented in Table 19, covering the workflow characteristics and scope of the BPA integrated in the tools covered by the categories described in Table 15.

Table 19 Overall comparison of characteristics of the LCA tools.

Category		BeDOT	ClimateStudio	ICEbear	LB+HB
WORKFLOW	**Required knowledge**	Moderate High	Low Moderate High	Low High	Low Moderate High
	Geometry input	Surfaces Volumes	Surfaces Volumes	Surfaces	Surfaces Volumes
	Adaptability	Low	High	Moderate	High
	Modelling level	Zone/Building	Zone/Building	Zone/Building	Zone/Building
	Output of results	Report Surface coloring	Report,Charts Surface coloring	Report Charts	Charts Surface coloring
SCOPE OF LCA	**Intended application**	Early design stages	Early design stages	Early design stages	Education Early design stages
	Building performance analysis	Energy Solar*	Energy Solar Daylight	Energy Solar* Daylight**	Energy Daylight Solar
	Complexity of input	Moderate	Low Moderate High	Low High	Low Moderate High
	Type of simulation	Dynamic	Dynamic/Quasi-steady state	Dynamic	Dynamic

*Solar heat load is calculated in the energy analysis

**Includes possibility to connect to daylight calculations e.g., from Honeybee

3.3.2.1 BeDOT

Building Early-stage Design Optimization Tool (BeDOT) is a tool developed by Bengt Dahlgren AB. This review focuses on the energy performance simulation part in the updated version of the script (BeDOT v1.3) developed by Fantin do Amaral Silva and Bergel Gómez (2018). It should be made clear BeDOT today is extended and further developed. Access to the tool was granted by Bengt Dahlgren AB.

Workflow

BeDOT includes seven modules: 0. Pre-processing, 1. geometry, 2. ground modelling, 3. solar radiation, 4. energy, 5. visualizing and 6. post-processing and data export. The data flow and calculations follow this order, downstream.

In the pre-processing module all inputs are retrieved. Geometry is imported from Rhino and the specification of properties, like internal heat gains, ventilation rates, U-values, and time schedules, are defined in an excel file.

The input is adapted and processed with the help of Honeybee, Ladybug and Daysim to create thermal zones with specified properties to run solar analysis for the solar gains. The energy calculation is performed within a component written in python and provides heating/cooling energy and power demands based on the calculation procedure in EN13790:2008 with hourly time steps. The results can then be visualized on the geometry or reported back to the excel file.

Adaptability

The users' possibilities to adapt the tool in different situations is mainly constrained to the Excel file and to Rhino. The Grasshopper script is mainly working as the calculation engine. A large benefit of moving the input specifications to an external Excel file is that the user is in full control of all data compiled in a commonly used environment as Excel and it is easy to save and document alternative settings and thereby evaluate alternative solutions.

The data required in the Excel file is primarily on a system level focusing on components, zones or building properties. This means that one can easily adjust these values to assess large changes in building design without extensive remodelling.

Required knowledge

Since the tool is packaged as a Grasshopper script rather than condensed into a plug-in it is to some extent harder to get a quick overview of the tool. Nevertheless, this provides a transparency to the user, and it does follow a clear and hierarchical logic.

The primary interfaces when using the tool and assigning input data are Excel and Rhino. This can be an advantage since one can assume Excel is known by the user and Rhino is used a design tool. However, the input in Excel requires detailed information and knowledge from the user, both about the building itself and about building technology. It is applied separated from the geometry and specification of, for instance, U-values and heat capacity, that depend on the choice of construction type and material is only applied as numbers, lacking the connection on influence of architectural design choices.

3.3.2.2 ClimateStudio

ClimateStudio is a software developed by Solemma LLC (Solemma LLC, 2022). It provides an extensive set of environmental analyses regarding daylight, sunlight, and thermal simulations among others. The tool is built on EnergyPlus and Radiance and is a plug in for Rhino and Grasshopper.

Workflow
The workflow in ClimateStudio is structured in the same way independent on whether the aim is an energy, daylight or sunlight analysis. Properties are assigned to the geometry which is then combined into a thermal or daylight model which is then passed into the simulation engines together with climate data from EnergyPlus weather files (EPW).

The construction of daylight models requires geometry with assigned material properties as well as sensor grids on the analysis surface. The thermal model requires thermal zones which are constructed of geometry with assigned thermal properties, and a program assigned to it, containing the thermal loads within the zone and their respective scheduling.

Adaptability
The input required to perform simulations in ClimateStudio can be defined on various levels. Materials, loads and schedules can either be entirely defined by the user or selected from the extensive library containing predefined settings. In the thermal model, the constructions can be built up by defining several material layers or chosen from predefined construction types in the database. This means that it is possible to quickly model on predefined values or to customize the model to capture a specific design.

The simulations are easily adaptable regarding resolution, analysis period and weather conditions and the results can be plotted on the model itself as surface coloring or in charts by the provided visualization components.

Required knowledge
Since ClimateStudio is offering a high flexibility, with various assessment types, it is adaptable to the earliest of design stages where the knowledge of the building is limited, but it also possesses the potential to be applied further into the design process with increased detail. Therefore, the required knowledge of the user depends on the application of the assessment.

3.3.2.3 ICEbear

ICEbear is a plug-in for building performance energy modelling developed at Aarhus University. It is aimed to be suitable to early design stages and was initially developed for Grasshopper, but also works with Sketchup and will be extended to Revit as well. Solar heat gain calculation is implemented in the energy calculation and there is a possibility to connect to daylight calculations performed in Honeybee or DIVA (idbuild.dk, 2022). The reviewed version is v 01.00.00.

Workflow
The workflow in Grasshopper when using ICEbear is very simplified. The only input data needed is the geometry divided into roof, external walls, floor,

windows, and floor facing ground. There is also possibility to add external shading geometry. When the geometry is set, one open a separate user interface where one selects number of occupants, location, glazing system and a zone template containing the data needed for the thermal simulation. By running the simulation one can then get both simplified and detailed results about energy demand, thermal comfort, daylight, and air quality.

Adaptability
The interface is adapted for quick modelling without the need for detailed information about the building. Instead, predefined templates for different type of use are provided. However, the tool contains the option to open these templates and in detail change the settings for the simulation. Looking at the simplified interface it is oriented towards the use by non-experts. The adaptable parameters are instead concentrated on the geometry itself and material properties, aspects which are closely related to architectural design in early stages.

Required knowledge
The tool is built in a way that non-experts easily and quickly can set up models and simulate the performance. It can be done by only provide the geometry and then make four selections: location, number of occupants, glazing type and a zone template. However, for both the input and the output more detailed options are provided. One can open and specify detailed simulations settings and the results can be investigated further by the detailed results.

3.3.2.4 Ladybug Tools (Honeybee + Ladybug)

Ladybug Tools is an open-source project consisting of a set of plug-ins for environmental design. In this review, the plug-ins Ladybug and Honeybee is studied. The Ladybug plug-in itself is created for analyzing weather data and provides e.g., sun path, thermal comfort, and wind analysis. Honeybee, in turn, is a plug-in establishing a link between EnergyPlus and Radiance. Hence it provides possibilities for both energy and daylight simulations (Ladybug Tools, 2022).

Workflow
The workflow in Honeybee starts by converting Rhino geometry into Honeybee Faces which is needed to create Honeybee Rooms and Honeybee Models. While the geometry and assigned material properties are enough to run a daylight or sunlight analysis, the energy simulations also require the definition of boundary conditions, thermal zones and programs assigned to the zones which contains the thermal loads scheduling. In addition, weather data and location are needed for all types of analysis, retrieved from EPW-files and sky models.

When the type of analysis is selected, and the analysis settings are defined the respective analysis is running via the respective simulation engine. Radiance for daylight and EnergyPlus for energy performance. The results are then easily visualized by coloring of grid or meshes which is included in several of the simulation components.

Adaptability

The extensive library of analysis and simulation models implemented in Honeybee and Ladybug allows for using the plug-in in many types of assessments along the design process. In addition, there is a large flexibility within each of the analysis types. Material properties and loads can be selected from a predefined database or specified entirely by the user. Meanwhile, simulation period, resolution and climate models can also be selected according to the purpose of the analysis.

Required knowledge

The various analysis types and climate models implemented in the plug-in require the user to decide when to apply the different simulations and how to set them up properly. The required knowledge very much depends on how detailed one wants to perform the simulation and for what purpose.

3.3.3 Summary and comparison

The experience of the reviewed BPA tools was to a large extent based on the sequence of choices the user must make to go from model to the simulation results. In this aspect, the ICEbear and BeDOT provided a rigid structure of the workflow, and the assessments were in this aspect standardized for the user.

Ladybug, Honeybee and ClimateStudio distinguish themselves from the previously mentioned BeDOT and ICEbear in the way that they are providing a wide set of simulation types and settings on several levels of detail. In that way the user can tailor the script to the specific use in a more extensive way. The workflow is in many aspects similar between Ladybug and Honeybee and ClimateStudio.

BeDOT and ICEbear provide a strict scope of the assessment and thereby contain a robustness of the tool ensuring consistent output, while the flexible nature of Honeybee, Ladybug and ClimateStudio makes them more dependent on the user but have the upside with possible application in a wider set of situations.

3.4 Comparison between LCA and BPA tools

This section covers the comparison of the main characteristics identified for the LCA and BPA tools in the review, compiled in Table 20.

Table 20 General characteristics in the review of LCA and BPA tools.

Characteristics	LCA tools	BPA tools
Required knowledge	Low/moderate	Moderate/high
• *Input in addition to geometry*	Material data	Material properties Analysis period Climate data Occupancy behaviour Schedule of loads Technical system
Workflow		
• *Sequence of modelling*	Material -> Component ->Building	Material/Component -> Thermal zone -> Building
Adaptability	Geometry (high) Calculation model (low)	Geometry (low) Calculation model (high)
• *In modelling of geometry*	Low requirements for compatibility with calculation model	Simplified model required for simulation
• *In Calculation model*	Generally strictly defined, well defined impact categories, LCA modules and reference study period	Adjustments of analysis type and settings: analysis period, climate conditions, schedules etc
Geometry input	Surfaces, volumes, (lines)	Surfaces, (volumes)
• *Function*	Representing quantities	Boundary conditions, analysis planes

In general, the BPA tools required deeper knowledge about the implemented calculation models. The LCA tools are built upon a clear methodology from the LCA framework, and the standardized assessment is to a larger extent predefined than the analysis types in the BPA tools. In addition, the building performance assessments involves to a larger extent input beyond geometry and material data. Specification regarding climate, technical building systems and occupancy behaviour makes the modelling more complex.

One source for the difference in the workflows of the tools is believed to be the implementation of the geometry. In the LCA tools, the geometry is in its fundamental sense used to establish a bill of quantities, converting geometry into amounts of materials or components. Hence, there are low constraints on the definition of the geometry, only requiring an organization into material or component types. In the BPA tools, geometry is more integrated in the simulation models which require defining boundary conditions and analysis planes. This imposes an importance of the spatial definition of the geometry in the BPA tools.

This is reflected in the adaptability in the tools. Where the geometry can more easily be adapted into the LCA workflow, the BPA tools demand a stricter, simpler, and more hierarchical definition of the simulation model into components and zones or analysis planes.

Further, as previously mentioned the LCA tools is built on a to a larger extent standardized methodology, as the BPA tools shows a wider diversity in types of assessment, which creates a discrepancy in the allocation of the adaptability in the tools.

3.4.1 Main takeaways

Based on the experience and attributes found in the tool review a set of main takeaways have been identified. These are brought into the tool development to deal with the aspects discovered in the review.

- BPA is considered to be the limiting aspect when integrating the workflows due to stricter requirement on geometry modelling and more additional input needed beyond the building design.
- The common level of BPA and LCA is the material and component level, then BPA requires additional input and modelling on zone and building level.
- The assessments and calculation models should be transparent, yet not adaptable in its scope to ensure consistency in the results of the tool regardless the users' prerequisites.
- The input data should be limited to aspects and information about the building relevant for, and known by, the architect in the early design stage.
- The detail of the input should be at the same level as the design, excessive input definitions slow down the use of the tool and increases complexity beyond the level design itself.
- The assessments should not depend on occupancy behaviour.

It is important to remember that the nature of Grasshopper, VPL and parametric design in general, allows for various approaches in modelling and scripting. Hence it can be utilized in many ways. Therefore, one should be aware that the outcomes of this review are specific to this project.

4 Tool Development

This chapter presents the method and the results from the process of the tool development.

4.1 Incremental Prototyping Method

The development of the tool was done with an incremental prototyping method. This means that the tool was divided into several prototypes, which were developed (built, tested, and improved) in parallel (Ganney et al., 2020). In this project it was utilized for the separate development of LCA, energy, daylight and sunlight prototypes which then was merged into the final tool. This is visualized in Figure 21.

This method is useful for developing software consisting of multiple modules which can be separated in the development. It is also identified to be suitable for development in a visual programming language like Grasshopper, since the prototypes can easily be connected to each other without major remodeling, which had been the case in text-based coding language. However, it is important to specify common principles for the prototypes to achieve consistency in the final tool (Hull, 2020).

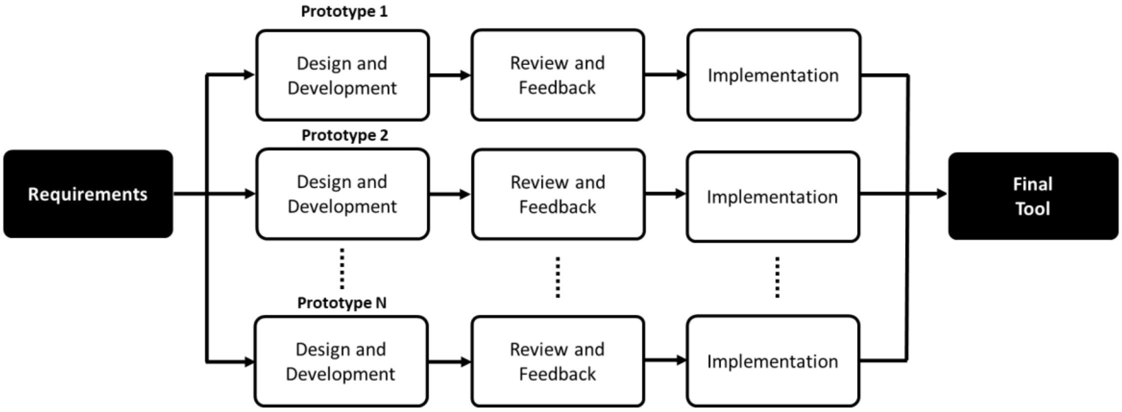


Figure 21 Application of the incremental prototyping method. Based on Javatpoint (2022) with the addition of merge into final tool.

The procedure of the tool development followed five main steps:

1. Requirement specifications
2. Design and development
3. Review and Feedback
4. Implementation
5. Merge into final product

Due to the limited scope of the project, the development was performed in one iteration of the method described above, while the ideal case would be a development in several iterations.

4.1.1 Requirement specification

The barriers and general requirements identified in the literature and tool review, were converted into specific tool requirements. These were then utilized to evaluate the final tool.

To guide the tool development with a user perspective even more, a user persona was established at this stage capturing the typical intended user of the tool. A user persona is a model representation of the typical user and is used in design to help the developer to be aware of the users' needs and requirements(van Boeijen & Daalhuizen, 2020). The user persona was created to represent barriers and requirements identified in the literature review regarding application of LCA and BPA in early design stages and the issues related to it.

4.1.2 Design and development

The tool was divided into four separate prototypes during the development, shown in Figure 22, namely an LCA, an energy, a daylight, and a sunlight prototype.

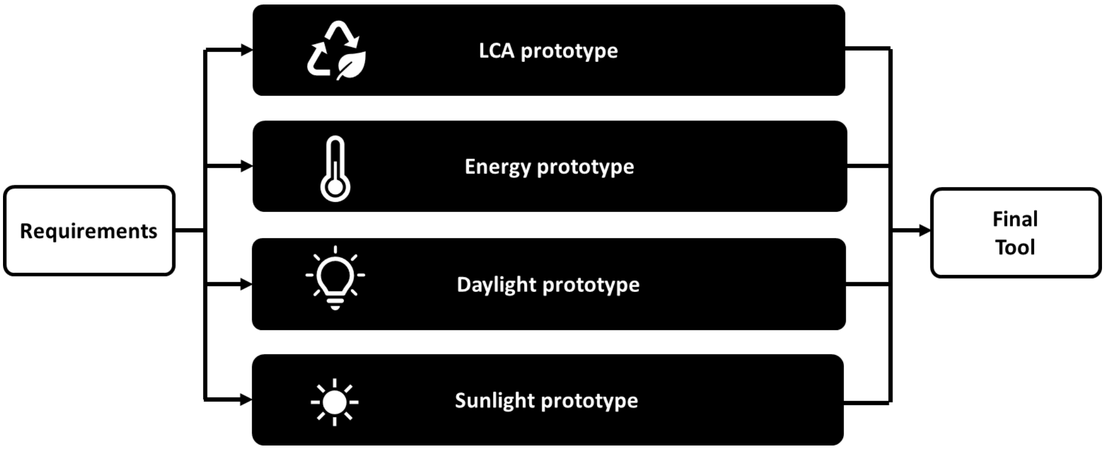


Figure 22 Tool development separated into four prototypes.

During the development, each prototype was isolated and developed individually through an iterative process following the incremental prototyping method, shown in Figure 23.

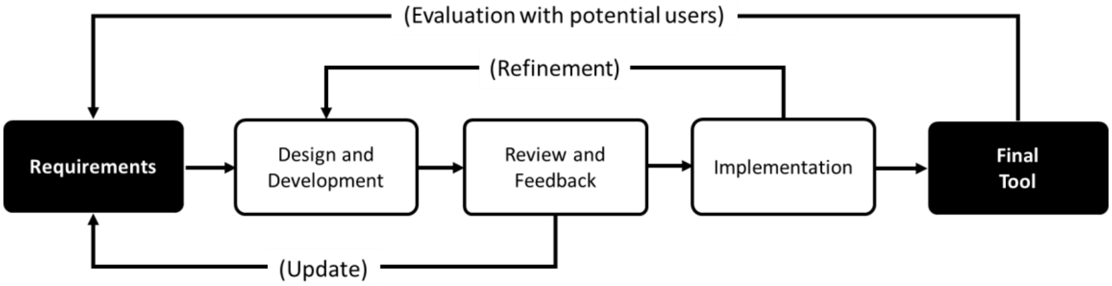


Figure 23 Iterative development of each prototype.

When the prototypes and their respective requirements were set, a first draft of them was made which explains the workflow connecting input data to the output data. The purpose of the design and development phase is to create a template for the prototypes on a general level that is the basis for the further development.

These first prototypes were drawn on paper with the purpose to be redrawn after the following review and feedback session. The reason was that paper prototypes are developed quickly, and a similar level is achieved for all of them. In addition, they are still open for alternative solutions and development.

4.1.3 Review and feedback

The drafts were then used in the review and feedback phase where the prototypes were reviewed and discussed together with potential users. The aim was to collect feedback to guide the further development.

A benefit with the incremental prototype approach is that this phase can be organized in such a way that the different professionals interviewed only need to be involved in the review of prototypes directly connected to their area of expertise. Hence, the review and feedback sessions also act as validation for relevancy and applicability of the tool in early design stages.

The collection of feedback was done with a feedback capture grid, exemplified in Figure 24, to allow for free discussions and to capture various types of feedback

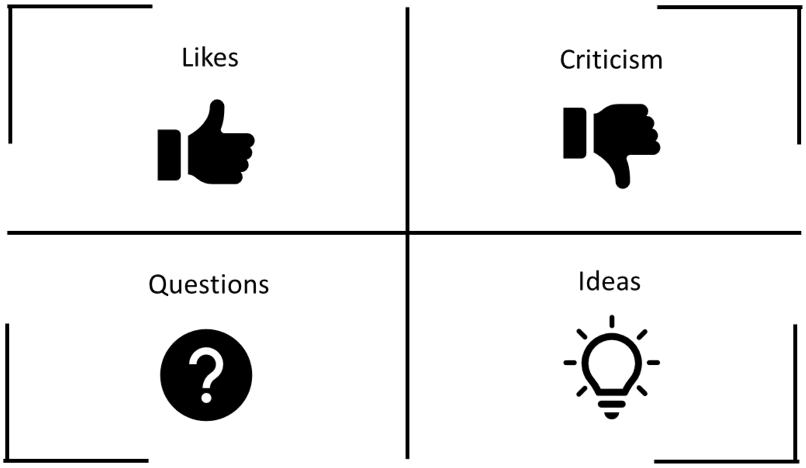


Figure 24 Feedback capture grid template. Adapted from Friis Dam & Yu Siang (2022)

4.1.4 Implementation and merge into final tool

When satisfactory functionality was reached the final prototypes were merged into one system for final evaluation. This is the stage where the prototypes are turned into modules with a common interface described as the final tool.

The implementation of the prototypes into the final tool is inspired by the framework developed by Aksamija and Brown (2018). They have developed a framework for performance-based design that integrates parametric design and performance simulation. The framework consists of four modules: geometry and analysis preparation, analysis and simulation, and visualization. Aksamija and Brown assessed the framework for energy, daylight and solar simulations and deemed it a promising development method for performance-based design tools.

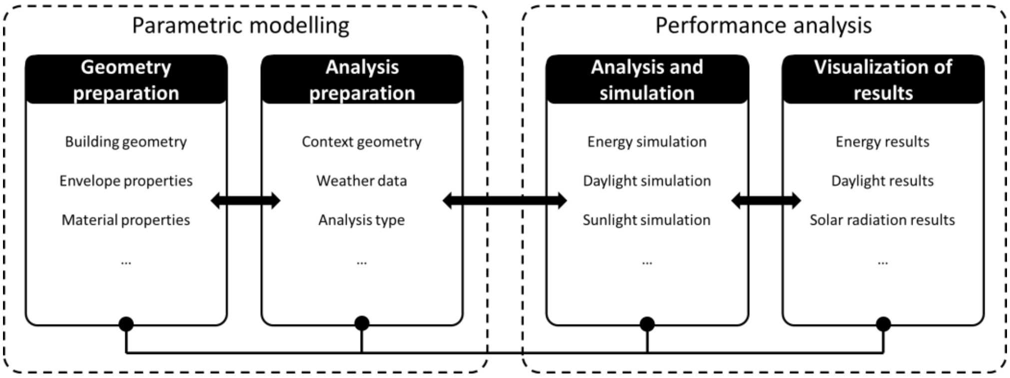


Figure 25 Framework for integration of parametric modeling and performance simulations. Adapted from Aksamija & Brown (2018).

By utilizing the framework described in Figure 25 the prototypes are organized into a general structure and hierarchy, shown in Figure 26. Each prototype has its own requirements, data flow and inner logic but is adapted to a common framework to accommodate for a shared interface, data handling and possibility to extend the tool.

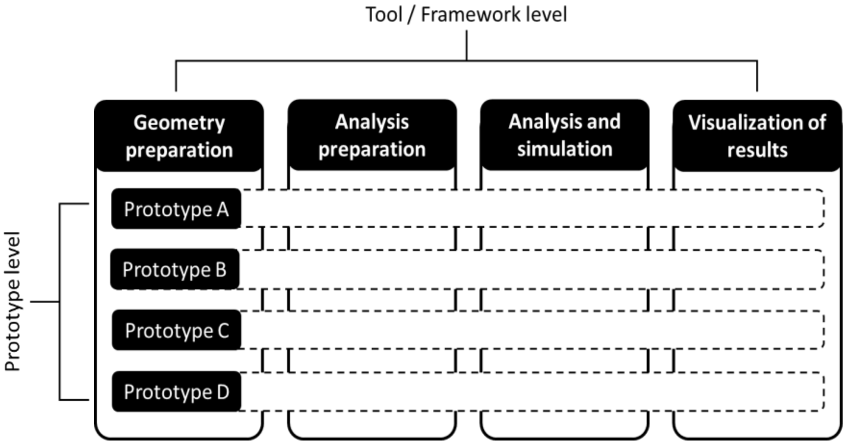


Figure 26 Concept of implementing the prototypes into a shared tool framework.

In this step, the individual prototypes are integrated into a common structure and hereafter referred to as modules in the tool framework, shown in Figure 27.

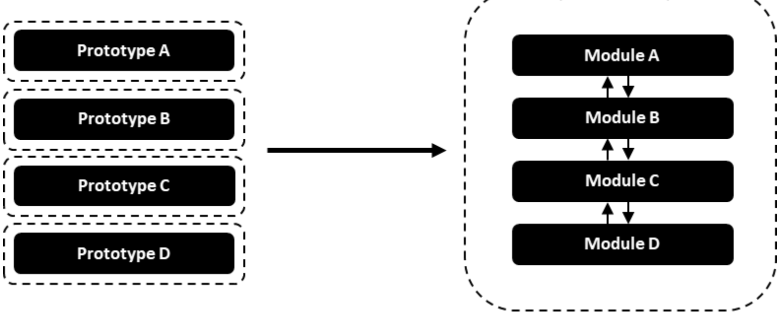


Figure 27 Conversion of individual separate prototypes into interconnected modules.

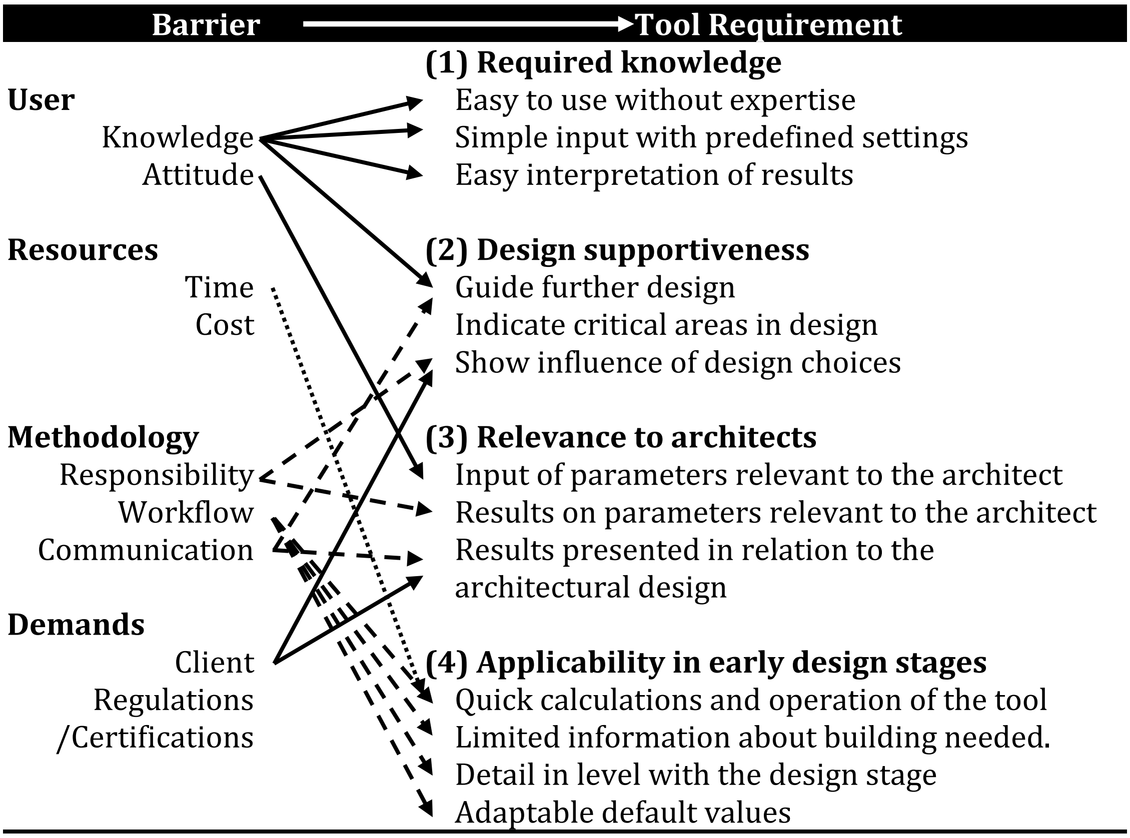
4.2 Requirement specification

The requirement specification guided the tool development and is based on the literature and tool review and formulated from the perspective of the user persona described in Section 4.2.1. The following statements formulated the principal requirements of the tool:

The tool should…
… not require expertise knowledge in neither LCA nor BPA **(1)**
… inform and support the further design work **(2)**
… be in the language of architects **(3)**
… be compatible with early design stages **(4)**

In this project, the specific focus was on the aspects presented in Table 21.

Table 21 Conversion of barriers into tool requirements for the development.



Barrier → **Tool Requirement**

User
Knowledge
Attitude

Resources
Time
Cost

Methodology
Responsibility
Workflow
Communication

Demands
Client
Regulations /Certifications

(1) Required knowledge
Easy to use without expertise
Simple input with predefined settings
Easy interpretation of results

(2) Design supportiveness
Guide further design
Indicate critical areas in design
Show influence of design choices

(3) Relevance to architects
Input of parameters relevant to the architect
Results on parameters relevant to the architect
Results presented in relation to the architectural design

(4) Applicability in early design stages
Quick calculations and operation of the tool
Limited information about building needed.
Detail in level with the design stage
Adaptable default values

4.2.1 User persona

Based on the findings in the previous studies regarding the current use of BPA and LCA in early design stages and the barriers and requirements connected to it a user persona has been developed. The purpose of the user persona is to characterize a typical user of the developed tool, represent the barriers with the current application of LCA and BPS and contextualize a typical situation in the early design stages. The characteristics or the user persona are summarized in Figure 28.

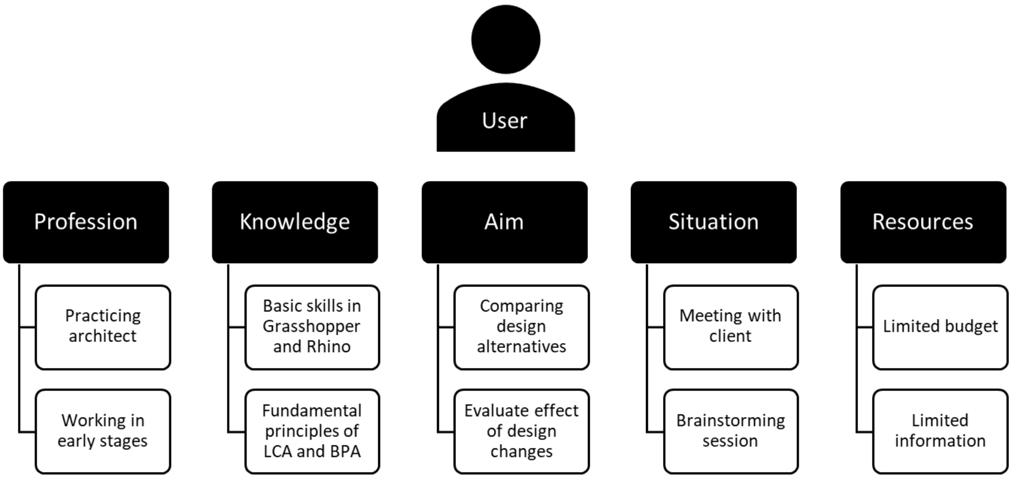


Figure 28 Overview of the user persona.

The user persona depicted in Figure 28 is a practicing architect involved in the early design stages. The user possesses basic skills in Grasshopper and Rhino and the knowledge regarding LCA and BPA is limited to the fundamental principles and terminology. The user's focus is on the architectural design, and they want to compare design alternatives and the effect on building performance of design choices. The situation could for instance be a meeting with a client or a brainstorming session, both characterized by quick modifications and communicative needs. In addition, the user has limited time and money, limited project information, and limited effort to invest in the activity.

4.3 Review and feedback

The review and feedback sessions were performed individually for each prototype with potential users and experts, Table 22. In addition to prototype A-D, treating LCA and BPA assessments, a prototype were added regarding the architect model and general aspects about early stages. A schematic illustration of each prototype was presented and afterwards discussions were conducted in a free manner to capture what the interviewee found interesting about the prototype and the topic. Additionally, the aim was to capture the experience of the interviewees about the current use of simulations in the design stages.

Table 22 List of interviewees for the different prototypes.

Interviewee	Description	Prototype
Interviewee 1	Architect working in competitions and early design stages	Architect model
Interviewee 2	Sustainability engineer at architect company	LCA
Interviewee 3	Sustainability engineer at architect company	Energy
Interviewee 4	Building physics engineer at architect company	Energy
Interviewee 5	Architect working with daylight and sunlight analysis workflows	Daylight Sunlight

4.3.1 Prototype: Architect model

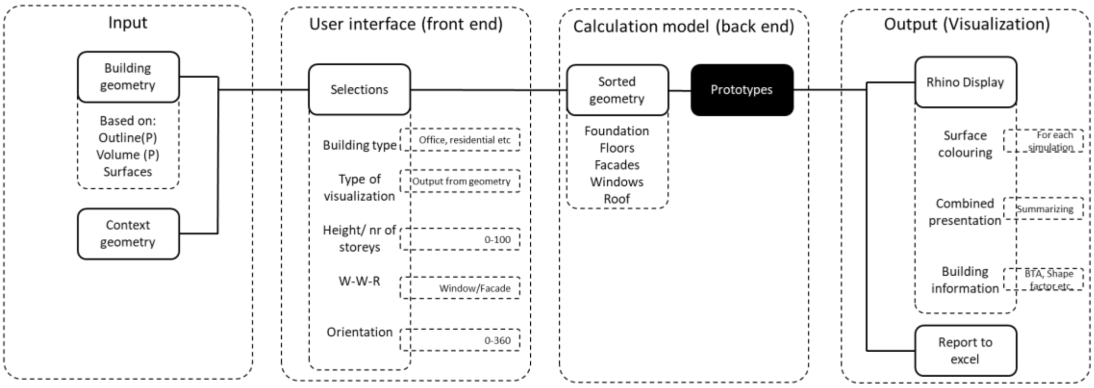


Figure 29 The architect model prototype used to support the review and feedback sessions.

The discussion with Interviewee 1, an architect working in competitions and early stages, treated both the prototype for the architect model as well as a more general topic about early stages and competition projects.

The overall conclusion about the competition stage of projects is that it is largely dependent on the competition brief and scale of the project. Hence the consideration of performance parameters is only done if needed. The workflow in competitions is often characterized by limited time and budget, hence it tends towards the aim of minimum effort. Interviewee 1 explained that daylight is the most common consideration, often to present the amount dark and light floor area in the building.

However, the interviewee predicted a near future with increased demands regarding consideration of performance parameters already in the competition stage, driven by both stricter regulations and demands from clients. Today, performance issues, for example daylight or environmental impact, are included in the competition stage if they are promoting or are a fundamental part of a design concept to create a unique selling point.

In the discussion specifically about the prototype Interviewee 1 was positive about the modelling required to use the tool. It was pointed out that it is preferred if the design process and modelling do not need to be steered in a certain direction for the use of the tool. A certain area of application where the interviewee could see benefit from a tool like this is the comparison of parallel solutions in the early stages.

From a user perspective Interviewee 1 highlighted the importance of making sure that there are options in the user interface relevant for the specific case, so the user does not become uncertain in what to choose. As a user of a tool like this, one wants to feel confident in the result and trust the indications provided. Therefore, it is also important to only provide options related to the capability of the tool and not give the appearance that the tool can do something beyond its capability. The feedback from the session is compiled in Figure 30.

Likes	**Criticism**
• Possibility to apply in phases where a lot of parameters can be investigated and with several solutions developed in parallel • Level of detail of the tool suits the investigative sketches in competitions • Graphical visualization in geometry that can be used in presentations	• Make sure that there are options relevant regardless type of project • Parameters like orientation and massing are often restricted by program • Clearly show the capacity of the tool, it should not pretend to capture aspects beyond its capacity
Questions	**Ideas**
• What type of buildings can be modelled? Mixed use? • What does the tool require in terms of modelling?	• Describe daylight in terms of dark/ light floor area • Limit the user options only to parameters covered by the tool, exclude aspects it cannot capture.

Figure 30 Feedback capture grid from the review of architect model prototype.

4.3.2 Prototype: LCA

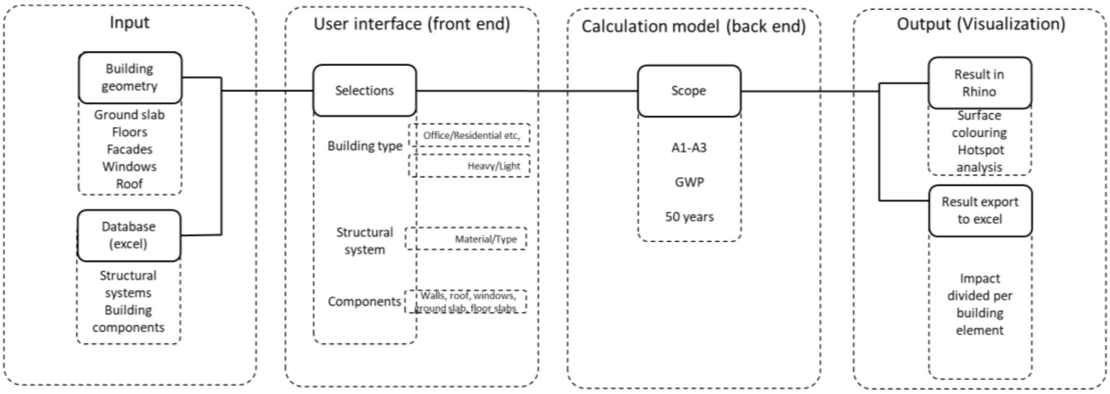


Figure 31 The LCA prototype used to support the review and feedback sessions.

According to Interviewee 2 who works as sustainability engineer, the application of LCA today in the architecture practice is mainly with the purpose of internal comparison within projects. A typical situation is to present arguments for material choices to the client. Detailed assessments for compliance with regulations and certification systems is normally distributed to external consultants. However, at the company of Interviewee 2 there is an ongoing process to increase the competence to be able to perform that type of LCA as well.

In general Interviewee 2 found the prototype on an adequate level of detail regarding model input and the choices in the user interface. However, a better transparency on the origin and type of reference data was requested. The inclusion of reference values is good to provide insight on the actual effect of design choices on a whole building level. In addition, in these early stages with simplified LCA the use of reference values may be irrelevant, instead the focus should be on the comparison of alternatives within the project itself to show the influence of design choices. The feedback from the session is compiled in Figure 32.

Likes	Criticism
• Good level of detail of the input in relation to architects working in early design stages • Good to include reference values on important aspects that are not calculated in the tool to provide relation on the overall influence of design choices	• Be more transparent with where the data is retrieved from. Calculated or reference values. • Deciding thermal mass (heavy or light) of the building is not really an input relevant for architects
Questions	**Ideas**
• Is the impact presented per phase as well? • How is the impact of the structural system estimated? • Parametrisation of the insulation thickness?	• Limit the floor slab area to be retrieved from parameters based on number of floors or storey height. • Possibility to include A4 and A5.1 since it is included in Boverkets climate database.

Figure 32 Feedback capture grid from the review of the LCA prototype.

4.3.3 Prototype: Energy

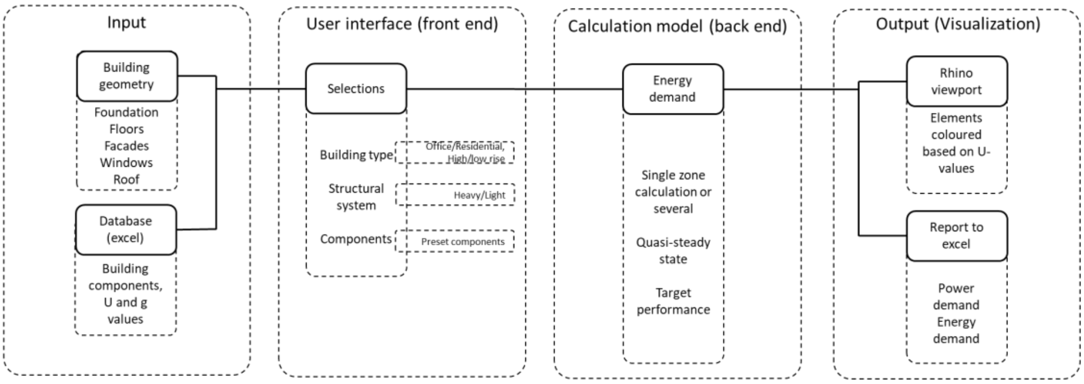


Figure 33 The energy prototype used to support the review and feedback sessions.

The review and feedback for the energy prototype was done at two occasions and mainly focused on the desired scope of the energy calculations implemented in the tool.

The interview with Interviewee 3, a sustainability engineer at an architecture company, highlighted that regardless of what type of energy calculation that is done the reliability is the key for the use of the tool and that the early calculations provide an indication of performance. Regarding the connection to the architectural design process Interviewee 3 considers the relation and balance between energy and form, material, and solar heat load as the main points of interest in the early-stage design.

Interviewee 4, who works as a building physics engineer at an architecture company, addressed the situation in Sweden with detailed development plans that are to a large extent limiting the extent to which the building volume can be varied.

Hence the discussion addressed the issue of making the tool able to capture the effect of different solutions even though large geometrical changes are not possible. The feedback also treated the scope calculations and to what extent assumptions are implemented in the prototype. A risk is that the implementation of predefined settings is that the result provided by the tool will reflect the assumptions rather than the design. A lot of the issues related to the energy performance of buildings are in the fields of other disciplines and thereby should not the tool be reliant on presumptions outside the domain of the architect profession.

An approach proposed by Interviewee 4 was to focus on indicating properties rather than more complex evaluative simulations in the stages of design addressed in the prototype. For example, the combination of average U-value and form factor of the building could be a powerful energy performance indicator, although it is mainly relevant for buildings without cooling needs, such as residential buildings and schools in Sweden that are designed without cooling systems. The feedback from the sessions is compiled in Figure 34.

Likes	**Criticism**
• The connection between material, form, LCA and energy performance • In general, a good idea to construct the prototypes on paper to be able to identify what to prioritize-	• Simplified models are always strived for, but need for validation for reliability even in early stages • Estimating energy demand is a complex process which quickly requires input on a more detailed level than the current stage of design, therefore it is not suitable for early-stage assessment by architects
Questions	**Ideas**
• Is there an established link between LCA and energy demand through the insulation thickness?	• Exclude assumptions needed that are related too other fields and regarding aspect that may be invalid later in design • Exclude influence of sunlight. It yields high complexity related to an extensive set of parameters not known in these stages of design. • Use an indicator instead based on U-value and form factor properties of the building

Figure 34 Feedback capture grid from the review of the energy prototype.

4.3.4 Prototype: Daylight

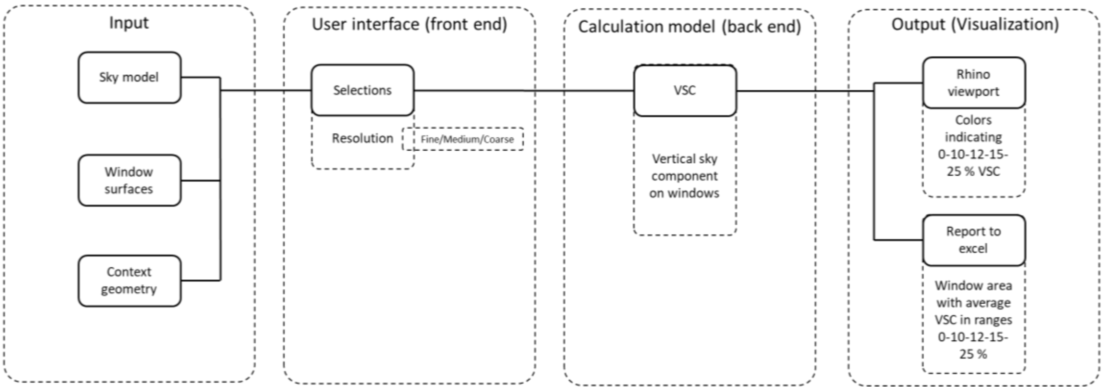


Figure 35 The daylight prototype used to support the review and feedback sessions.

Interviewee 5, an architect responsible for developing daylight and sunlight analysis workflows, believes that the reason for why daylight analysis is a main aspect of building performance handled by architects in practice is due to the obvious connection to the architecture design. Both the input and output of daylight simulations are easily accessible and the measures to handle daylight issues are limited to geometrical form, window properties and material choices, aspects which architects work with.

Regarding the daylight prototype the discussion with Interviewee 5 mainly treated how the result should be presented and how the performance could be summarized in a performance indicator. The use of vertical sky component (VSC) is reasonable for the targeted stage of design, but the regulations and certifications regarding daylight is only targeting the worst performing situations. Hence the analysis should indicate these areas. The feedback from the session is compiled in Figure 36.

Likes	Criticism
• The use of VSC is powerful and a reasonable limitation in these stages of design. • VSC is often used to check conditions before a more detailed analysis is performed and is becoming more accepted as an analysis to show compliance with demands	• Regulations only focus on the worst cases (critical rooms) so the assessment should capture that • It is difficult to turn daylight into a single score indicator, essential to show variation in relation to geometry.
Questions	**Ideas**
• Is the sky-model in the analysis defined by the user or the predefined? • Are the results in any way related to the interior design or only presented as façade conditions?	• Show the results for different VSC-ranges, present ratio of area within each interval • Relate the results to the interior, for example by indicating possible room depths

Figure 36 Feedback capture grid from the review of the daylight prototype.

4.3.5 Prototype: Sunlight

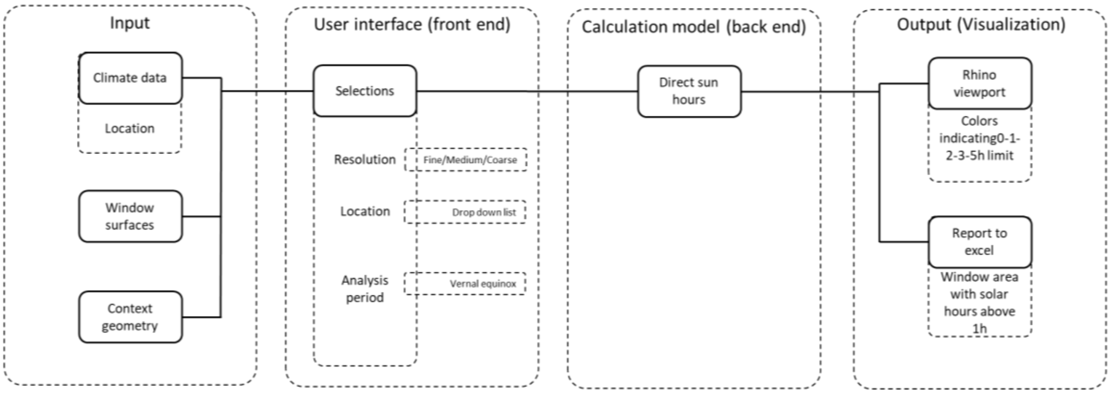


Figure 37 The sunlight prototype used to support the review and feedback sessions.

The review of the sunlight prototype covered similar topics as for the daylight prototype. Similarly to daylight, only the worst case is interesting since certifications and regulations focus on the minimum requirements. The presented prototype was focusing on the direct sunlight hours which is a demand for residential buildings. It is a way to analyse the sunlight availability on the building envelope describing the conditions on the site.

Interviewee 5 also requested a clearer connection between the simulations results and the interior design. The relation between the conditions on the façade and the indoor environment is, according to Interviewee 5, a very interesting topic in research and development for implementation in architecture design. This is also true for the daylight simulations. The feedback from the session is compiled in Figure 38.

Likes	**Criticism**
• The simplicity and minimum input needed makes it easy to use • The possibility to changes orientation is a benefit if geometry is imported from other softwares with different directions	• Regulations only focus on the worst cases (critical rooms) so the assessment should capture that • Solar heat load is often the limiting aspect of sunlight conditions
Questions	**Ideas**
• Which analysis period is used? For direct sunlight hours the vernal equinox (autumn) is a good starting point to capture the conditions.	• Different focus depending on building type, solar heat load or direct sunlight hours • Connect the sunlight conditions to the daylight conditions. They are often treated together since they can be conflicting.

Figure 38 Feedback capture grid from the review of the sunlight prototype.

4.3.6 Main takeaways

The review and feedback sessions are summarized into a set of main takeaways to implement in the development:

- Prioritize internal comparison of alternatives as evaluation method
- Provide options that are relevant for all projects so that the user finds applicable options for the specific case (make the tool independent on type of building)
- Limit assumptions regarding aspects related to other disciplines
- Prioritize simplified indicators over detailed simulations based on an extensive set of assumptions
- The tool capability should be clear for the user
- Provide a link between exterior daylight and sunlight conditions to the interior environment, show light and dark floor area

4.4 Developed Tool

The developed tool is constructed as a proof-of-concept for integration of LCA and BPA implemented in Grasshopper. This chapter presents the conceptual framework and functionality of the tool as result from development.

4.4.1 Tool architecture

The tool is built with user interface and calculation engine in Grasshopper. The modelling of geometry is done in Rhino and a database with building components is created in excel. The schematic structure of the tool is illustrated in Figure 39.

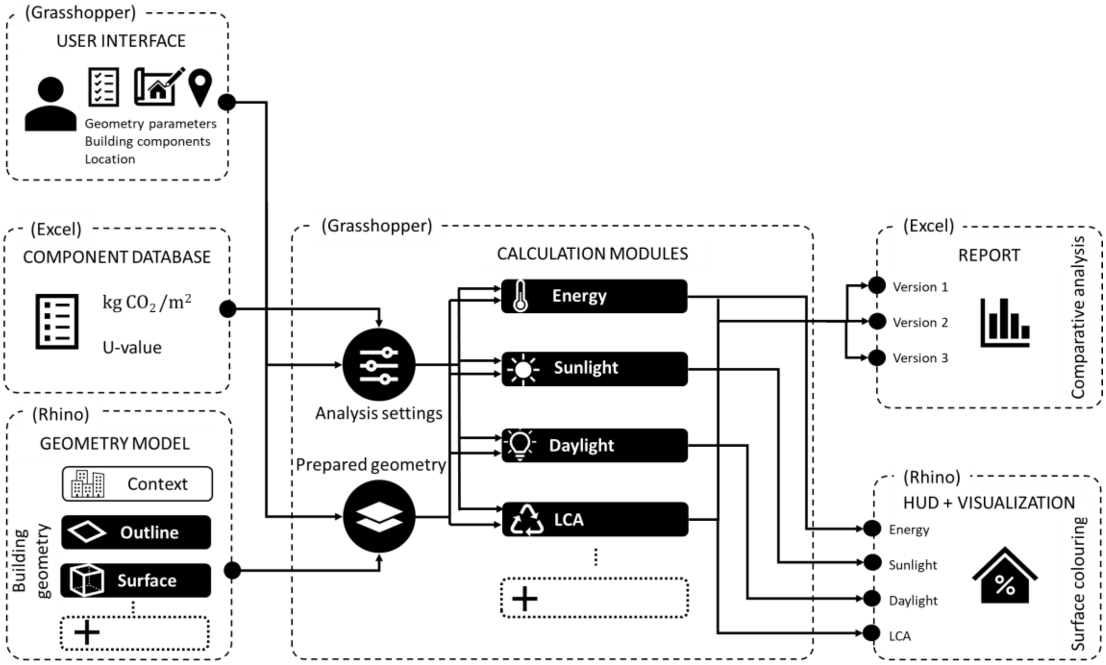


Figure 39 Schematic structure of the tool architecture.

The tool is built to require a reduced input by the user, allowing for quick modelling of different design alternatives. Focus was on limiting the input to information known in early stages, leaving out occupancy behavior and properties of technical systems. In that way assumptions needed for the use of the tool and the early stages is limited. The input and output of the tool is presented in Table 23 and is mainly related to geometry and material properties.

Table 23 Input and output in the tool.

Input	Calculation	Output
Building outline		Embodied carbon
Window area		U-value average
Number of storeys		Shape factor
Storey height	→ ⚙ →	Direct sunlight hours
Context buildings		Vertical sky component
Location		Light floor area
Building components		Solar heat load

The results from the tool are provided in two ways. Firstly, visualization in the Rhino viewport has the intent to present the result in relation to the building geometry. Hence it indicates critical areas in design and have a close connection to the spatial aspects of the architectural geometry. The second type of results provided is the export into an excel report which is developed for the iterative and comparative aspects of architectural optimization. It allows for reporting the results from different design alternatives for internal comparison between the designs and performance indicators.

The core of the tools is the implementation of four calculation modules developed from the implementation of the four prototypes. These are built upon simplified single score performance indicators regarding environmental impact, energy performance, daylight, and sunlight conditions, shown in Figure 40.

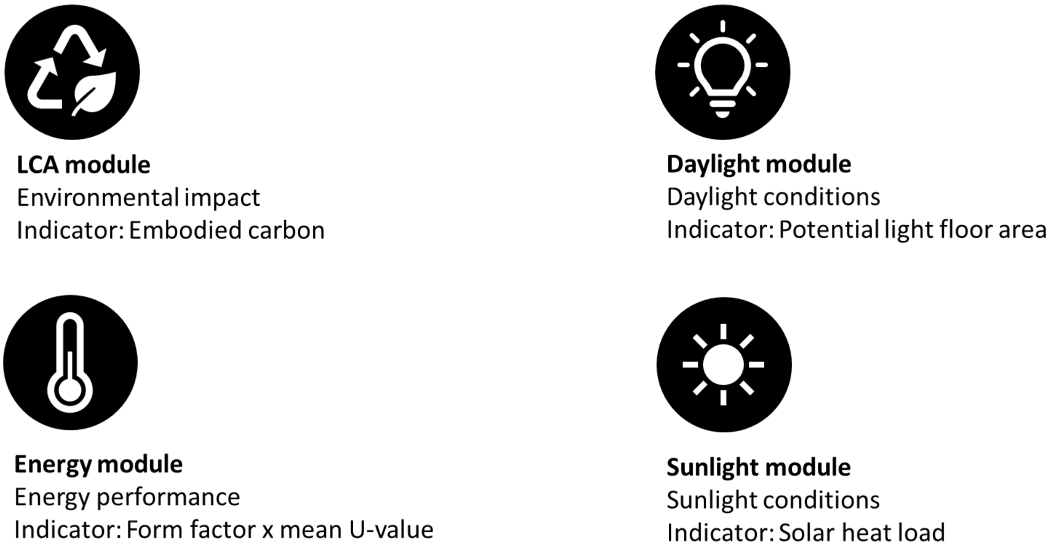


Figure 40 Performance indicators implemented in the tool.

4.4.1.1 LCA module

The LCA module covers the environmental impact assessment built upon an embodied carbon indicator. The LCA modules considered in the assessment is A1-A3 (the product stage), A4 (transport to site) and A5 (waste of material). This is the data included in the database provided by Boverket (Boverket, 2022a).

The considered building elements are the thermal envelope, structural system, and internal walls. The area of the elements in the thermal envelope are directly retrieved from the 3D model multiplied with the environmental data from the component database. The internal wall area is estimated by an internal wall to floor area ratio.

Types of structural system are provided categorized by main material (concrete, steel, timber) and type of building (multi-residential, office, school) based on reference values from Malmqvist et al. (2021). It is defined as embodied carbon per square meter floor area.

Overall, the scope of the assessment is compatible with the Swedish climate declaration (Boverket, 2021d). It is summarized in Table 24.

Table 24 Scope of the environmental impact assessment in the tool

Scope of assessment	
Life cycle modules	A1-A5
Impact category	GWP
Considered elements	Roof, Windows, External walls, Internal walls, Structural system, Ground slab
Functional unit	m^2 floor area

4.4.1.2 Energy module

The energy performance indicator provided in the tool is the combination of the mean U-value and Form factor, see Equation (4). The mean U-value are calculated according to Equation (3) by weighting the U-values for ground slab, external walls, windows, and roof by area. However, thermal bridges are accounted for by overall increasing the U-value by a factor of 30% according to Miljöbyggnad (SGBC, 2020) instead of specifying linear and point thermal bridges. The form factor is calculated according to Equation (2). In detail, the energy performance indicator is calculated according to Equation (8).

$$1{,}30 \times \frac{\sum UxA}{A_{envelope}} \times \frac{A_{envelope}}{A_{floor}} \;, [\frac{W}{Km^2}] \qquad (8)$$

4.4.1.3 Daylight module

The daylight performance indicator is based on the Advanced VSC method where the estimated maximum room depth is utilized to describe the ratio between potential light floor area and dark floor area. The Advanced VSC method defined by equation (5) are implemented and the light and dark floor area are defined as described by Figure 41.

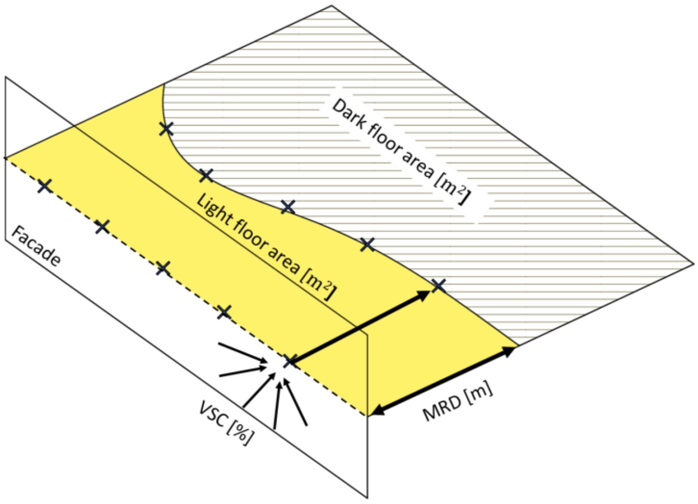


Figure 41 Illustration of the light floor area definition.

4.4.1.4 Sunlight module

The performance indicator regarding sunlight is based on the solar heat load calculation described in Equation (6). It is connected to the light floor area calculations described in Section 4.4.1.3 by defining the room area as the light floor area derived from the Advanced VSC method. Instead of utilizing the pre-set with solar irradiance of 800 W/m^2 the irradiance is simulated on the same sensor points used in the Advanced VSC calculations. The peak of solar irradiance for the period between the vernal equinoxes are implemented in the calculation. In that way shading geometry is accounted for. The implementation of Equation (6) is described by Equation (9) together with Figure 42.

The sunlight module also includes simulation of direct sunlight hours on the façade for the vernal equinox t0 show the shading conditions and access to sunlight on the site.

$$SHL = I_{sol}\, g_{sys} \frac{WWR \times RH}{RD}, [\frac{W}{m^2} floor\ area] \qquad (9)$$

$SHL = Solar\ heat\ load [W/K]$
$I_{sol} = Solar\ irradiance\ (simulated)\ [W/m^2]$
$g_{sys} = Shading\ factor\ [-]$
$WWR = window\ to\ wall\ area\ ratio\ [-]$
$RH = Room\ height\ [m]$
$RD = room\ depth, based\ on\ the\ Advanced\ VSC\ method\ [m]$

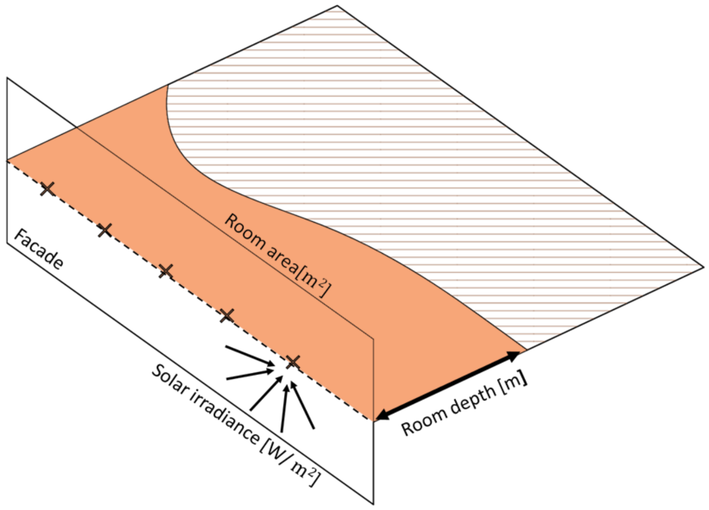


Figure 42 Illustration of room area definition in solar heat load calculation.

4.4.1.5 Combined assessment

The tool provides simultaneous assessment on the four performance indicators from the respective calculation module together with floor area and window-to-floor area ratio. The results are combined in a radar chart, Figure 43, for comparative evaluation of alternative design proposals according to the Design alternatives approach illustrated in Figure 7.

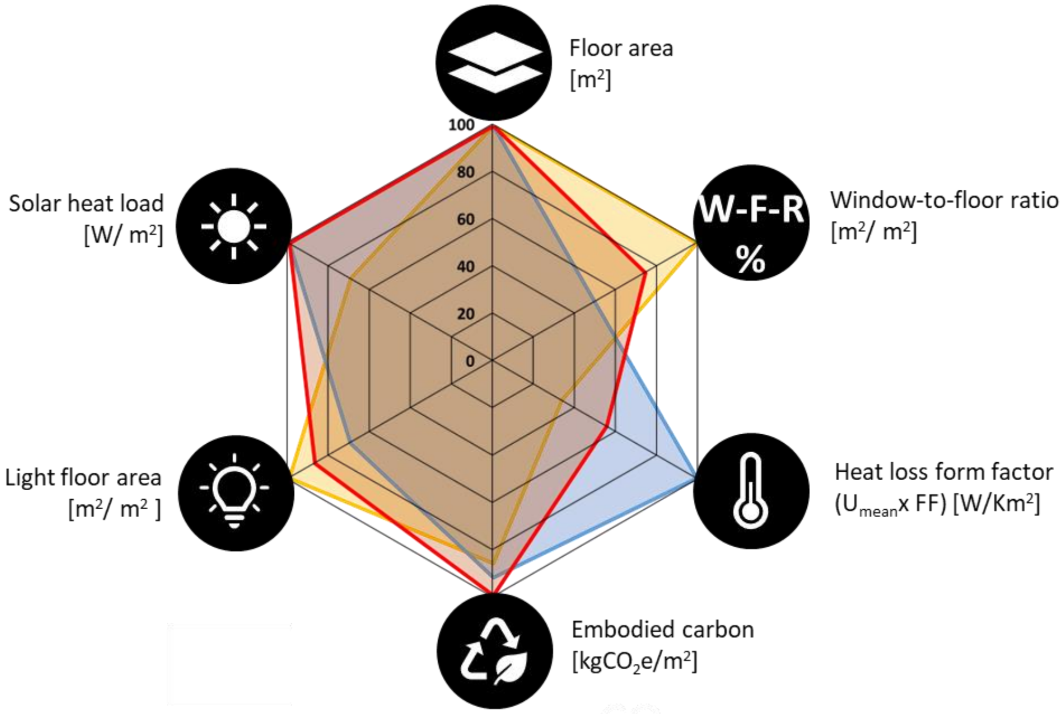


Figure 43 Combined assessment for the performance indicators implemented in the tool. The red, blue, and yellow areas represent different design alternatives evaluated against each other.

In addition, each assessment module and performance indicator are assigned a heads-up display (HUD) showing instant feedback from the assessment results in relation to the geometry in Rhino. These are appended in Appendix B.

4.4.2 Software implementation

The tool is developed in Grasshopper. The full script is illustrated in Figure 44.

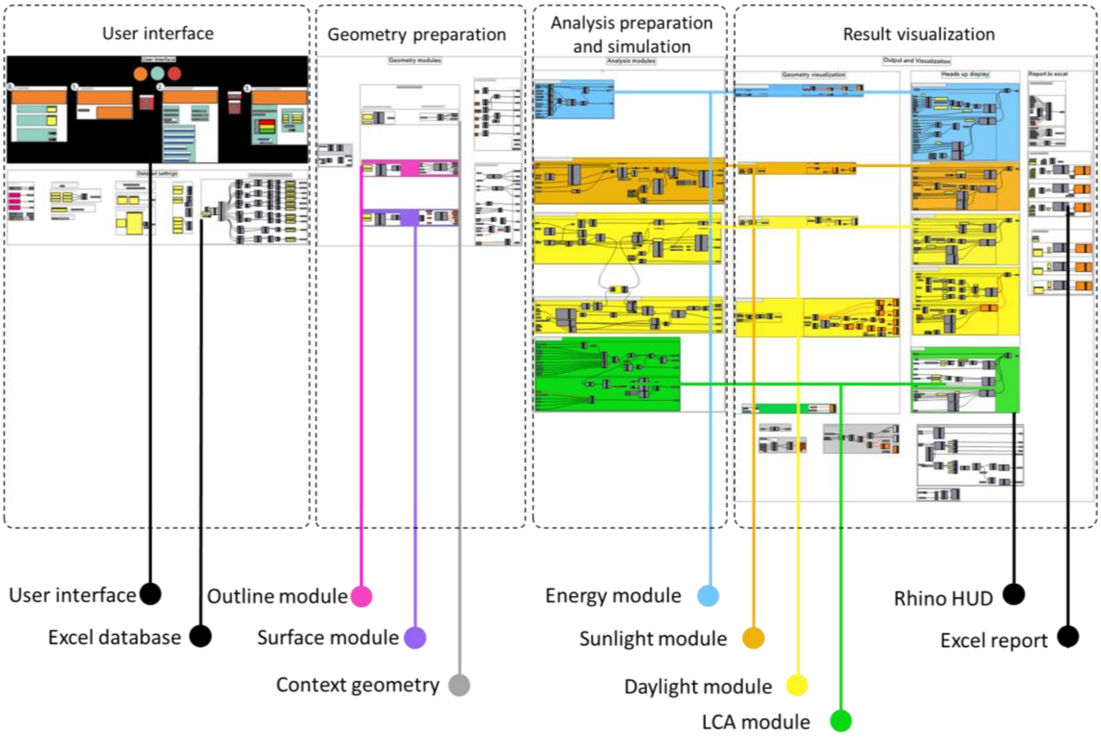
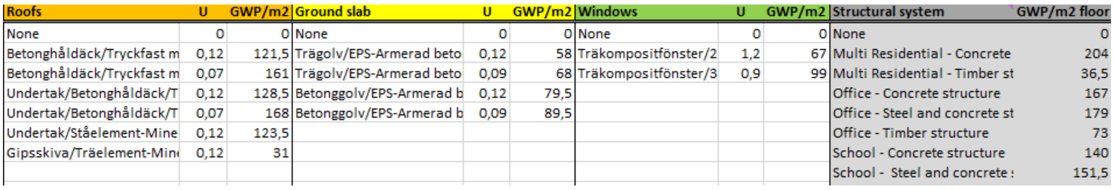


Figure 44 Full Grasshopper script of the tool.

The component database established in Excel, shown in Figure 45, is built for the easy addition of alternative component types of external walls, windows, roofs, ground slabs and structural system. Thereby, the users can build their own library with references from previous studies or projects, or simply create new ones by calculating U-values and embodied carbon per square meter.



Roofs	U	GWP/m2	Ground slab	U	GWP/m2	Windows	U	GWP/m2	Structural system	GWP/m2 floor
None	0	0	None	0	0	None	0	0	None	0
Betonghåldäck/Tryckfast m	0,12	121,5	Trägolv/EPS-Armerad beto	0,12	58	Träkompositfönster/2	1,2	67	Multi Residential - Concrete	204
Betonghåldäck/Tryckfast m	0,07	161	Trägolv/EPS-Armerad beto	0,09	68	Träkompositfönster/3	0,9	99	Multi Residential - Timber st	36,5
Undertak/Betonghåldäck/T	0,12	128,5	Betonggolv/EPS-Armerad b	0,12	79,5				Office - Concrete structure	167
Undertak/Betonghåldäck/T	0,07	168	Betonggolv/EPS-Armerad b	0,09	89,5				Office - Steel and concrete st	179
Undertak/Stålelement-Mine	0,12	123,5							Office - Timber structure	73
Gipsskiva/Träelement-Min	0,12	31							School - Concrete structure	140
									School - Steel and concrete :	151,5

Figure 45 Snapshot of the component database in Excel.

Plug-ins used in addition to the regular Grasshopper component library are detailed in Table 25.

Table 25 Plug-ins used in the tool development.

Plug-in	Developer	Reference
Human	andheum	(Food4Rhino, 2019)
Ladybug Tools	Ladybug Tools	(Food4Rhino, 2022a)
Conduit (Proving Ground)	Nathan Miller	(Food4Rhino, 2018)
TT Toolbox	CORE studio	(Food4Rhino, 2017)

4.5 Tool demonstration

The tool demonstration aims to demonstrate the tool functionality and output through a test case. It is done for the parametric version of the tool, meaning that the geometry is generated from the outline representing the footprint of the building, Figure 46.

Figure 46 Geometry for Version 1 and 2 to the left and Version 3 to the right.

Based on the outlines in Figure 46 three alternative building designs are created and evaluated with the use of the tool. The three design versions are created from the same site representing an urban context. Version 1 and 2 are based on the rectangular outline in Figure 46, and Version 3 is based on the L-shaped footprint. Futher specification of building properties are compiled in Table 26.

Table 26 Specification of the three design versions. The arrows show what is changed in relation to the base case in version 1.

	V1: Base Case	V2: Modified	V3: L-shape
Building footprint:	900 m^2	900 m2	900 m^2
Number of storeys:	8		
Total floor area [m^2]:	7200		
Storey height [m]:	3,0		
Building height [m]:	24		
Form factorm[-]:	0,68 →		**0,83**
W-W-R [%]:	30 →	**20**	
Shading factor, g_{sys} [-]	0,5 →	**0,3**	
Ground slab [U/GWP/m^2]:	0,12 / 146 →	**0,09 / 158**	
External walls [U/GWP/m^2]:	0,15 / 113 →	**0,09 / 124**	
Windows [U/GWP/m^2]:	1,2 / 67 →	**0,9 / 99**	
Roof [U/GWP/m^2]:	0,12 / 122 →	**0,07 / 161**	
Structural system [GWP/m^2]:	37		
Internal Walls [GWP/m^2]:	20		

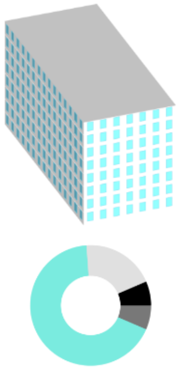
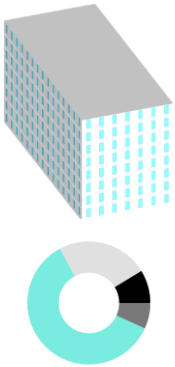
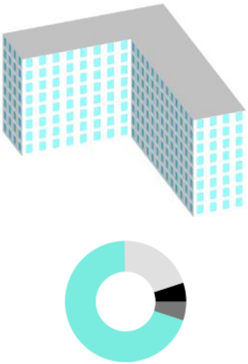
As seen in Table 26Table 26, the difference between the Base Case and the Modified version are type of constructions for the building components and window to wall area ratio. Meanwhile the difference between the base case and the L-shape version only is the overall building geometry. This is chosen to show the effect of improved thermal properties and geometric alternatives on the results.

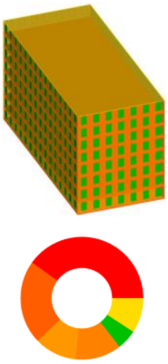
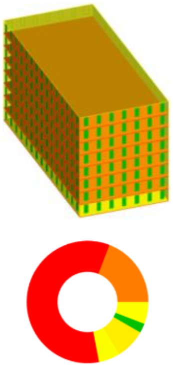
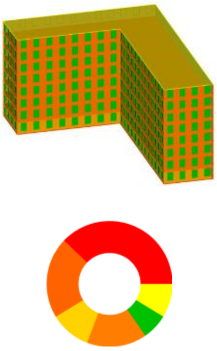
- Version 1: Base Case
- Version 2: Improved U-value
- Version 3: Higher form factor

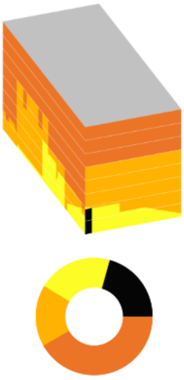
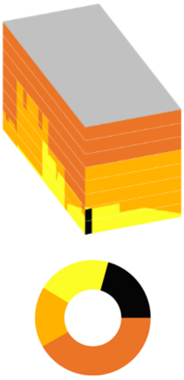
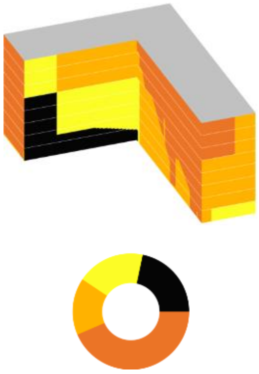
4.5.1 Results in Rhino

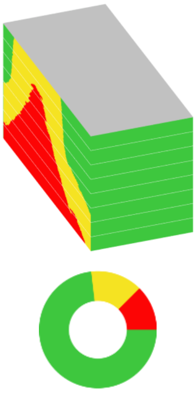
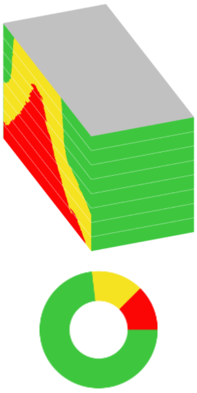
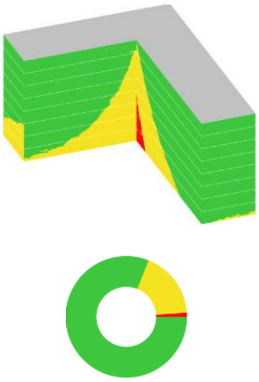
The results for each analysis are displayed in the HUD in the Rhino viewport for immediate feedback for the user. In Table 27, extracts from the result for the respective version are assembled side by side for comparison. Full detail of the HUD and visualization in Rhino can be seen in an example in Appendix B.

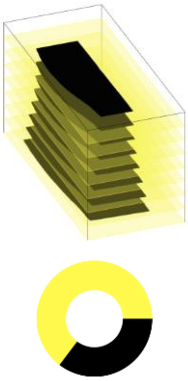
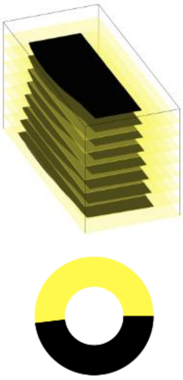
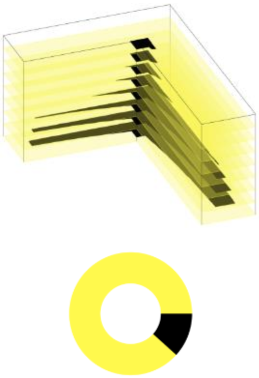
Table 27 Analysis visualizations retrieved from the HUD for the three versions.

Energy indicator	**Base Case**	**Modified**	**L-shape**
UxA Roof **UxA Windows** **UxA External walls** **UxA Ground slab**			

LCA indicator	**Base Case**	**Modified**	**L-shape**
Biggest impact **x** **x** **x** **Least impact**			

Sunlight condition	Base Case	BC-Modified	L-shape
DSH > 4 2h < DSH < 4h 1h < DSH < 2h DSH < 1h			

Daylight condition	Base Case	Modified	L-shape
VSC > 25 % 15 % < VSC < 25 % VSC < 15 %			

Daylight potential	Base Case	Modified	L-shape
Light floor area Dark floor area			

4.5.2 Results in Excel

The tool is constructed to benefit from comparing different design alternatives to optimize the design during the exploration in early stages. This is done by reporting the results to the Excel template where alternative solutions can be compared through a set of single score key performance indicators derived from the calculations and simulations in the tool, Figure 47.

The complete Excel report produced of the tool demonstration cases can be found in Appendix C.

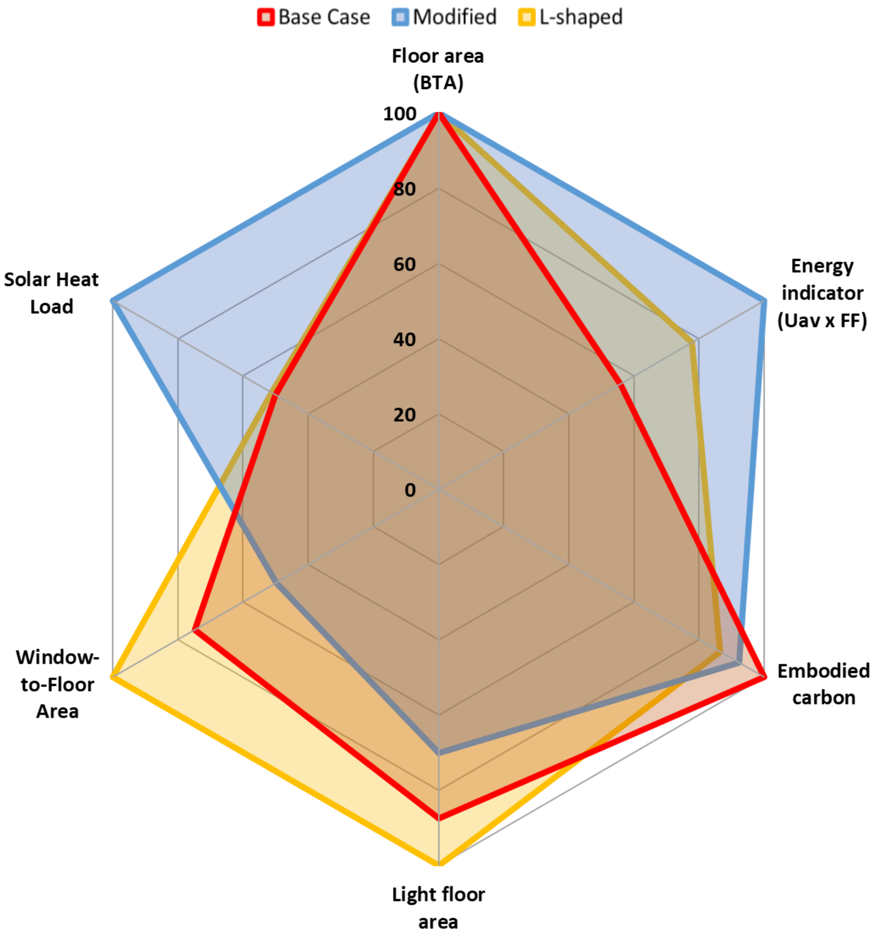


Figure 47 Radar chart from the Excel template with overview of key performance indicators for the three versions.

Figure 47 shows the internal comparison of the three alternative designs through six key performance indicators, which also is presented in Table 28. The best performing version is assigned 100 % for the considered indicator while the other versions are shown in relation. In this case, for instance, meaning that the L-shaped building has the most share of light floor area while the Modified version only is performing about 70 % of that.

The blue chart is covering the biggest part of the chart and hence the Modified version performs the best in a combined analysis of all indicators. But it is up for interpretation since the chart is providing equal weighting of all indicators. Specific number for each indicator and version can be found below in Table 28.

Table 28 Numeric values of the key performance indicators.

Indicator indicator	Base Case	Modified	L-shape
Floor area [m^2]	7200	7200	7200
Energy indicator [W/m^2K]	0,30	0,17	0,39
Embodied carbon [$kgCO_2e/m^2$]	165	179	175
Daylight potential (light floor area) [%]	65	52	88
W-F-R [%]	13	8,7	17,4
Solar heat load [W/m^2]	42	21	41

Energy performance indicator

Looking more closely at the energy performance indicator in Figure 48 one can see the average U-value and the form factor plotted together. The chart should be interpreted in the way that the closer to origin the better potential for a thermal efficient building. The Modified building shows the best result regarding the combination of average U-value and form factor. The Base Case is based on the same geometry and thereby have the same form factor, but a higher U-value is limiting the potential energy efficiency of that version. The L-shape building, due to its geometrical properties has both higher U-value and form factor in comparison to the other versions.

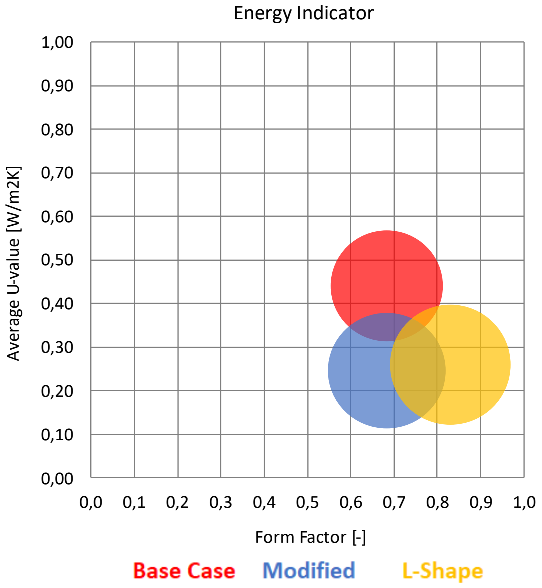


Figure 48 Form factor and average U-value for the three designs. The closer to origin the better. The area of the circles represents the embodied carbon in the design.

In addition to the U-value and the form factor, the bubble chart in Figure 48 also shows the relation to the embodied carbon through the area of the circles. Meaning that Version 2 that shows the best conditions for energy efficiency entails the largest amount of embodied carbon.

Environmental indicator

The embodied carbon is presented in a stacked bar chart as shown in Figure 49. In that way the contribution from the different building components can be seen.

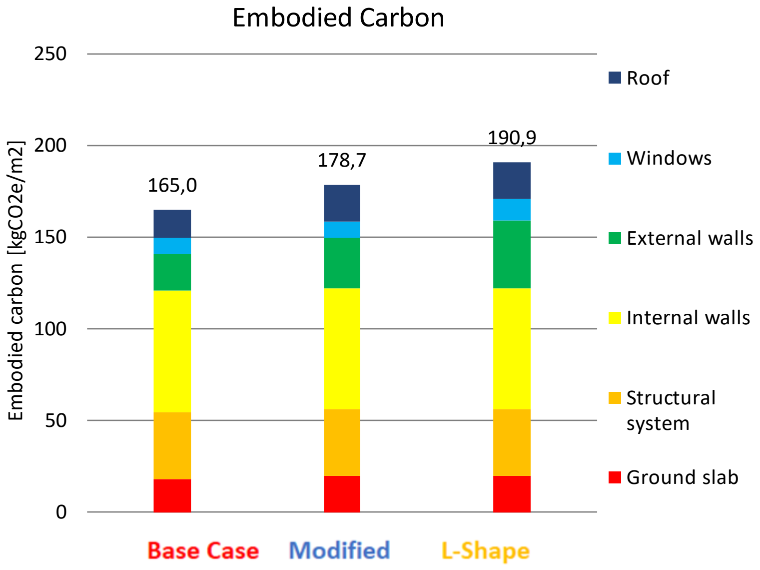


Figure 49 *Embodied carbon for the building and distribution per building component.*

By interpreting Figure 49 one can see the difference between the Base Case and the Modified version that are based on the same geometry. The Modified version results in a higher value of embodied carbon through improved U-values and reduced window-to-wall ratio, while the difference between the Base Case and the L-shaped building is only a consequence of the different geometry where the L-shaped building is less compact with a larger thermal envelope.

Sunlight indicator

To get a more detailed overview of the sunlight conditions, the façade area is divided into ranges depending on the direct sunlight hours on the surfaces, see Figure 50. In that way the share of façade area within critical regions can be tracked.

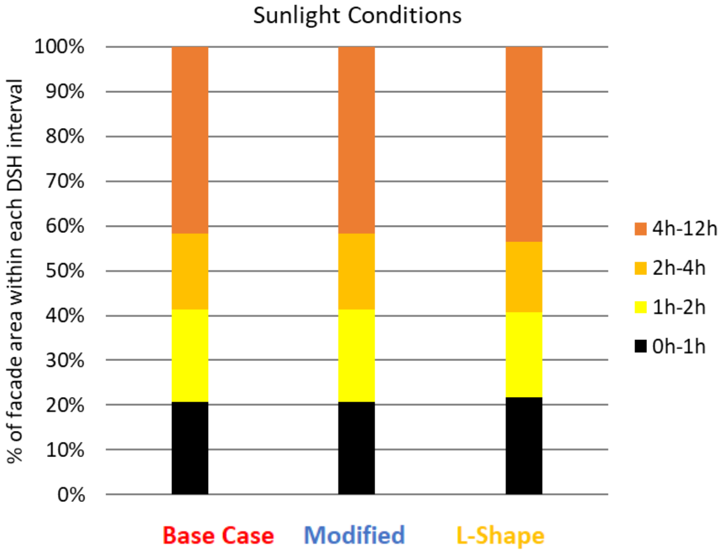


Figure 50 *Distribution of direct sunlight hours on façade.*

This indicator is dependent on the building shape, orientation, and adjacent building geometry. Consequently, the Base Case and the Modified version gets similar results. The L-shaped building geometry, however, gets an average of 4,2 h of direct sunlight hours on the façade, compared to 3,8 h for the two other versions. Figure 50 shows that this difference does not mean that the L-shaped building performs better since the façade area with direct sunlight hours below 1h increases slightly.

Daylight indicator

The daylight conditions are estimated by vertical sky component. Figure 51 shows the distribution on the façade area within critical the ranges. The results show that by changing the geometry to the L-shape in this case decreases the ratio of critical façade area.

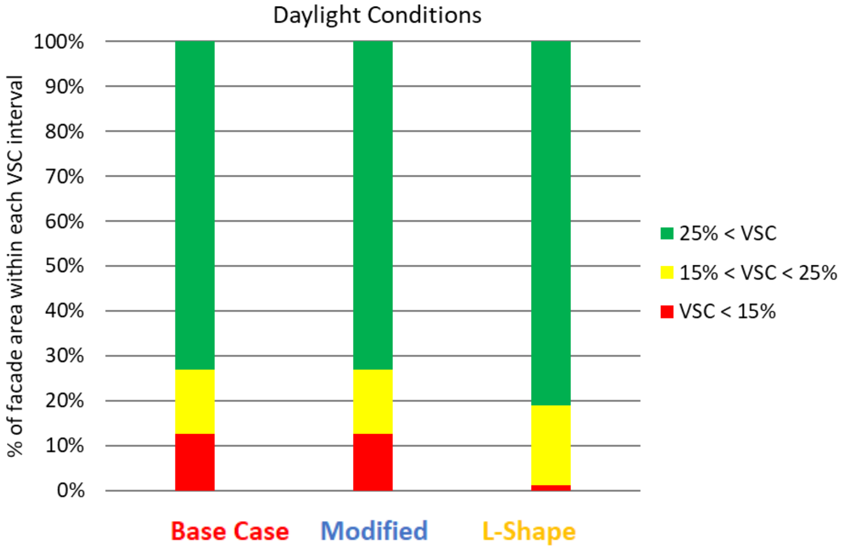


Figure 51 Distribution of vertical sky component on façade.

In addition, based on the vertical sky component a prediction is made on the potential light floor area which was 65 % for the Base Case, 52 % for the Modified and 88 % for the L-shaped building.

4.6 Parametric study

A parametric study was conducted as a sanity check of the tool functionality. Sanity checks are used in software development for fast and brief evaluation with focus on confirming that the software shows reasonable results and functionality. Thereby it is assured that the development is sufficient for continuation of more comprehensive testing, such as validation (Sammi et al., 2011).

In this project the aim was to check whether the tool results agree with what can be expected and that it was relevant to continue with user evaluations.

The parametric study was made for the thermal envelope to assess the functionality of the tool through a sanity check. The relation between WWR and embodied carbon, average U-value, potential light floor area and solar heat load were studied. The same cases as in the tool demonstration in Section 4.5 is used.

As expected, the relation between average U-value and embodied carbon have a linear relation to the window to wall area established calculation models in the tool, Figure 52.

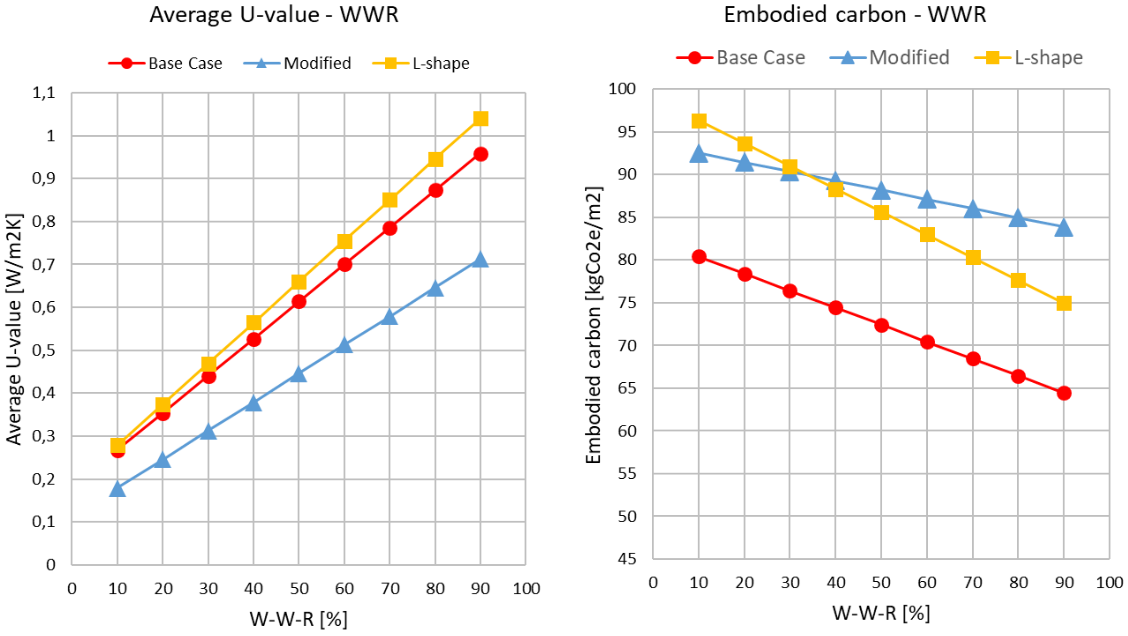


Figure 52 *Left: Relation between window-to-wall area ratio and average U-value of the thermal envelope.*

Right: Relation between window-to-wall area ratio and embodied carbon of the thermal envelope.

As Figure 52 shows, a difference between the three versions can be seen not only in the absolute values, but also in the rate of change of both U-value (Left) and embodied carbon (Right). It depends on the internal ratio between the window and the external wall properties. Hence an opposite behavior is possible.

Looking at the U-value graphs Figure 52 (Left) one can see that all cases have a different relationship. In the modified case, the U-values of the windows and façade are closer to each other than in the base case, hence a decreased slope can be seen in the modified case. The L-shaped building have an increased envelope area and thereby an increased slope in comparison to the base case due to the larger influence from the façade on the results.

A similar linear relationship can be seen between the window to wall area ratio and embodied carbon in the thermal envelope, Figure 52 (Right).

Regarding the potential light floor area, a non-linear relationship to the window to wall area ratio can be seen, Figure 53 (Left). The influence is higher between low window ratios and loses effect at higher window percentages as large areas of the floor already is covered. The solar heat load also shows a non-linear relation since it is calculated in relation to the light floor area, Figure 53 (Left).

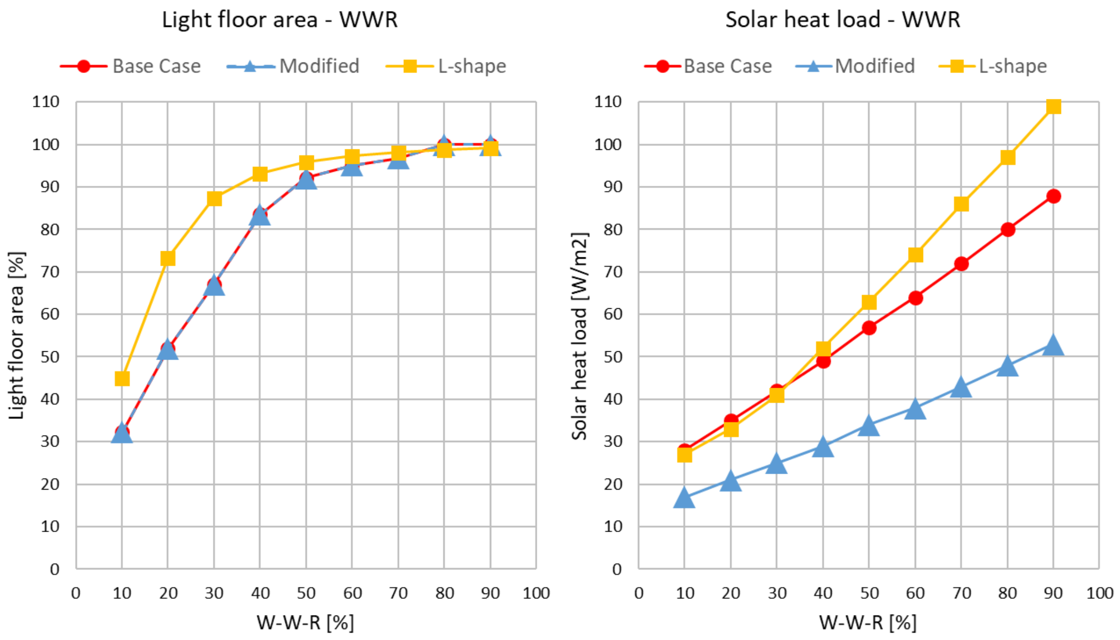


Figure 53 *Left: Relation between window-to-wall area ratio and the potential light floor area.*

Right: Relation between window-to-wall area ratio and the solar heat load.

Figure 53 also indicates the effect of the building geometry with the difference between the form factors, which here specifically is a matter of depth of the floor plan, where the L-shape building is the shallowest and thereby has a higher percentage of potential light floor area and solar heat load. Worth mentioning is that this is of course also highly dependent on the VSC and solar irradiance conditions on the façade.

The solar heat load also shows a different relationship towards the window to wall area ratio depending on the shading factor which is seen between the base case and the modified case in Figure 53 (Right).

Overall, the relations and dependencies shown in Figure 52 and Figure 53 seem reasonable and in line with what can be expected, therefore the tool is considered sufficient for user evaluation.

5 Tool Evaluation

This chapter covers the results from the tool evaluation which was performed through a tool demonstration for potential users.

5.1 Method

The goal of the user evaluation was to compile feedback and evaluate the tool performance from the perspective of potential users, in this case architects and building designers working in early design stages. The evaluation focused on assessing the four main areas of requirements defined for the tool development listed below:

- Required knowledge
- Design supportiveness
- Relevance to architects
- Applicability in early design stages

The evaluation aimed to connect to the barriers and requirements defined for the tool development and identify key aspects for further development as illustrated in Figure 54.

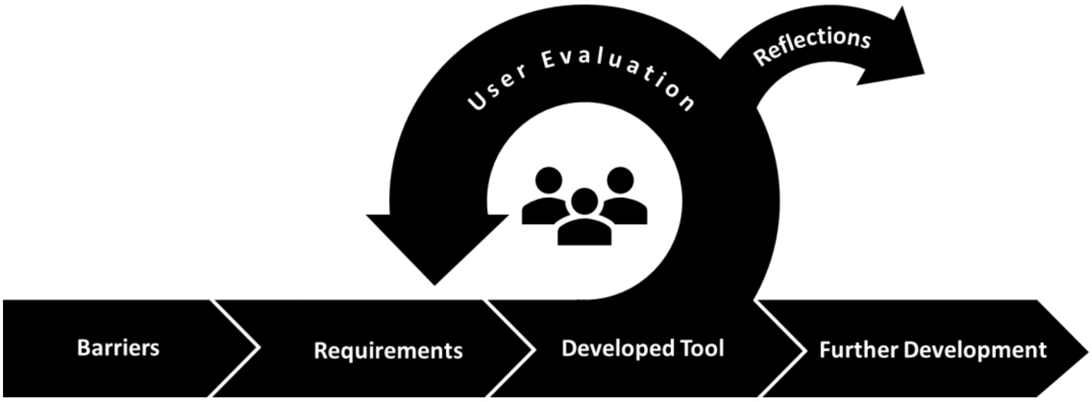


Figure 54 The relation of the user evaluation to the development process.

The evaluation was done through tool demonstrations. The demonstrations were conducted by generating the three design alternatives described in Section 4.5 and showing the results. It was done in sessions with one to two attendees each and lasted for 30-45 minutes. The demonstrations were held either online or in physical meetings. The feedback from the tool demonstration was gathered in two ways: in a feedback capture grid, and in a follow-up questionnaire.

The attendees were encouraged to comment and provide response during the demonstration. The feedback was collected and categorized in the feedback capture grid with the subcategories Likes, Criticism, Questions, and Ideas. No questions were prepared so the comments provided were based on the attendees' initial impressions.

The survey was sent to the attendees immediately following the demonstration and the questions aimed to evaluate the tool characteristics listed in Table 29, which is corresponding to the tool requirements defined in Table 21.

Table 29 Characteristics evaluated and the related survey questions.

Requirement	Characteristic evaluated	Question number
-	Respondents' experience	1
-	General impressions	2-5
(1)	Required knowledge	6-7
(2)	Design supportiveness	8-13
(3)	Relevance to architects	14-17
(4)	Applicability in early design stages	18-21

The survey contained the 21 questions compiled in Table 30. The answers are either written as comments or by rating from 1-6. By providing an even number of alternatives in the rating the respondents must take a stand when answering even though they want to select mid value.

Table 30 Questions in the survey.

Nr	Question / Statement	Answer
1	The respondents' rating of their own competence and experience.	(1-6)
2	What is your first impression of the tool?	Text
3	In what situations in building design would the tool be useful?	Text
4	In what type of projects would the tool be useful?	Text
5	What do you think can limit the use of the tool in practice?	Text
6	The tool can be used independent by you in early stages to make decisions based on LCA and BPA aspects.	(1-6)
7	Rate the level of knowledge required in the use of the tool	(1-6)
8	The tool supports architects to make decisions based on both LCA and BPA aspects in early design stages.	(1-6)
9	The tool provides clear feedback on how design decisions influence the LCA and BPS aspects.	(1-6)
10	The tool clarifies LCA and BPS aspects in conflict with each other.	(1-6)
11	The tool indicates critical/problematic areas in the design regarding LCA and BPS aspects.	(1-6)
12	The results are visualized in a way that supports the design.	(1-6)
13	What would make the tool even more design supportive?	Text
14	The input and choices made in the tool are relevant for you as an architect in early design stages.	(1-6)
15	The results are relevant for you as an architect in early stages.	(1-6)
16	Are there any input/ choices/ results that are missing in the tool?	Text
17	Are there any input/ choices/ results that are superfluous/ irrelevant in the tool?	Text
18	The tool can easily be integrated/ used in early design stages.	(1-6)
19	The level of detail in the 3D modelling is too high/low.	(1-6)
20	In relation to early design stages: The level of detail on the input and choices made in the tool are too high/low.	(1-6)
21	In relation to early design stages: The level of detail of the results are too high/low.	(1-6)

5.2 User evaluation results

This section presents the results from the user evaluation in the form of a feedback capture grid and aggregated results from the survey response. The results are also summarized in relation to the tool requirements which have been guiding the tool development.

The tool was demonstrated to 9 persons (8 architects and 1 sustainability engineer) in 6 sessions, see Table 31.

Table 31 Attendees in the tool demonstrations.

Session	Attendees	Job description	Experience
Session 1	Architect	Working with development of parametric design tools with focus on sustainability	7 years
	Architect	Lead architect	14 years
Session 2	Architect	Varying type of projects and stages with some focus on sustainability	4 years
	Architect	Studio manager, working with residential, office and urban planning projects	22 years
Session 3	Architect	Projects of varying scale, both early and late stages	3 years
	Architect	Projects of varying type and scale, from tenant adaption of offices to detailed development plans	1 year
Session 4	Architect	Urban and strategic planning	5 years
Session 5	Architect	Office projects, daylight, and sunlight analyses	4 years
Session 6	Sustainability engineer	Parametric analysis, sustainability questions	2 years

5.2.1 Feedback capture grid

The feedback, comments and discussions occurring during the tool demonstrations are summarized in the feedback capture grid in Table 32. They are solely based on topics initiated by the demonstration attendees.

Table 32 Feedback capture grid with the comments from the attendees during the tool demonstration.

Likes	**Criticism**
• Fast modelling and feedback • Good level of complexity for early design stages. • Simplicity and user-friendliness • Not too heavy iterations from the user perspective, no need to process detailed input data. • The room depth indication is very supportive. • The comparison is interesting when exploring the design space • Possibility to show reasons behind decisions for clients • Capture complexity by providing multiple indicators • Readability of the excel report, immediate overview • The 3D visualization is providing great support for the user compared to tabular data.	• Assumptions, rules of thumb, shortcuts and scope of the calculations need to be commented upon, transparency is important. • Summarizing the solutions in percentages can be misleading. • Can't see in detail how the change of components leads to higher/ lower environmental impact. • Missing alternative ways to model the building geometry • Rhino/Grasshopper maybe not used in the projects
Questions	**Ideas**
• How is the sensor grid for the analysis created? • Interpretation of energy indicator graph (U-value, form factor)? • Is it possible to import models from other softwares? • Can you use it for multiple buildings? • Are there restrictions on the modelling of the ground? • How are the internal walls considered? Can you include several types? • Is the Excel sheet a template or a database with components?	• Weighting of result parameters. • Include potential best-case scenario to set target and optimize performance. • Split the visualization of the U-values between opaque and translucent components. • Include a way to measure the potential room depth. • Implement a way to store the daylight/sunlight simulation results. • Include alternative ways of modelling/ import models • Create template and manual for the tool.

As shown in the feedback capture grid in Table 32 several comments were collected during the demonstration's sessions. The positive feedback yields an indication that the scope of the tool is appreciated by the architects attending the demonstration. The comments expressed that the tool satisfies use in early stages as the simplicity of the tool provides quick feedback and quick iterations from the user perspective while still providing valuable information to the user in form of several indicators capturing complexity and internal comparison to guide the design work.

To a large extent, the criticism of the tool treated the transparency of the tool which was requested to be higher. This was also reflected in the questions, which to a large extent covered a clarification of functionality and assumptions in the tool. Another recurring criticism and question were about the possibility of alternative ways of geometry modelling in combination with potential connection to other software which is more compatible with the design process of the attendees.

The ideas provided from the attendees were to a large extent about the type and presentation of the results, which potentially indicates in more detail what architects wants, or expects, from a tool like this. The possibility to weight the indicators depending on their importance in projects was a recurring comment in three of the sessions, but a side comment was also that it may be providing too much complexity. Also, the merge of indicators turned into percentage may be misleading and difficult to interpret and utilize for the user.

Generally, the response to the visualization was that the internal comparison within alternatives in a project is just right in the early stages and is what is used in design development and communication with clients. However, some comments about the possibility to see the best-case scenario for the design conditions and potential optimization were discussed, which is interesting further into the design process.

Lastly, the attendees in the tool demonstrations expressed a large interest and excitement in the topic and stated the importance of considering life cycle and building performance aspects in the early stages of building design. The attendees expressed that the tool demonstration aroused an interest in trying the tool in real cases which is seen as a good grade in the evaluation.

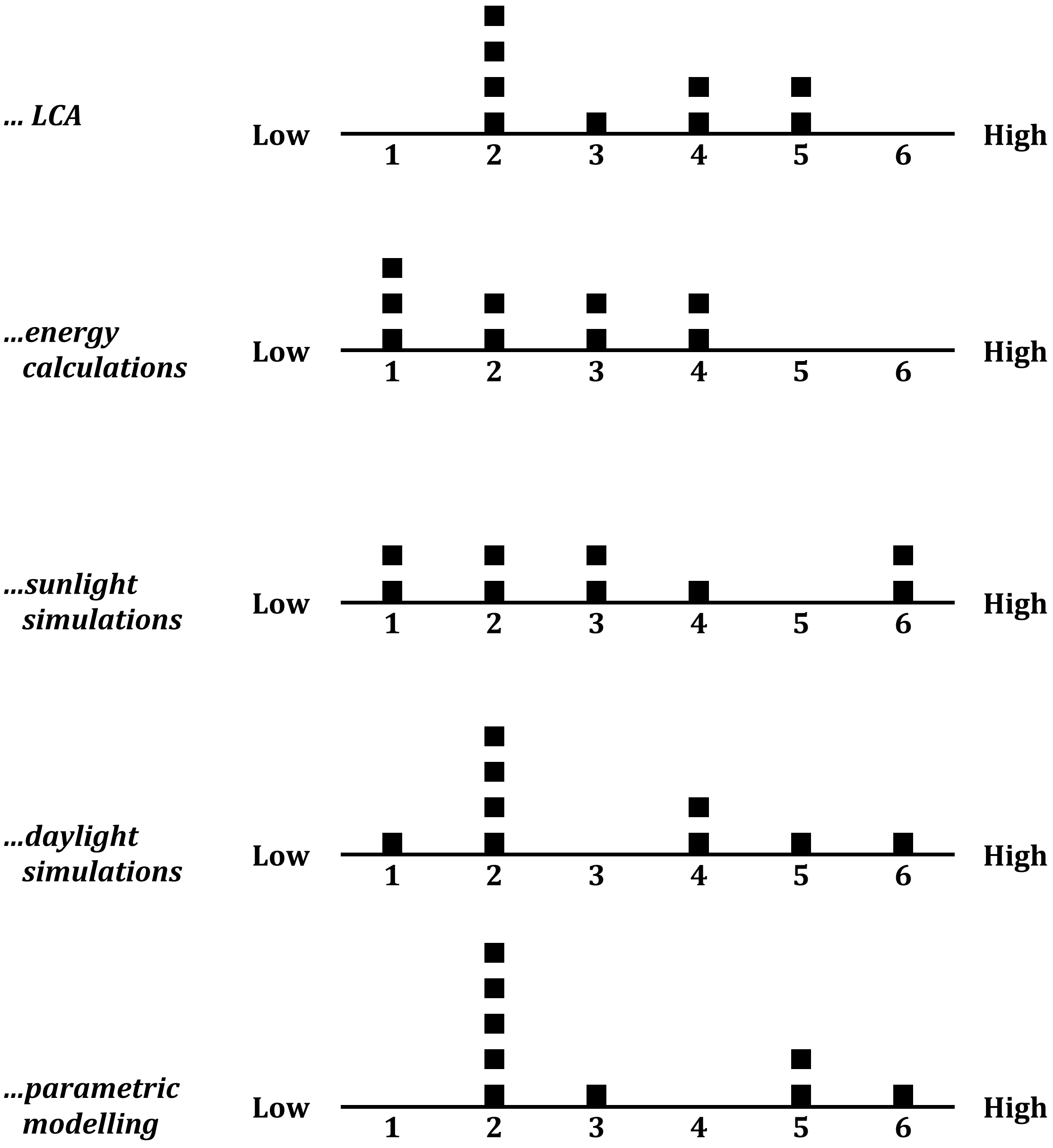
5.2.2 Results from the survey

The respondents graded their own experience regarding; LCA, energy calculations, daylight simulations, sunlight simulations, and parametric modelling as shown in Table 33.

This question aimed to clarify from which knowledge background the response in the survey comes from. A rather diverse estimation of the respondents' own knowledge was received, Table 33. All topics in the question included a big span in the answers from low to high, but the response regarding energy calculations is the most unified, tending towards low to moderate knowledge. This is important to bring into the interpretation of the results.

Table 33 The respondents' rating of their own prior knowledge.

1. ***The respondents rating of their own competence and experience regarding…***



5.2.2.1 General impressions of the tool

The following four questions (2-5) aimed to capture the respondents' overall impressions of the tool.

2. ***What is your first impression of the tool?***

The respondents express an interest and importance in the topic the first impressions included that the tool has potential to be useful and helpful in early design stages. Both to assess impact of design choice and to increase awareness of the client and establish sustainable solutions in early stages. The tool is said to be well suited for quick assessments in early stages design. The comments also included a statement that the tool at first sight felt complex and difficult to overview, but another answer regarded the tool as easy to understand.

3. ***In what stages/ situations in design would the tool be useful?***

The stages of design when the tool could be useful according to the survey respondents included: property development, detailed development plan work, initial studies, and investigations, especially during the first sketches of the architectural design, before the massing of the volume and the placement on the site have been determined. It has the potential to be used to motivate decisions in communication with clients, for instance in workshops, and to increase the understanding of the topic.

4. ***In what type of projects would the tool be useful?***

The response included answers ranging from schools, offices and residential buildings to urban planning projects and architectural competitions. One reflection was that the tool may be better suited for projects of larger scale since more generalisations can be made in those projects, indicating a potential for application in urban planning.

All projects would benefit from simple and quick comparisons. Since the focus of the tool is on early design stages it has the potential to be comprehensive for all types of projects, in particular larger projects where a larger budget for the conceptual phase exists.

5. ***What do you think can prevent/limit the use of the tool in practice?***

The answers mentioned that limited knowledge of the user is one important aspect for the implementation in practice and for the correct application in projects. Especially when it comes to the trust and interpretation of the results and translating them into design.

Another aspect is that it is yet another tool to learn and may therefore imply a resistance for uptake in practice. One answer said that limited interest and knowledge in Rhino and Grasshopper probably would be the largest barrier. Specifically, the Grasshopper interface is complicated for the novice and could prevent widespread use. However, one respondent thought that the demo showed a reasonable level regarding technical complexity, since it is reasonable to expect a certain level of skill from the user.

A key factor is also the flexibility in the geometry modelling and level of complexity to import your own geometry from other software since sketching may occur in other software.

Two of the respondents provided comments on the relation to early design stages, highlighting the importance of how fast the tool is, both in calculations and also for the user. It is essential not to slow down the quick and intense iterative process in early stages.

5.2.2.2 Required knowledge

The following four questions (6-7) aimed to capture the level of required knowledge of the tool.

6. ***The tool can be used independently by you in early stages to make decisions based on LCA and BPA aspects.***

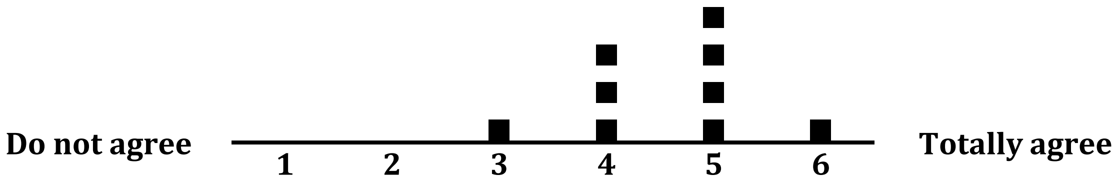
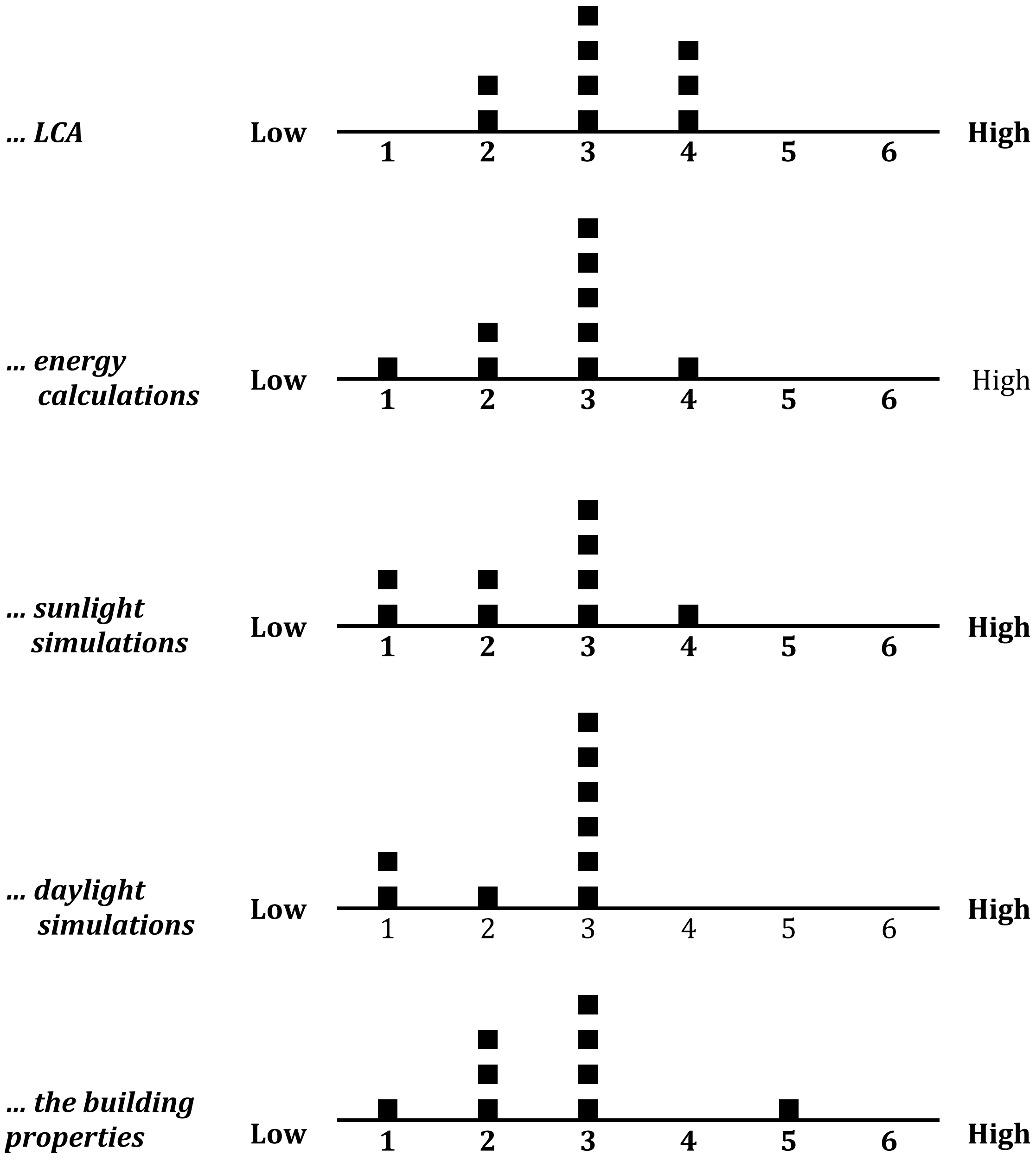


Figure 55 The respondents' rating of independent use of the tool.

Table 34 Rating of the knowledge required to use the tool.

7. ***Rate the required level of knowledge the tool demands from the user from your perspective as an architect about…***



The responses in Figure 55 show that the respondents to a large extent agree that the tool can be used independently by them. However, additional comments explained that knowledge about the main parameters in the tool is required and that some input from experts may be needed to assign correct material data unless the database in Excel is prepared.

The majority of the answers shown in Table 34 show that the required knowledge to operate the tool is graded between low and medium. Additional comments state that specific knowledge is mainly required for the interpretation of the results. Another comment says that knowledge in Rhino and Grasshopper is essential. One respondent stated that the need for U-values and LCA data for building components may require specific knowledge from the user.

5.2.2.3 Design supportiveness

The following questions (8-13) aimed to capture the design supportive character of the tool.

8. ***The tool supports architects to make decisions based on both LCA and BPA aspects in early design stages.***

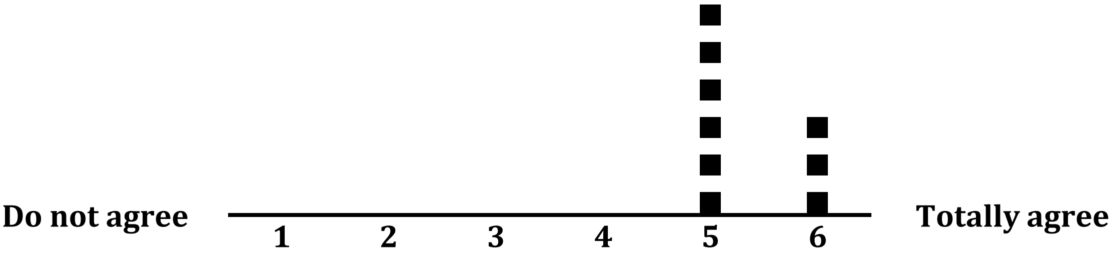


Figure 56 Rating of the tool's supportiveness in early stages.

Figure 56 shows that the respondents rate the supportive character of the tool highly.

9. ***The tool provides clear feedback on how design decisions influence the LCA and BPA aspects.***

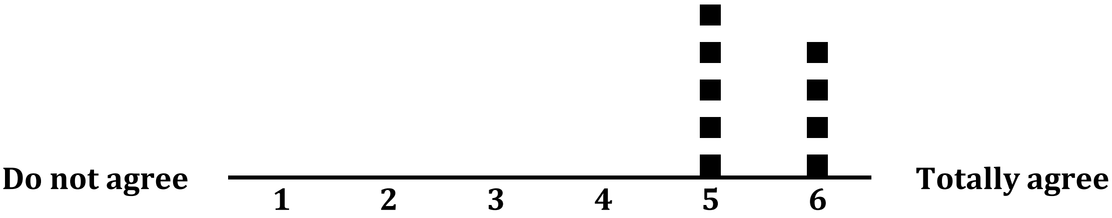


Figure 57 Rating of how the tool clarifies the influence of design decisions.

Figure 57 shows that the respondents agree that the tool clarifies how design decisions influence the LCA and BPS results.

10. The tool clarifies LCA and BPA aspects in conflict with each other.

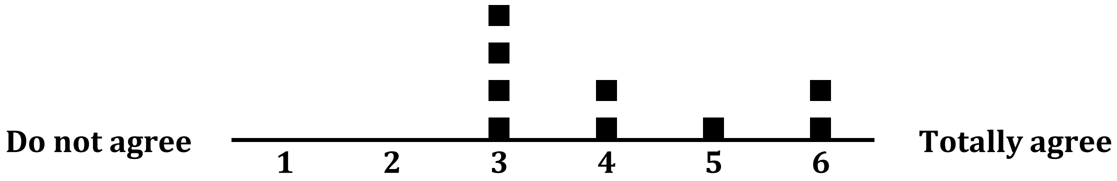


Figure 58 Rating of the tool’s capability to capture LCA and BPS aspects in conflict with each other.

Figure 58 indicates a varying perception about the capability of the tool to capture conflicting LCA and BPS aspects, primarily in the medium to high range.

11. The tool indicates critical/problematic areas in the design in regard to LCA and BPA aspects.

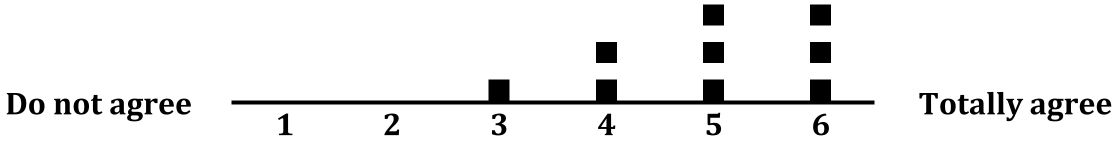


Figure 59 Rating of the tool’s capability to capture critical areas in design.

Figure 59 indicates that the respondents rate the capability of the tool to indicate critical areas in design on a medium to high level.

12. The results are visualized in a way that supports the design process.

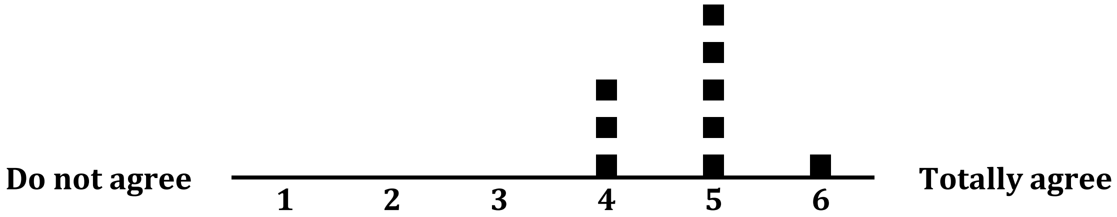


Figure 60 Rating of the supportiveness in early design stages of visualizations.

Figure 60 shows that the respondents agree to a large extent that the results are visualized in a supportive way.

13. What would make the tool even more design supportive?

In its current state, the tool focuses on comparing alternatives internally within a project. One way to increase the supportiveness could be to include references on limiting and good performance values to a larger extent.

A recurring comment is that the interface can be simplified and potentially outside Grasshopper for easier application of the tool. The closer to the sketch that the results can be presented the easier it is to make quick decisions. Architects work in a wide set of software, and a lot have never used Rhino/Grasshopper. Therefore, it would ease the use if the tool existed as a plug-in for the most common software with a simplified user interface.

Another suggestion was to provide the possibility to weight the indicators according to their importance for the individual project and to highlight the relation between the considered indicators.

Finally, comments regarding the flexibility of the design alternatives, generated by the tool, was provided as architects may want to influence the design even more than by the provided parameters.

5.2.2.4 Relevance to architects

The following questions (14-17) treated the relevance for architects of the tool.

14. ***The input and choices made in the tool are relevant for you as an architect in early design stages.***

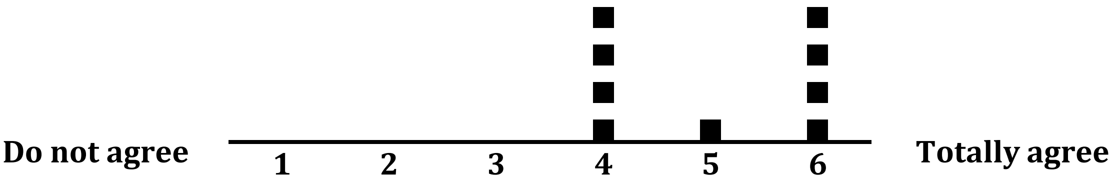


Figure 61 Rating of the relevance of the input in the tool.

As Figure 61 shows, the input and choices made in the tool are rated to be relevant for architects in early design stages on a medium to high degree. Additional comments say that the window to wall area ratio may be hard to know, but that overall, the parameters are relevant. Another respondent likes the possibility to exclude components by assigning zero values in the Excel database.

15. ***The results from the tool are relevant for you as an architect in early design stages.***

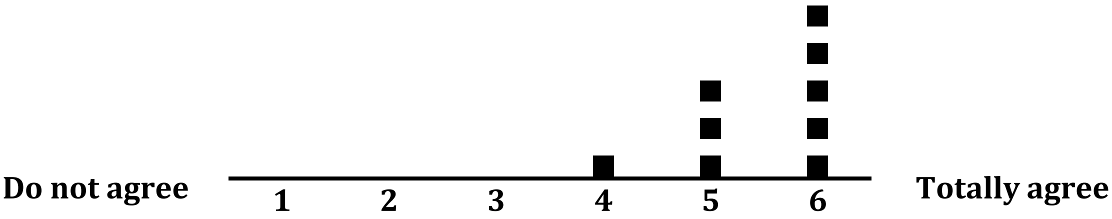


Figure 62 Rating of the relevance of the results produced by the tool.

The answers seen in Figure 62 are consistent in saying that the results provided from the tool to a high degree is relevant for the early-stage architectural design process.

16. ***Are there any input/ choices/ results that you are missing in the tool?***

One comment in the response expresses that the number of choices and parameters is well weighed for the purpose of the tool. Several answers states that it is hard to answer the question without having used the tool in a real project. One suggestion is to include input about the site, for instance, ground material since it affects the environmental impact.

17. Are there any inputs/choices/results that are superfluous/irrelevant in the tool?

One comment expresses a thought that the sunlight analysis in its current state is not relevant since it is the solar access in the interior that is interesting and dimensioning of the design, not the access of sunlight on the façade.

5.2.2.5 Applicability in early design stages

The following four questions (18-21) aimed to capture the tool's applicability in early design stages.

18. The tool can easily be integrated/used in early design stages.

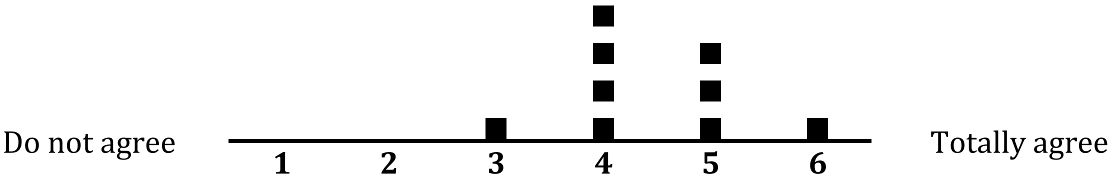


Figure 63 Rating of the level of applicability of the tool in the early design stages.

Figure 63 shows that the respondents on a medium to high level agree on that the tool is easily integrated in the early stages of the design process.

19. The level of detail in the 3D modelling of the building is...

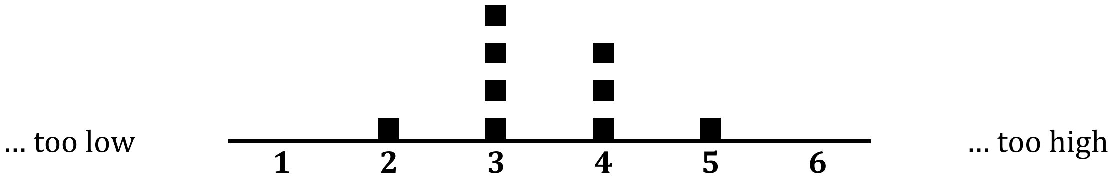


Figure 64 Rating of the level of detail in the building geometry modelled in the tool.

Figure 64 shows a varying perception about the detail of the building geometry but in summary indicating an adequate level. Comments provided suggest that a possibility to model simple facades including windows would be a great improvement. Another respondent would like to see a reversed process: instead of generating a volume from a set of parameters, applying the set of parameters to already defined volumes.

Table 35 indicates that the respondents generally consider the input in the tool to be on an adequate level in relation to early design stages, although complementary comments stated that better answers could be provided if the tool had been tested in a real case. The importance of predefined components in the Excel database was also expressed by a respondent.

Table 35 Rating of the level of detail in the input in the tool in relation to early design stages.

20. *In relation to early design stages: The level of detail on the input and choices made in the tool are, regarding…*

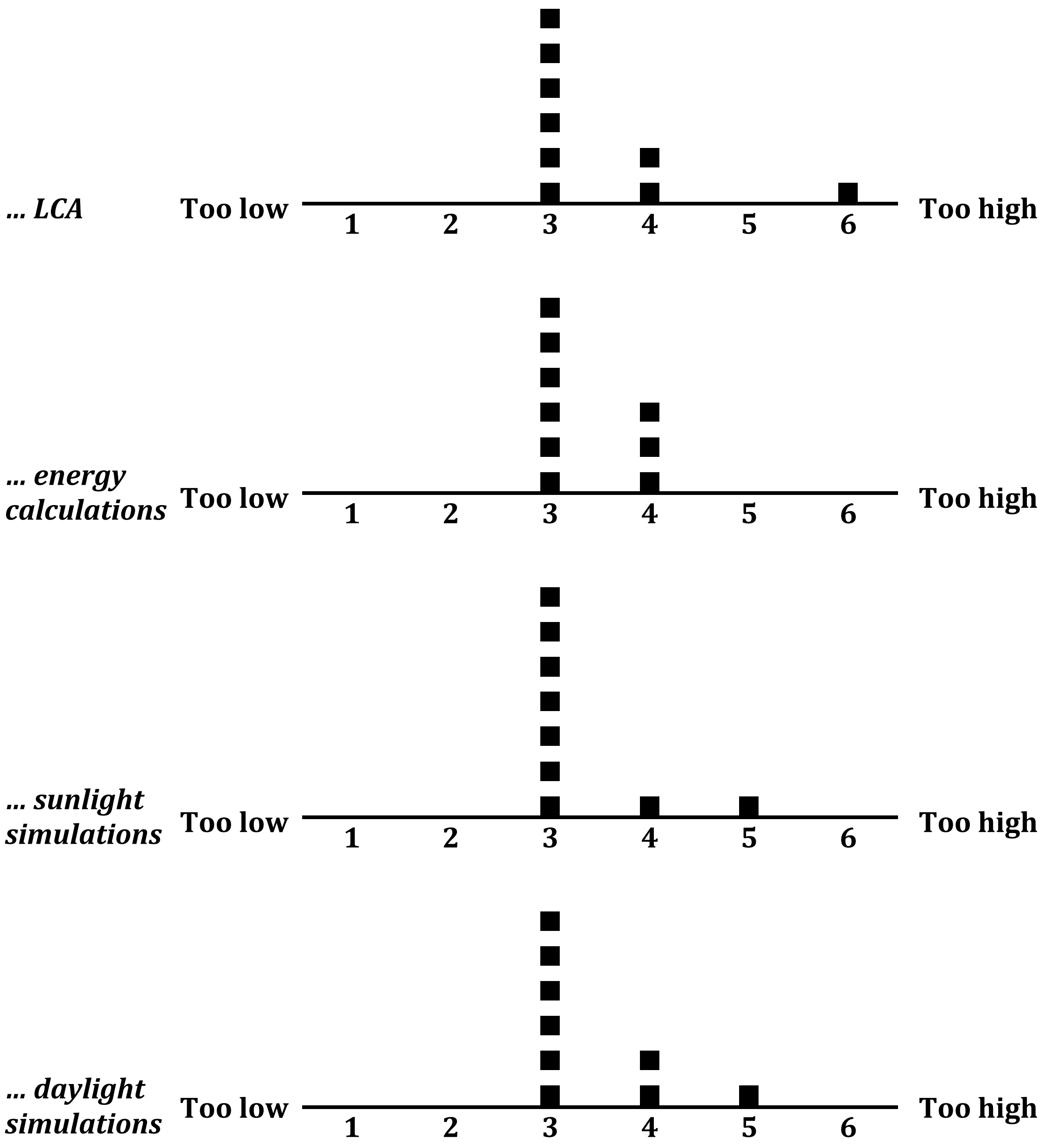


Table 36 Rating of the results' level of detail in relation to early design stages.

21. In relation to early design stages: The level of detail of the results are, regarding…

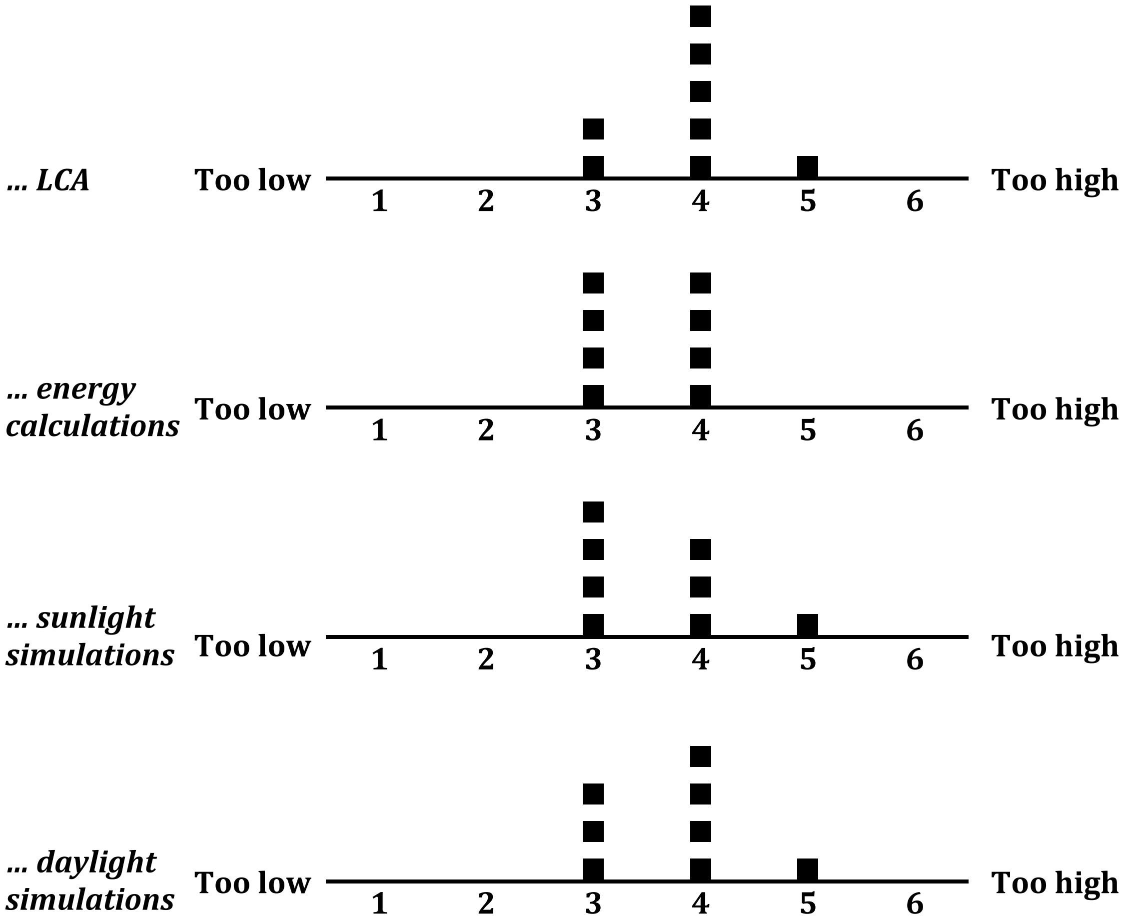


Table 36 shows that the respondents rate the detail of the results on a good level, slightly towards too high detail.

5.2.3 Summary of results

The response in the survey and the discussions during the demonstration varied a lot, as did the respondents' rating of their own experience regarding the covered aspects in the project. However, the responses in the survey questions can be summarized to give an overview of the tool evaluation.

The responses to the questions with rating answers are compiled in the radar chart in Figure 65, with the minimum and maximum grade provided by any respondent, as well as the overall mean grade. It shows that the respondents consider the tool supportive, clarifying the influence of design decisions and that the assessments implemented in the tool are relevant for the scope of early-stage design.

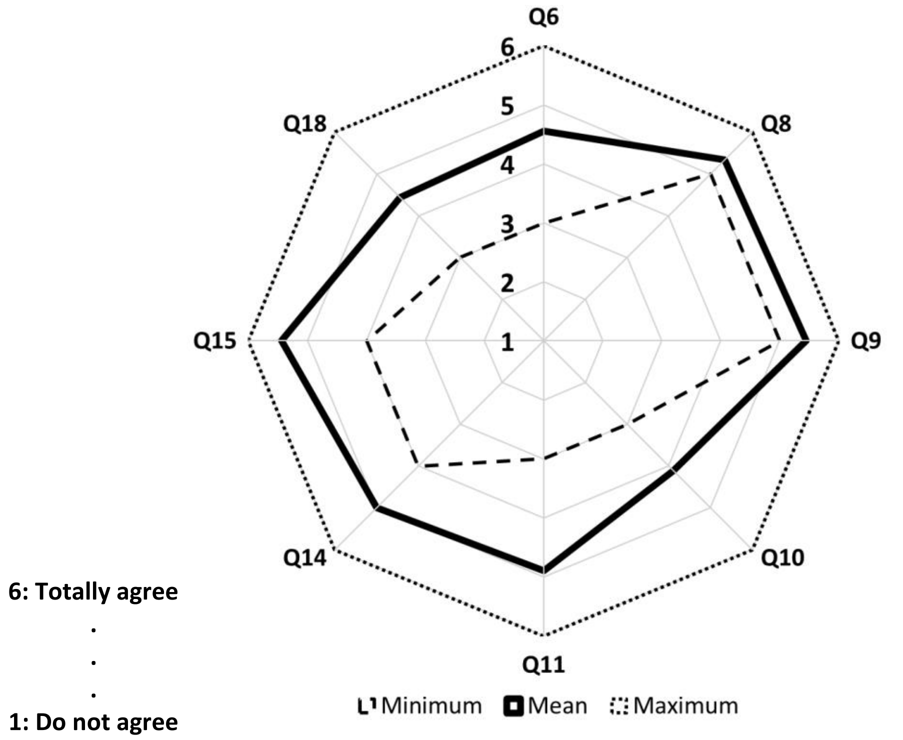


Figure 65 *Summary of the responses to the rating questions in the survey.*

Questions included in the radar chart in Figure 65 are listed in Table 37.

Table 37 *Questions for summary of results.*

Nr	Question
6	The tool can be used independent by you in early stages
8	The tool supports decision-making based on LCA/BPA aspects
9	The tool provides clear feedback on decisions influence on the indicators
10	The tool clarifies LCA and BPA aspects in conflict with each other.
11	The tool indicates critical areas in the design regarding LCA/BPA aspects.
12	The results are visualized in a way that supports the design process.
14	The inputs are relevant for you as an architect in early stages.
15	The results are relevant for you as an architect in early stages.
18	The tool can easily be integrated/ used in early design stages.

It should be noted that the responses regarding the capability of the tool to clarify conflicting aspects are rated the lowest. It indicates that the relation between the implemented indicators needs further refinement. Other aspects rated slightly lower are the applicability in early design stages and the possibility for independent use in early stages. Comments regarding this suggests that this is related to the technical knowledge needed for use of Grasshopper and the limited flexibility regarding the input of geometry.

Altogether, the responses to the evaluation indicate a good potential of the tool as a concept for applicability in early design stages, addressing the defined requirements, and suggests valuable points for improvement.

6 Discussion

This chapter discusses the methods, results and the corresponding limitations of the project and provides recommendations on further development.

6.1 Literature review

The literature review treated application of LCA and BPA tools in early design stages and the barriers limiting, or preventing, the uptake in design practice. The identified barriers for application of LCA and BPA in early design stages overlap to a large degree as they can be derived to origin from similar sources, namely, the user (the building designer), available resources, established working methodologies and industry demands.

Of the identified barriers, a differentiation can be made into two types: preventing and limiting barriers. On the one hand, barriers such as lack of awareness and absence of demands stressing the design stages prevent LCA and BPA from being performed. On the other hand, barriers such as difficult interpretation of results limit the influence of assessments on the building design.

As the review is based on previous studies that were conducted through surveys and interviews, the results are derived from summarized response from a large number of architects. It therefore captures the most extensive and widespread aspects regarding application of LCA and BPA in architectural design. In addition, the barriers for the application of LCA and BPA in the described context seems well-documented and established as stated by Purup and Petersen (2020). The identified barriers are recurring in the reviewed sources and to a large extent relate to fundamental characteristics, such as the quick and intuitive attributes of the early design stages, the detailed and comprehensive aim of building performance and life cycle assessments, as well as the discrepancies between different disciplines involved in building design.

Since the thesis is conducted in the Swedish context the aim was to consider papers based on recent investigations relevant for the Swedish industry. As there was a lack of literature focusing on the Swedish context, literature from other European countries was considered to be representative and the focus was on aspects considered to be universal and consistent in a long-term perspective.

6.2 Tool review

The tool review focused on workflows, required knowledge, and adaptability of parametric tools in Grasshopper. It was also performed to find similarities and conflicting characteristics of LCA and BPA tools designed for early-stage assessments.

The characteristics of the tools were to a large extent defined by the extent to which the calculation methodologies were standardized and guided the user through the assessment. A relation was seen between the experienced flexibility of the tools and the required knowledge from the user. A higher adaptability of the tool introduced more decisions related to simulation and calculation procedures and therefore a more profound experience regarding LCA and BPA was required to use those tools.

The review indicates that the workflow of BPA tools is the limiting factor for an integration with LCA tools, both regarding required knowledge and workflow adaptability. This is primarily due to the geometry in BPA tools requiring a well-defined and simplified geometric definition that is further integrated in the calculation model. The use of the LCA tools only requires that the geometry is organized according to material or component type. In addition, the BPA tools involves more input beyond geometry and material properties, such as climate data, occupancy and technical systems which introduces several assumptions.

In summary, the LCA tools in general had a clearer consistency in the workflow built on the methodological framework of LCA. The BPA tools, on the other hand, included a larger diversity in the type of assessments, coming from many disciplines. This was experienced as a difference in the adaptability of the tools. The LCA tools had a strictly standardized calculation methodology, whereas the BPA tools allowed for a flexible change of scope of assessment. For instance, sunlight assessments could consist of either direct sunlight hours or irradiance simulations.

It should be mentioned that the nature of the Grasshopper environment allows for alternative ways to use the same plug-in and customize scripts for the specific purpose at hand. Hence the outcome of the review could differ in another context.

6.3 Tool development

The incremental prototyping method applied in the development utilized the possibility to develop individual prototypes in parallel. The separation allowed for a quick iterative development of each prototype which was a key aspect in this project to implement updates in each prototype. In that way the prototypes could be developed along the project process and individually adapted to the tool requirements.

Another advantage of developing the prototypes in parallel was the possibility to individually assess and review the LCA, energy, daylight, and sunlight prototypes with experts from the industry related to each topic.

The experienced drawbacks with keeping the prototypes separated in the development was that it limited the interrelation between the different assessments. For example, a more refined integration of the daylight and sunlight assessments could have been possible if developed in combination. This is by the author believed to limit capability of the tools to capture the sophisticated relation between the performance indicators. In that way, prototypes closely related to each other lead to overlapping work in the tool development.

Nevertheless, by separating and developing the prototypes strictly according to each analysis method, as done in this project, the method can be used to identify subtle differences the type of assessment in the prototypes.

Therefore, a critical phase in the development was the merge of the prototypes into a common framework structure. The merge of the prototypes confirmed the expectations from the tool review that the BPA would be the limiting aspect in the integration. Extra attention was put on getting the correct geometry definition for implementation in the daylight and sunlight simulations to ensure appropriate orientations and sensor grid placements. Consequently, this was limiting the flexibility in the geometry modelling compatible with the tool.

The review and feedback sessions confirmed the findings in the literature review about the current implementation of LCA and BPA in building design. The primary application of these types of assessments are in the late stages of design for compliance with regulations while the early design work is often characterized by the minimal effort invested in these stages. There was an agreement that factors such as the limited time, budget and demands restricts further implementation. Daylight and sunlight simulations was regarded as the main performance aspects involved in the early design together with an increasing application of LCA.

The most defining decision done in the tool development was based on the discussion in the review and feedback session of the energy prototype. It treated whether to implement a simulation or calculation estimating the energy performance or limit the implementation to a simplified indicator. The approach proposed was to minimize the dependency on assumptions related to other professions and to instead limit the tool to the aspects relevant and in control of architects in their early design process, namely geometry and material. It is believed to increase the transparency of the tool and make it less dependent on assumptions that may not be valid in next stage of design.

The developed tool is built upon the combination of simplified performance indicators on environmental impact, energy, sunlight, and daylight. The focus in the development was to implement assessments based on input relevant to architects and limit the use of assumptions related to other disciplines. Instead, the tool implements indicators directly related to the architects' main parameters to influence design in the early stages, namely geometry and material.

The energy indicator is simplified to a combination of U-value and form factor but holds benefits for early-stage application. It provides a direct connection between geometrical design and choice of material and thereby entirely related to parameters controlled by architects in early stages. This was the reason why Interviewee 4 proposed the indicator in the review and feedback session. In addition, it is connected to the embodied carbon indicator though the geometrical and material aspects implemented.

The embodied carbon indicator provides a simplified assessment of the environmental impact for quick evaluation of design alternatives both by evaluating different material choices but also for trade-off with daylight, for example.

The advantage of using VSC as a daylight indicator is that VSC have been identified as powerful for early-stage assessment. This has led to the development of models such as the Advanced VSC method by Pacheco et al. (2021). The method provides a link between exterior façade conditions and interior design which is supporting the design development.

The room depth provided from the Advanced VSC method is also utilized in the sunlight indicator. Sunlight is often evaluated for critical rooms but the implementation in the tool provides the maximum total solar heat load for the light floor area estimated from the daylight indicator and hence a combination of daylight and sunlight potential is derived from the tool. However, it should be noted that it is difficult to interpret, especially in early stages, whether sunlight is an asset or a drawback. Thereby the solar heat load may be regarded as the least relevant indicator for architects in this type of tool. Nevertheless, it is included since it is to a large extent determined by the building geometry.

The tool provides two approaches for the evaluation of building design. It can be used to identify critical areas in design through the mapping of the results onto the geometry or used for comparative evaluation of several design alternatives based on the provided indicators. The main benefit of integrating the performance indicators into a common interface is that both conforming and conflicting aspects are captured and hence the multifaceted influence of design decisions are captured.

6.4 Tool evaluation

Due to the limited selection of attendees in the evaluation one should be cautious about the feedback and results from the tool demonstration and survey. Therefore, the answer base should be further studied and extended to ensure that they reflect a representative selection of the industry.

However, the answers still provided useful comments and indications about the tool performance. The respondents rating of their own competence showed a large variation, both capturing the user persona described in Section 4.2.1 as well as more experienced users. The evaluation basis therefore responds to a diverse point of departure among the respondents.

The reason for evaluating the tool by a demonstration, rather than user tests, was to be able to include respondents with limited experience in Rhino and Grasshopper and ensure that core functionality of the tool is shown to the attendees. In addition, it allowed for evaluation of the tool focusing on the aspects of the integration of LCA and BPA in relation to design practice.

However, comments from the attendees in the demonstration sessions and the survey addressed that testing the tool on real projects would allow them to provide richer feedback.

The attendees showed a large interest in the topic and could see several benefits of application of the tool for communication with clients and argumentation for design decisions in early stages. They considered it suitable for many types of projects such as schools, offices, and residential buildings, specifically in larger projects where generalizations can be made, and the budget allows for investigations in the early stages. A potential for application in urban planning was also highlighted by the evaluation.

The survey revealed possible barriers restricting the implementation of the tool in practice. These were mainly related to software issues. For instance, the complicated interface of Grasshopper, the technical knowledge required related to it and that it is an additional tool to learn. However, the approach towards these aspects where differing a lot and the feedback depended on the individual experience, specifically regarding parametric design, Grasshopper and Rhino. The feedback also highlighted that the limited flexibility in the modelling of the geometry could interfere with the design process and restricts the applicability.

Nevertheless, the fast iterations and reduced input to create and evaluate design alternatives was considered as a key factor for the applicability of the tool. Overall, the responses highlighted a promising potential for application of a tool like this in early design stages to support the architects' decision-making. It was considered to be adequate for independent use by architects due to the limitation to parameters in their control in early stages.

6.5 Further development

This thesis is based on the notion that the implementation of LCA and BPA, respectively, in the early design stages allows building designers to inform their decisions when they have the largest impact. Consequently, the possibility to improve the performance aspects of the design is increased. This project extends this concept by combining LCA and BPA into a framework for application in early stages. Therefore, a proposed question for research is whether this integration is increasing the probability to reach an improved building performance, compared to separate assessments, or if the advantages are only limited to the time efficiency of a combined assessment.

The incremental prototyping method used in the tool development is developed for an iterative process. Hence the natural continuation of this project would be to step into the next iteration with further evaluation, refinement of requirements and implementation in the development.

A further evaluation of the tool is proposed on one hand, through user tests with architects in real projects for a deeper mapping of the applicability in the design process. On the other hand, through validation of accuracy and reliability of the result by comparison to established software. A suggestion for further research is to investigate how well the implemented indicators relate to the final performance of the building. Thereby the indicators can be calibrated by weighting according to their internal relative impact. The possibility to weight the parameters was also proposed in the evaluation addressing the fact that the indicators vary in relevance from project to project.

The evaluation also revealed that the tool also suggested application of the tool in urban planning projects. According to the author, this aspect has a high development potential of the tool since the performance indicators are suitable on a larger scale.

Potential further research is also to develop and implement potential best-case scenarios in the tool to reveal optimization potential, in addition to the current internal comparison of design alternatives. An idea is to investigate the trade-off between the included LCA and BPA indicators to find potential tipping-points.

Finally, the author is aware that there exist other desirable aspects and indicators to develop and implement in the framework. For instance, economy was mentioned in the evaluation.

7 Conclusion

The aim with this thesis was, firstly, to identify the requirements for integrating combined Life Cycle Assessment (LCA) and Building Performance Assessment (BPA) in early stages of architectural design, and secondly, to evaluate them through implementation in an incremental prototyping method in the development of a parametric tool. The resulting tool integrates performance indicators on environmental impact, energy, sunlight, and daylight.

The identified barriers were categorized into limitations of the building designers present in the early design stages, the scarce amount of detailed information, lack of resources, deficient methodologies, and insufficient demands. The barriers for LCA and BPA show similarities. Primarily related to the difficulties in turning performance results into design decisions, limited budget, lack of demands stressing the design phase, and that tools and methods for LCA and BPA do not conform with the quick and intuitive design process when detailed data is scarce.

The tool review revealed discrepancies and potential conflicting aspects between the workflows in existing LCA and BPA tools. The workflow in the BPA tools was concluded to be the limiting aspect in an integration, predominantly because it required a stricter geometry definition since the geometry is embedded in a sophisticated way in the calculation models compared to the LCA tools.

The identified conflicts and demands were summarized into four main areas of tool requirements: required knowledge, design supportiveness, relevance for architects and applicability in early design stages. Specifically, the tool should be possible to use without expertise neither in LCA nor BPA and guide further design. It should treat design parameters in control and responsibility of architects in early stages and be quick to operate, both in input processing and calculation, to fit the early design stages.

The developed tool was evaluated through tool demonstrations with eight architects and one sustainability engineer, and a subsequent survey. The response from the demonstration indicated that the architects see a potential in utilizing this type of assessments to support their own design, but also in communication with clients. Thereby an increased awareness of these aspect can be introduced early in design. The feedback agreed that the tool is applicable in the design process, can be used independently by architects to support early stage-design, and is capturing parameters in the domain of early-stage architectural design. An expansion of the tool towards urban planning is proposed for further development.

The incremental prototyping applied in the tool development showed essential advantages due to the possibility of isolating the parallel developed prototypes and addressing the requirements in each one of them individually. However, it is crucial to establish a shared structure for all prototypes to accommodate the merge into a common framework. The main drawback was the limited interrelation between the prototypes before the merge.

Nevertheless, the method is developed for an iterative process, hence further iterations of the development would be ideal for the application and evaluation of the method. Since the tool is developed at a conceptual level further development and validation is required for application in specific projects.

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Appendix A: Tool review test case

Result from scripting the test cases in the tool review. Each plug-in was used to model and evaluate the box described in Figure 66.

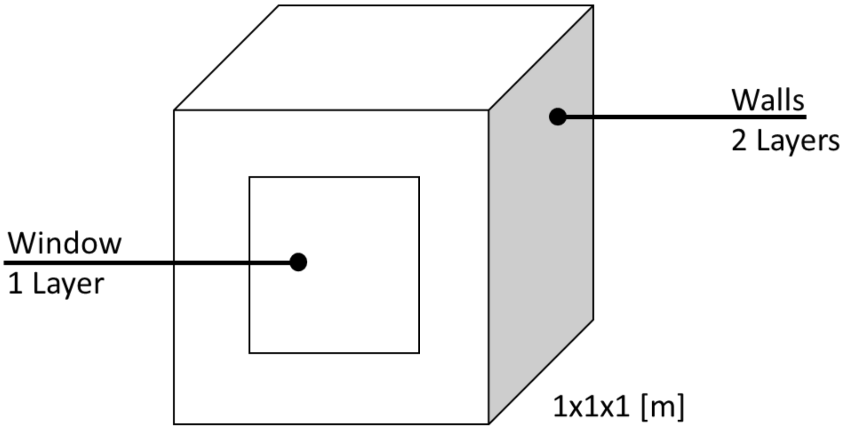


Figure 66 Geometry used in the case study.

LCA tools

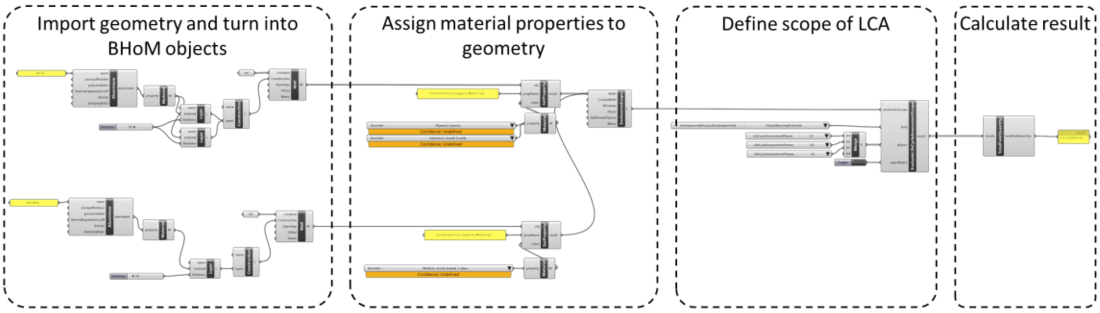
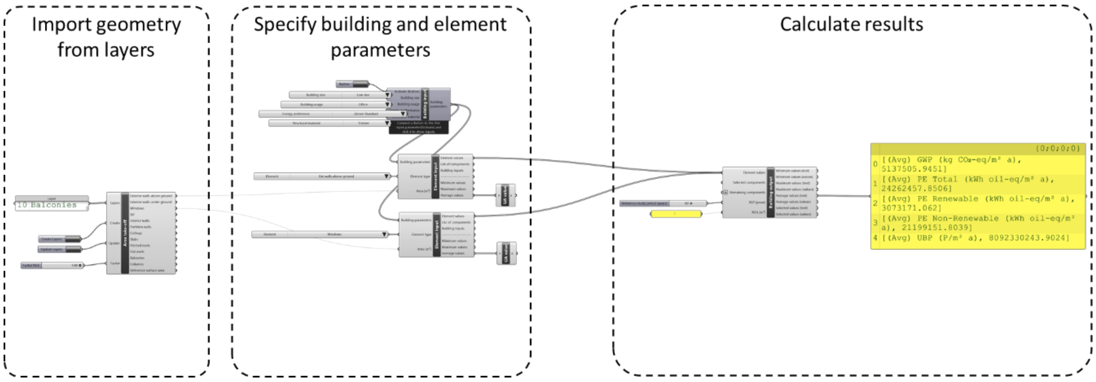


Figure 67 BHoM script for the test case.



```
                                        (0;0;0;0)
0 [(Avg) GWP (kg CO₂-eq/m² a),
  5137505.9451]
1 [(Avg) PE Total (kWh oil-eq/m² a),
  24262457.8506]
2 [(Avg) PE Renewable (kWh oil-eq/m² a),
  3073171.062]
3 [(Avg) PE Non-Renewable (kWh oil-eq/m²
  a), 21199151.8039]
4 [(Avg) UBP (P/m² a), 8092330243.9024]
```

Figure 68 Bombyx top-down script for the test case.

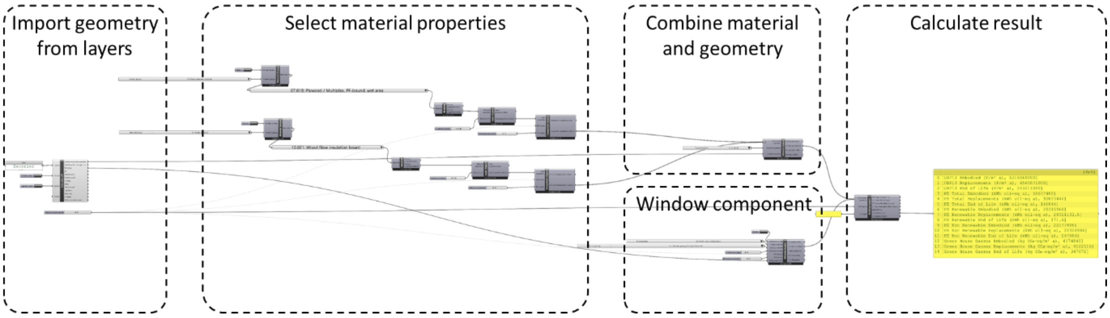
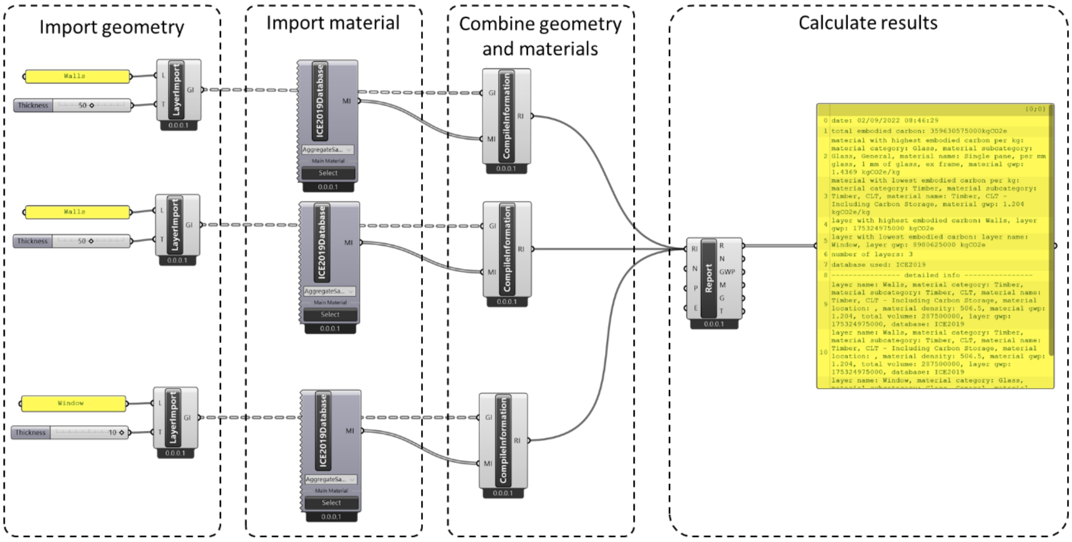
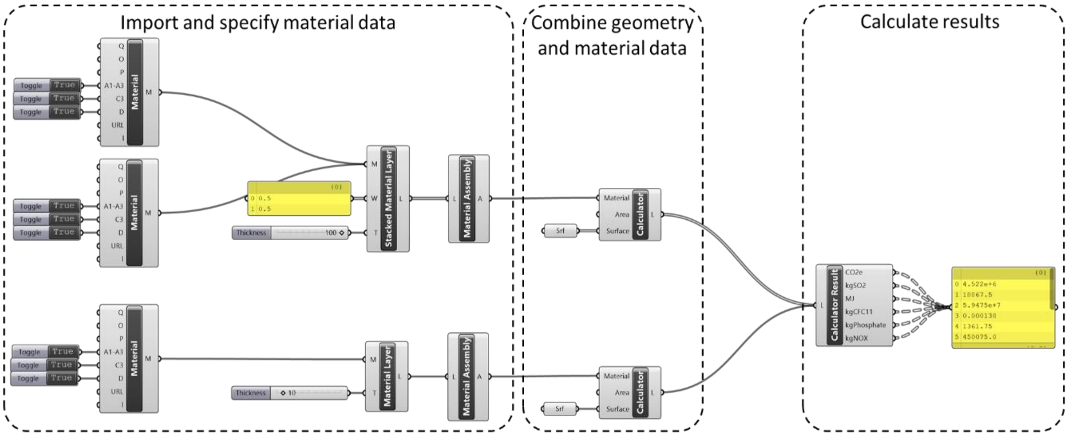


Figure 69 *Bombyx bottom-up script for the test case.*



```
{0;0}
0  date: 02/09/2022 08:46:29
1  total embodied carbon: 359630575000kgCO2e
   material with highest embodied carbon per kg:
   material category: Glass, material subcategory:
2  Glass, General, material name: Single pane, per mm
   glass, 1 mm of glass, ex frame, material gwp:
   1.4369 kgCO2e/kg
   material with lowest embodied carbon per kg:
   material category: Timber, material subcategory:
3  Timber, CLT, material name: Timber, CLT -
   Including Carbon Storage, material gwp: 1.204
   kgCO2e/kg
4  layer with highest embodied carbon: Walls, layer
   gwp: 175324975000 kgCO2e
5  layer with lowest embodied carbon: layer name:
   Window, layer gwp: 8980625000 kgCO2e
6  number of layers: 3
7  database used: ICE2019
8  ---------------- detailed info ---------------
   layer name: Walls, material category: Timber,
   material subcategory: Timber, CLT, material name:
9  Timber, CLT - Including Carbon Storage, material
   location: , material density: 506.5, material gwp:
   1.204, total volume: 287500000, layer gwp:
   175324975000, database: ICE2019
   layer name: Walls, material category: Timber,
   material subcategory: Timber, CLT, material name:
10 Timber, CLT - Including Carbon Storage, material
   location: , material density: 506.5, material gwp:
   1.204, total volume: 287500000, layer gwp:
   175324975000, database: ICE2019
   layer name: Window, material category: Glass,
```

Figure 70 *Cardinal LCA script for the test case.*



```
{0}
0 4.522e+6
1 18067.5
2 5.9475e+7
3 0.000138
4 1361.75
5 450075.0
```

Figure 71 *Tortuga script for the test case.*

BPS tools

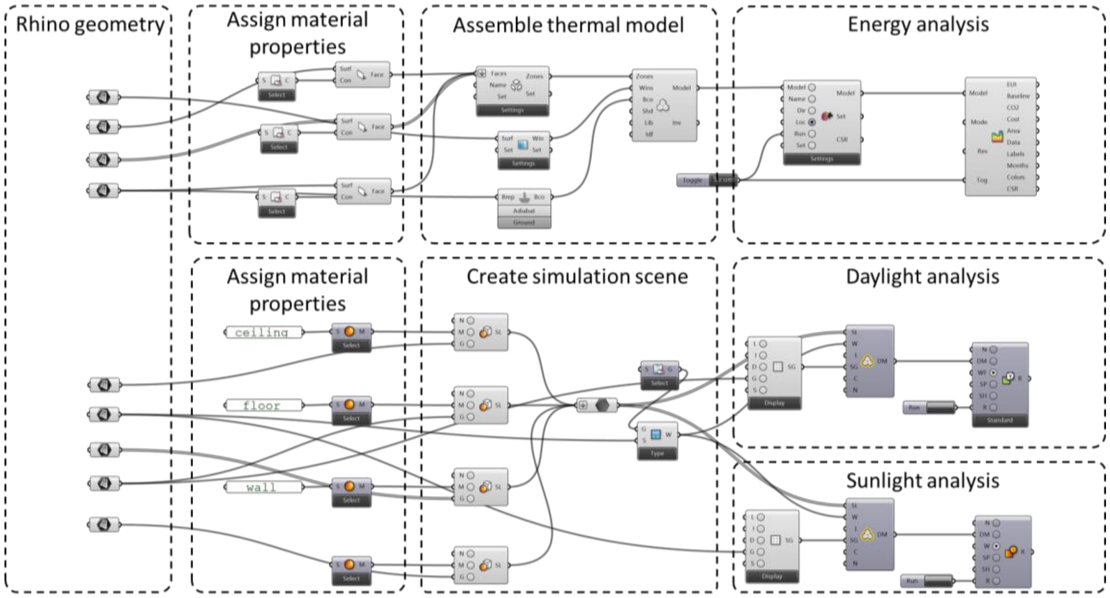


Figure 72 ClimateStudio script for the test case.

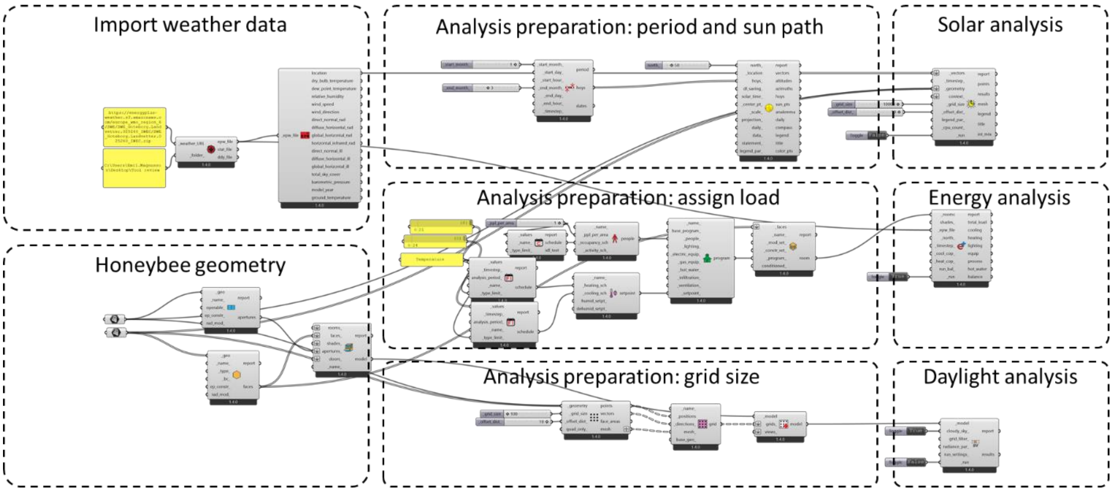


Figure 73 ICEbear script for the test case.

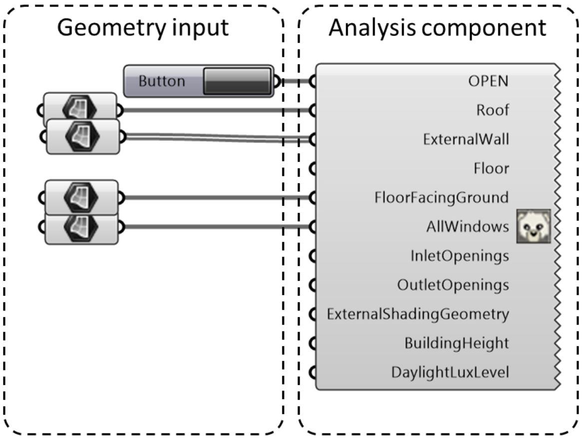
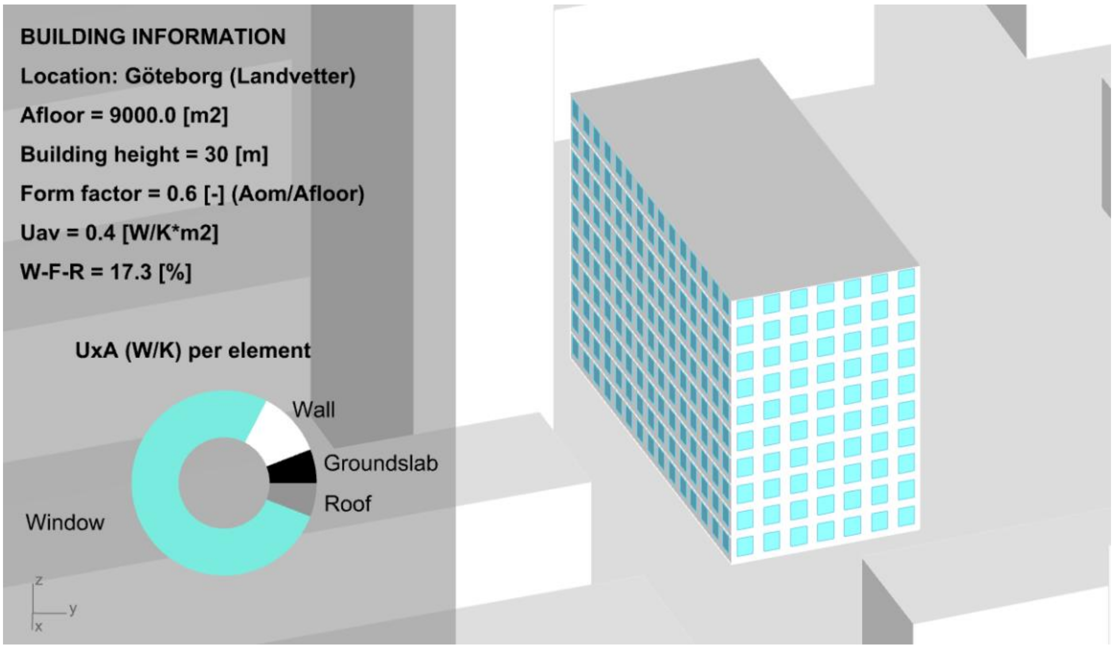


Figure 74 Ladybug and Honeybee script for the test case

Appendix B: Rhino HUD and visualization



BUILDING INFORMATION

Location: Göteborg (Landvetter)

Afloor = 9000.0 [m2]

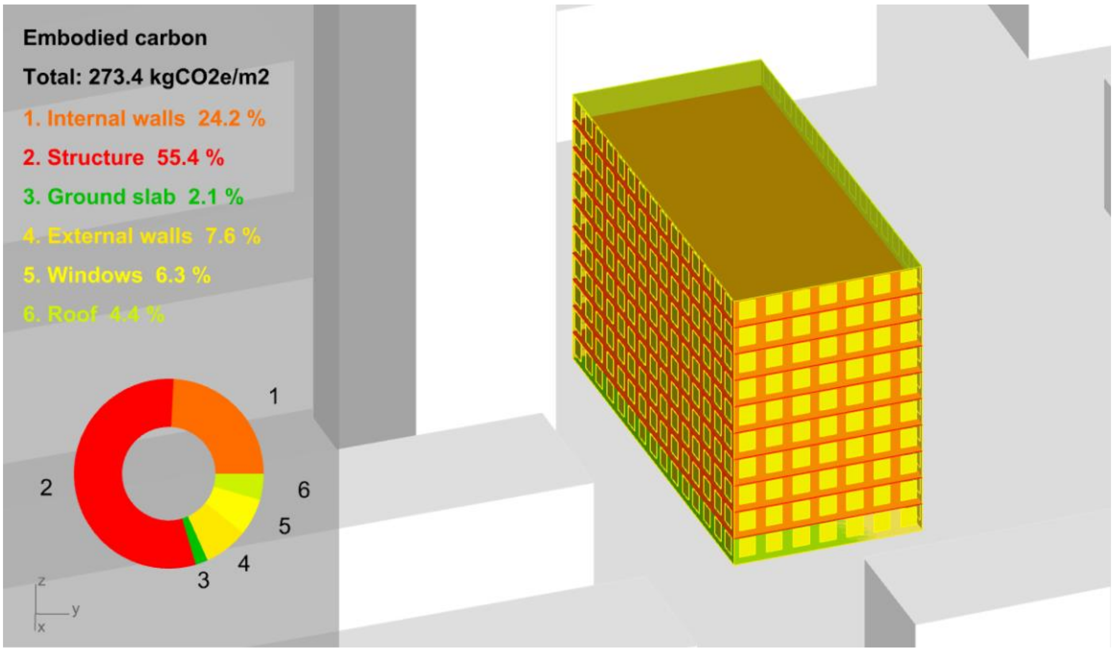
Building height = 30 [m]

Form factor = 0.6 [-] (Aom/Afloor)

Uav = 0.4 [W/K*m2]

W-F-R = 17.3 [%]

Figure 75 Visualization of the energy indicator and building information.



Embodied carbon

Total: 273.4 kgCO2e/m2

1. Internal walls 24.2 %
2. Structure 55.4 %
3. Ground slab 2.1 %
4. External walls 7.6 %
5. Windows 6.3 %
6. Roof 4.4 %

Figure 76 Visualization of embodied carbon.

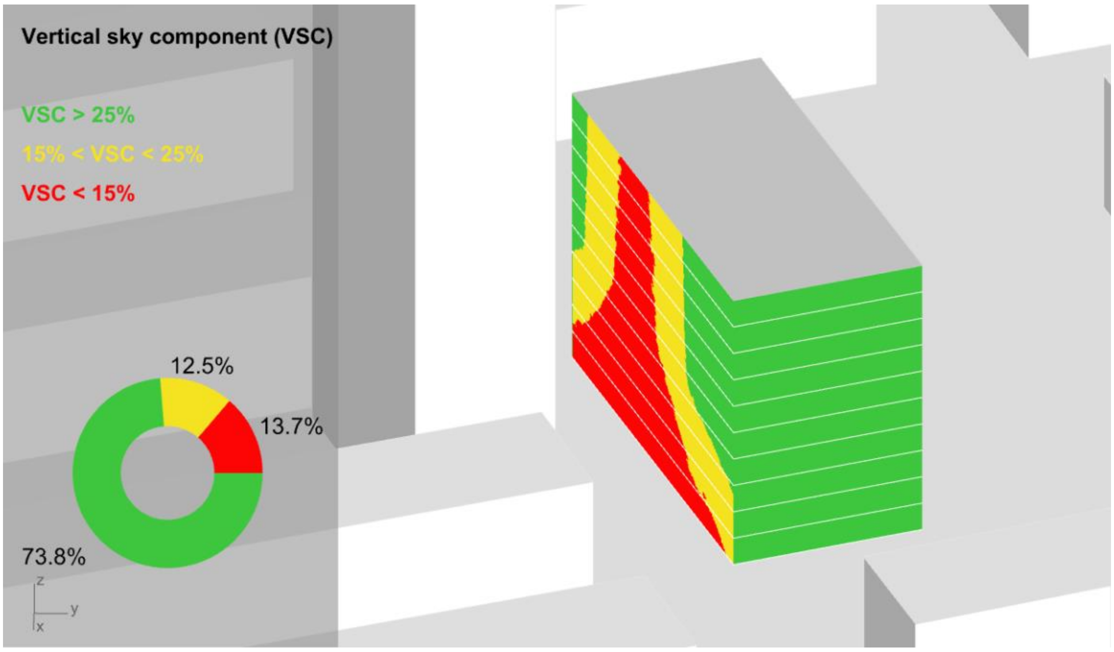


Figure 77 Visualization of the VSC results.

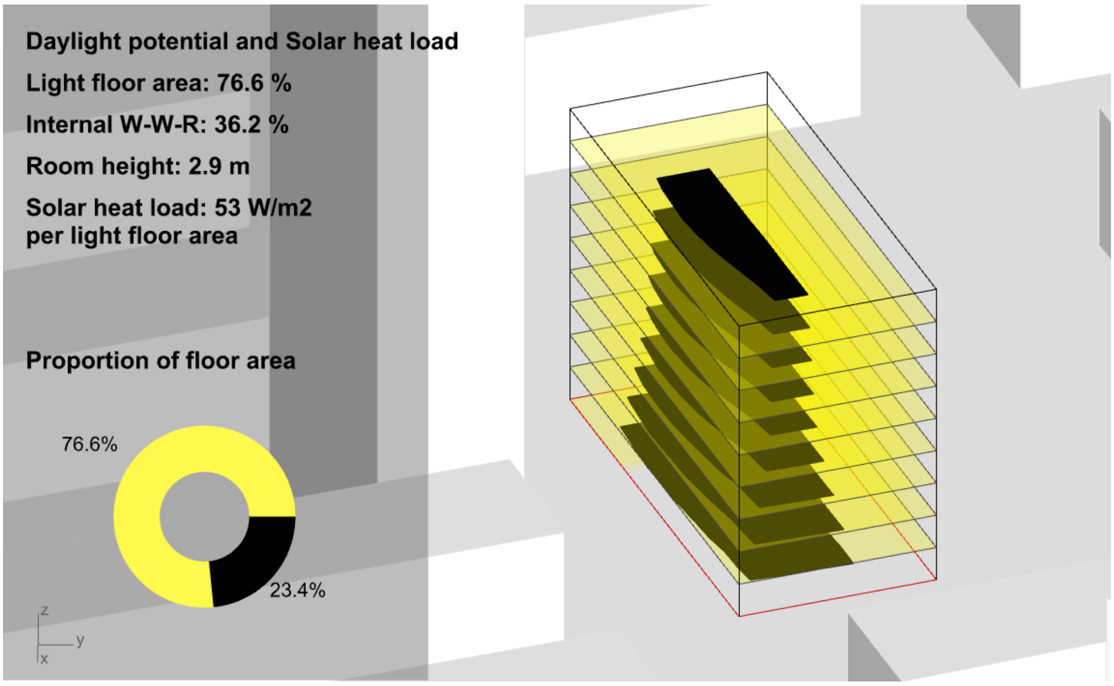


Figure 78 Visualization of the potential light floor area based on the Advanced VSC method.

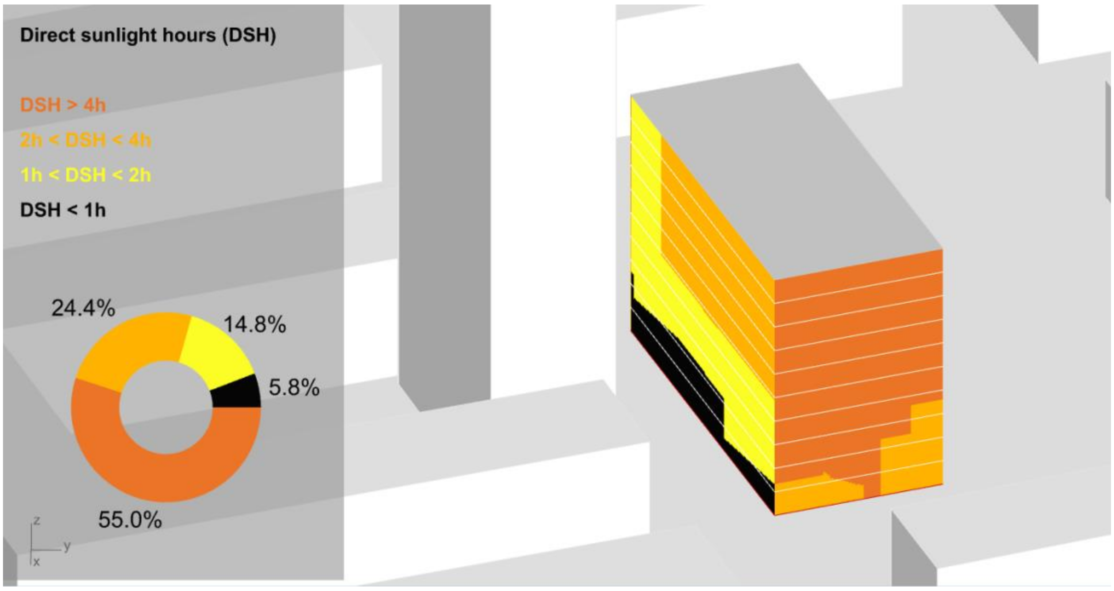
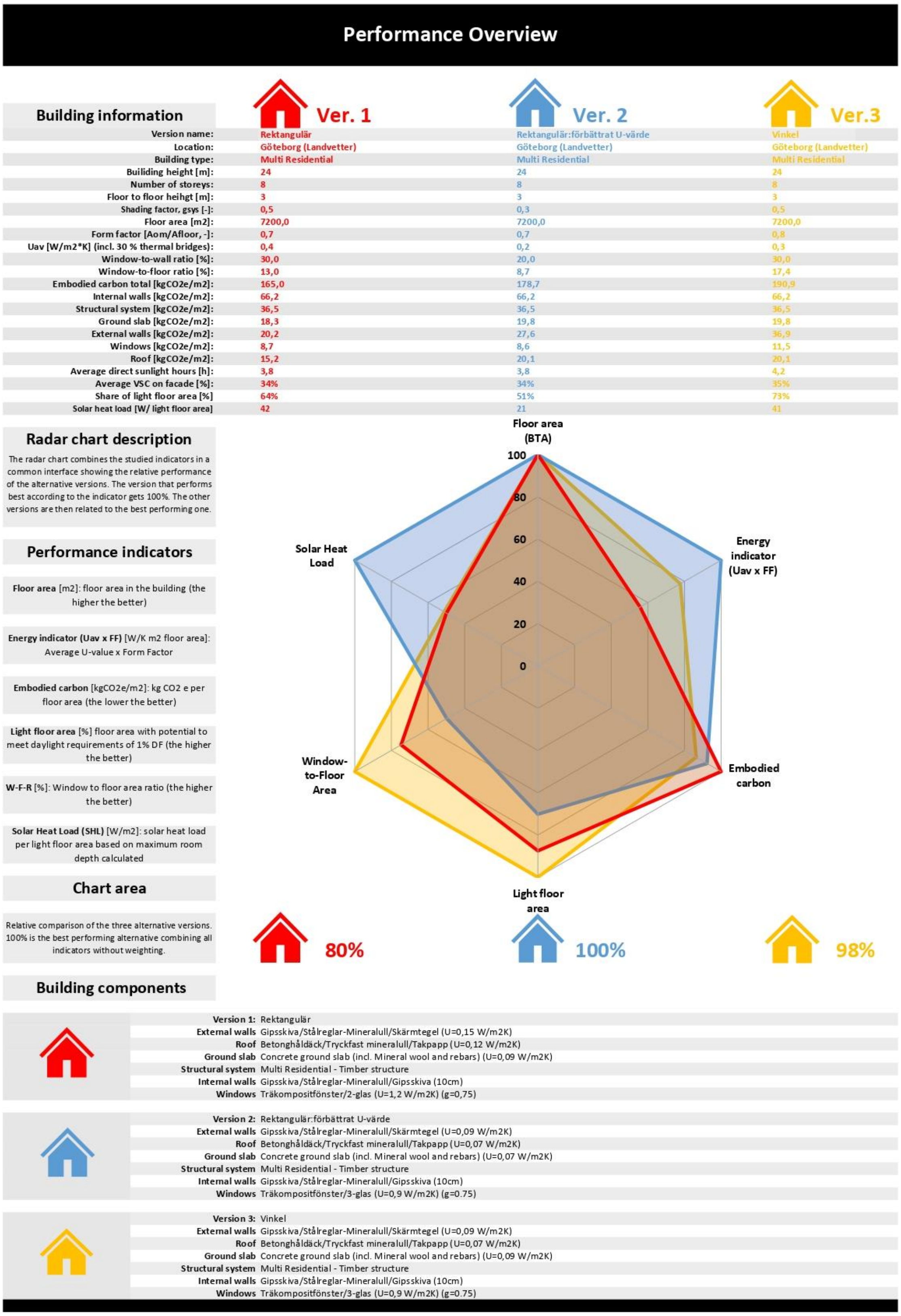


Figure 79 Visualization of direct sunlight hours.

Appendix C: Result report



Performance Overview

Building information

	Ver. 1	Ver. 2	Ver.3
Version name:	Rektangulär	Rektangulär:förbättrat U-värde	Vinkel
Location:	Göteborg (Landvetter)	Göteborg (Landvetter)	Göteborg (Landvetter)
Building type:	Multi Residential	Multi Residential	Multi Residential
Builiding height [m]:	24	24	24
Number of storeys:	8	8	8
Floor to floor heihgt [m]:	3	3	3
Shading factor, gsys [-]:	0,5	0,3	0,5
Floor area [m2]:	7200,0	7200,0	7200,0
Form factor [Aom/Afloor, -]:	0,7	0,7	0,8
Uav [W/m2*K] (incl. 30 % thermal bridges):	0,4	0,2	0,3
Window-to-wall ratio [%]:	30,0	20,0	30,0
Window-to-floor ratio [%]:	13,0	8,7	17,4
Embodied carbon total [kgCO2e/m2]:	165,0	178,7	190,9
Internal walls [kgCO2e/m2]:	66,2	66,2	66,2
Structural system [kgCO2e/m2]:	36,5	36,5	36,5
Ground slab [kgCO2e/m2]:	18,3	19,8	19,8
External walls [kgCO2e/m2]:	20,2	27,6	36,9
Windows [kgCO2e/m2]:	8,7	8,6	11,5
Roof [kgCO2e/m2]:	15,2	20,1	20,1
Average direct sunlight hours [h]:	3,8	3,8	4,2
Average VSC on facade [%]:	34%	34%	35%
Share of light floor area [%]	64%	51%	73%
Solar heat load [W/ light floor area]	42	21	41

Radar chart description

The radar chart combines the studied indicators in a common interface showing the relative performance of the alternative versions. The version that performs best according to the indicator gets 100%. The other versions are then related to the best performing one.

Performance indicators

Floor area [m2]: floor area in the building (the higher the better)

Energy indicator (Uav x FF) [W/K m2 floor area]: Average U-value x Form Factor

Embodied carbon [kgCO2e/m2]: kg CO2 e per floor area (the lower the better)

Light floor area [%] floor area with potential to meet daylight requirements of 1% DF (the higher the better)

W-F-R [%]: Window to floor area ratio (the higher the better)

Solar Heat Load (SHL) [W/m2]: solar heat load per light floor area based on maximum room depth calculated

Chart area

Relative comparison of the three alternative versions. 100% is the best performing alternative combining all indicators without weighting.

Ver. 1	Ver. 2	Ver.3
80%	100%	98%

Building components

Version 1:	Rektangulär
External walls	Gipsskiva/Stålreglar-Mineralull/Skärmtegel (U=0,15 W/m2K)
Roof	Betonghåldäck/Tryckfast mineralull/Takpapp (U=0,12 W/m2K)
Ground slab	Concrete ground slab (incl. Mineral wool and rebars) (U=0,09 W/m2K)
Structural system	Multi Residential - Timber structure
Internal walls	Gipsskiva/Stålreglar-Mineralull/Gipsskiva (10cm)
Windows	Träkompositfönster/2-glas (U=1,2 W/m2K) (g=0,75)
Version 2:	Rektangulär:förbättrat U-värde
External walls	Gipsskiva/Stålreglar-Mineralull/Skärmtegel (U=0,09 W/m2K)
Roof	Betonghåldäck/Tryckfast mineralull/Takpapp (U=0,07 W/m2K)
Ground slab	Concrete ground slab (incl. Mineral wool and rebars) (U=0,07 W/m2K)
Structural system	Multi Residential - Timber structure
Internal walls	Gipsskiva/Stålreglar-Mineralull/Gipsskiva (10cm)
Windows	Träkompositfönster/3-glas (U=0,9 W/m2K) (g=0.75)
Version 3:	Vinkel
External walls	Gipsskiva/Stålreglar-Mineralull/Skärmtegel (U=0,09 W/m2K)
Roof	Betonghåldäck/Tryckfast mineralull/Takpapp (U=0,07 W/m2K)
Ground slab	Concrete ground slab (incl. Mineral wool and rebars) (U=0,09 W/m2K)
Structural system	Multi Residential - Timber structure
Internal walls	Gipsskiva/Stålreglar-Mineralull/Gipsskiva (10cm)
Windows	Träkompositfönster/3-glas (U=0,9 W/m2K) (g=0.75)

Performance Indicators

Environmental indicator

Unit

Kilogram carbon dioxide equivalents [kgCO2e] per building gross floor area [m2 BTA]

Scope of assessment

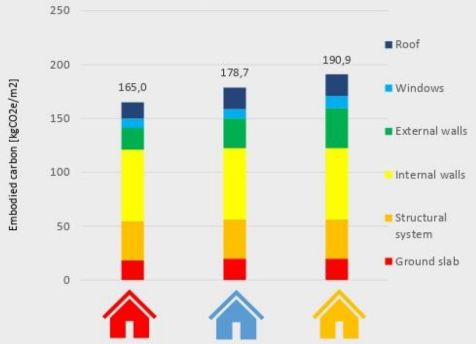
LCA modules:

Product stage	A1: Raw material supply A2:Transport A3: Manufacturing
Construction stage	A4: Transport A5: Construction/Installation

Considered elements

Structural system
Building envelope
Interior walls

Global warming potential, GWP [kgCO2e/m2 BTA]



The red line represents reference mean impact for the same type of building retrieved from "*Referensvärden för klimatpåverkan vid uppförande av byggnader*"

Energy performance indicator

The energy performance is described by the combination of two indicators. Average U-value (Uav) of the thermal envelope and the form factor (FF) of the building

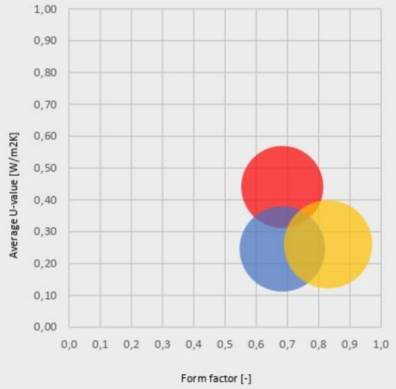
The size of the circles represents the embodied carbon

The closer to origo the better energy performance

Uav x FF

- 🟥 0,30095 W/K m2 floor area
- 🟦 0,16796 W/K m2 floor area
- 🟧 0,216008 W/K m2 floor area

Average U-value <-> Form factor



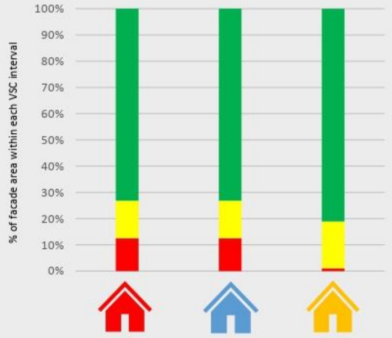
Daylight indicator

The daylight conditions are calculated using Vertical Sky Component (VSC) which expresses the access to daylight on the window surfaces.

Limits based on recommendations from the City of Gothenburg

🟩	VSC > 25 %	Normally no changes needed
🟨	15% < VSC < 25%	Probably some changes needed
🟥	VSC < 15%	Major changes needed

Vertical sky component



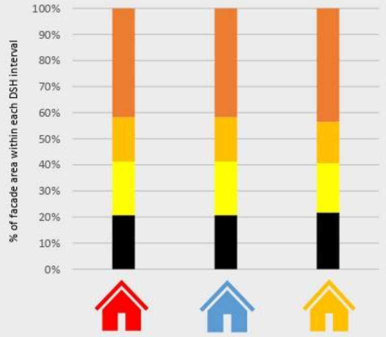
Average VSC [%]:	34%	34%	35%
Light floor area[%]:	64%	51%	73%

Sunlight indicator

The daylight conditions are analysed with direct sunlight hours (DSH) on the window surfaces. It is calculated for the vernal equinox in autumn.

🟧	4h - 12h	
🟨	2h - 4h	
🟨	1h - 2h	
⬛	0h - 1h	Critical areas

Direct sunlight hours



Average DSH [h]:	3,8	3,8	4,2

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