CISU4 Project

Thesis study with VELUX A/S

Methodology for integrated building performance assessment with use of computational design in the early design stage

Student: Elham Abdollahi Alibeik

Supervisor: Arne Remmen

Aalborg University - June 2023

Tables of Contents

Project Framework

This project is a collaboration between Aalborg University (AAU) and VELUX A/S-Denmark.

The company intends to develop a tool that can enable architects and designers to have an overall view of environmental aspects in the early stages of their design and help them make better decisions.

As European regulations in the construction industry become stricter to meet the goals set by authorities aiming for 55% carbon reduction by 2025, being climate neutral by 2050, and also providing a healthy indoor environment for occupants, the need for platforms, methods, and tools to achieve these ambitious goals is emerging (— *SDG Indicators*, n.d.).

Sustainability consists of three pillars environmental, social, and economic (Figure 1) and this concept can be used to address sustainability matters in buildings. As per the company's interest and direction, this study focuses on the environmental and social aspects of building sustainability. This can be a starting point to improve all three sustainability aspects in the future.

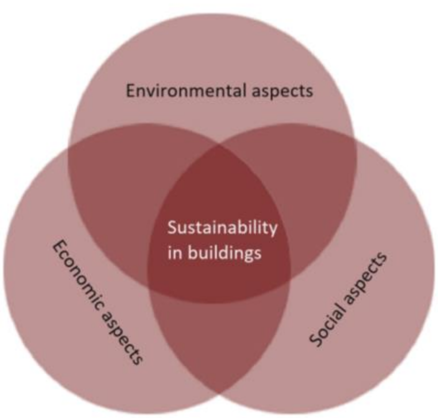


Figure 1.*Sustainability in buildings and its three pillars (Author, 2023).*

There are different design parameters that architects are most concerned about and the need to see their impact on building performance is crucial. Their design choices can impact building performance in different aspects significantly, and this is the reason why this tool can be a significant help for different stakeholders in the industry.

My project in VELUX includes the creation of the workflow, through script development, and the simulation analysis for different case scenarios and variations. The scope of this project is to investigate the impact of different design choices on environmental and social qualities in the building.

Different design parameters can impact environmental and social aspects, which are the two of the three aspects of sustainability. However, the evaluation of various design parameters can be difficult and time-consuming for designers and companies with an architectural intent. Therefore, a simplified and quick tool can smoothen designers' paths and guide them to choose wisely their designs. Using a parametric workflow allows designers to observe the impact of their choices in an integrated way and not in isolation. A tool that does not follow traditional linear workflow, but is not complicated, can be used in early design stages and can provide a holistic overview of the building's performance. It is important to clarify that the scope of this Master thesis is not the sole development of the tool since research and development will be continuing further. This study only covers a part of the whole project in order to achieve the ultimate goal.

The project was initiated when I started working with VELUX A/S during a six-month internship from September-2022 to February-2023 and its development continues since then. Before the internship project, the extent of the need for such a tool was investigated through interviews with different architects in small-scale architectural firms in Europe conducted by VELUX A/S as explained in the "architects point of view" section below. The core of the internship project included testing of functionalities and necessary inputs and parameters and building simulations on daylight, thermal comfort, energy, and life cycle assessment. This Master's thesis is a continuous work of the project that uses some already findings and covers more unexplored areas in order to have comprehensive research.

I believe this collaboration between Aalborg University and VELUX/S can bring valuable input to both sides.

List of Abbreviation

Abbreviation	Definition
EU	European Union
CEN	Comite European de Normalisation
UN	United Nation
CIE	Commission Internationale de IEclairage
DF	Daylight Factor
DA	Daylight Autonomy
DAmax	Maximum Daylight Autonomy
sDA	Spatial Daylight Autonomy
UDI	Useful Daylight Illuminance
WFR	Window-to-Floor Ratio
WWR	Window-to-Wall Ratio
SHGC	Solar Heat Gain Coefficient
VT	Visible Transmittance
CAD	Computer-Aided Design
BPS	Building Performance Simulation
DOE	Department of Energy
EPW	EnergyPlus Weather
HVAC	Heating, Ventilation, and, Air Conditioning

EP	EnergyPlus
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied (PPD)
LCA	Life Cycle Assessment
EN	European Standard
OH	Operative Temperature
GHGs	Green House Gases

List of Figures & Tables

Chapter 1

1. Introduction

1.1 Research Background

The building industry contributed to more than 34% of energy demand and 37% of carbon emissions in 2021 while the operational energy demand has increased by 4% since 2020. These facts increase the gap between the sector performance and the ambitious goals set in the Paris Agreement for decarbonization by 2050. Taking immediate action, investing, and focusing on the energy performance of buildings to reduce the energy demand and carbon emissions is crucial, especially during the current time with climate uncertainties, energy crisis, and resource scarcity (*CO2 Emissions from Buildings and Construction Hit New High, Leaving Sector off Track to Decarbonize by 2050*, 2022).

The construction industry accounts for a huge amount of raw material consumption which is 40% globally for new construction (*Consumption in the Construction Industry*, 2022), and this amount is increasing as the population, income per capita rise, and living standards, unfortunately, change (Figure 2) (OECD, 2019), and a very low amount of these materials gets recycled or reused.

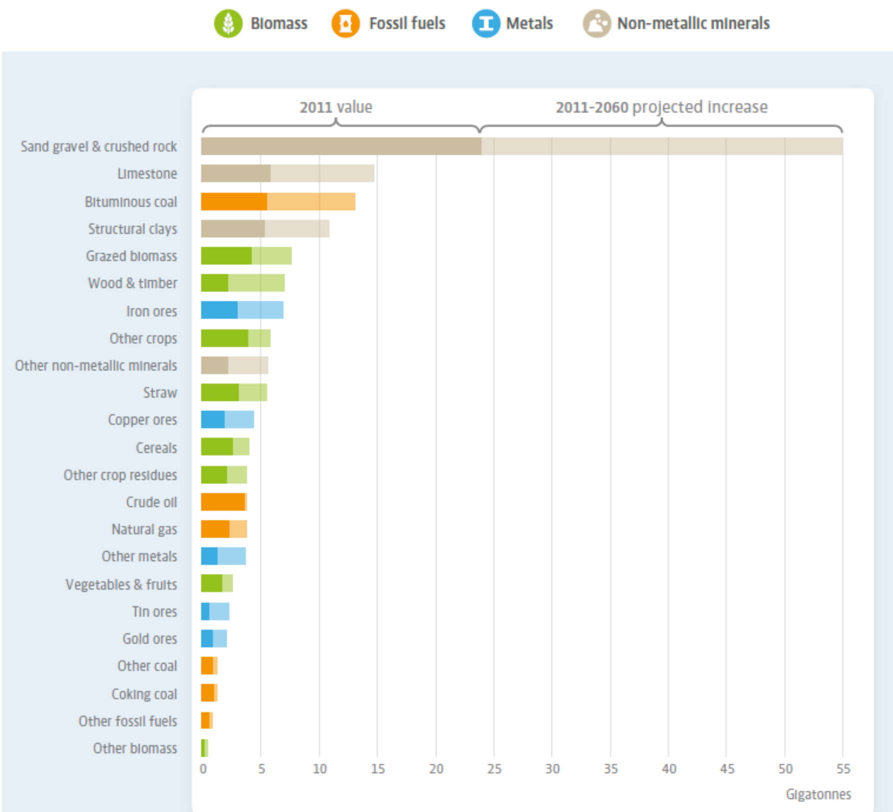


Figure 2. Construction material with the most share in total material use in 2011 and 2060 (OECD, 2019).

The building sector has a big share in carbon emissions but also plays a key role in the built environment's green transition, as it has a huge potential in reducing carbon emissions and overcoming climate crises. Also, poor indoor environments cause health issues which is critical because people spend most of their time indoors and it cannot be any compromise on indoor environment quality (IEQ) since it affects people's health, well-being (physical and mental), and also productivity level (Figure 3) (Samet & Spengler, 2003). Especially after the pandemic and increasing health challenges, more focus, and awareness on healthy living, the importance of indoor environment quality, and occupants satisfaction are placed (*How COVID-19 Made Healthy Indoor Environments and Wellness a Priority | The Edge Vol 4*, 2020).

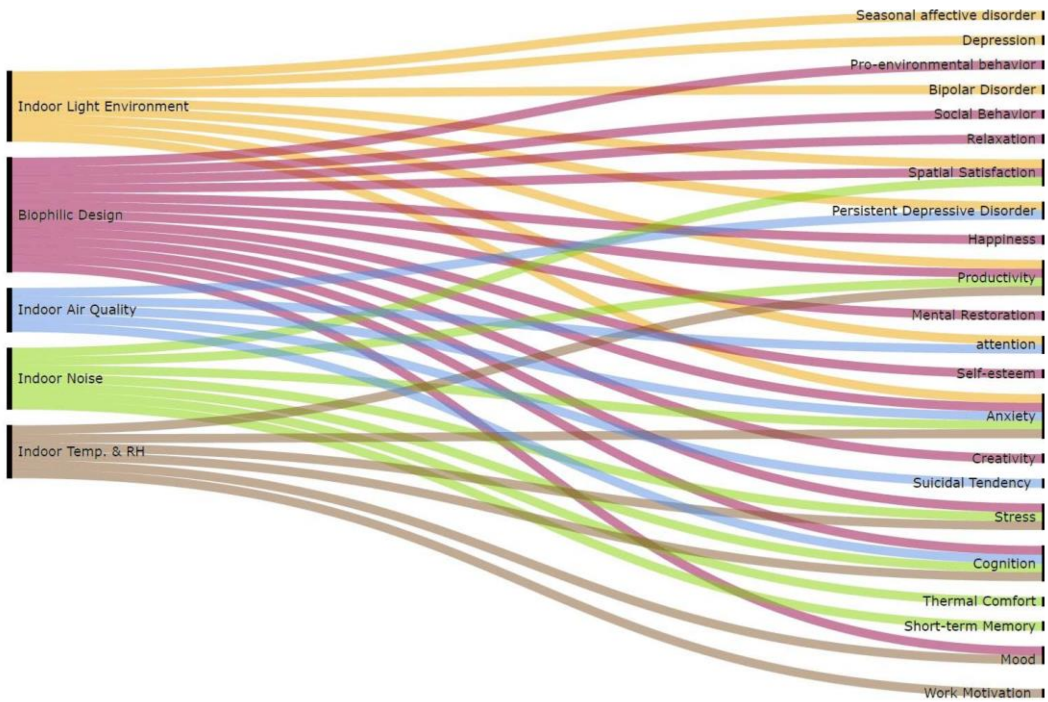


Figure 3.*Relation between different environmental factors on mental health (Bing Bing Guo, 2022).*

Stricter and tighter regulations in the building industry have been set by authorities due to the current climate emergency to overcome the environmental and social challenges. Standards are introduced to act as a common language (Explained Thoroughly in the Standards chapter) at national, European, and international levels. Methodologies to meet the requirements are adopted and used as tools and guidelines in the sector to comply with the high ambition for energy efficiency and an improved indoor environment. Therefore, the different stakeholders and decision-makers involved in the building sector need to be more aware and concerned to move towards building performance improvement (*Standardsfortheenvironment.Pdf*, n.d.) (*CEN-CENELEC*, 2020).

Healthy buildings for both people and the planet are not only energy-efficient buildings with reduced environmental impact, but also those buildings that provide occupants with a healthy indoor environment, which means good air quality, sufficient daylight availability, and comfortable temperature ranges. Building sustainable buildings within the planetary boundaries is critical and can only happen with the use of a multidisciplinary and integrated approach in building design to balance the interaction and possible contradicting effects of comfort, energy, and environment simultaneously (Fu, 2018).

There are different parameters for each core indicator of sustainability (Table 1) as stated in a report published by the United Nations (*Guidance on Core Indicators for Sustainability and SDG Impact Reporting*, 2022).

Dimensions, indicators, and their parameters		
Environmental area	Social area	Economics area
• Climate Change (embodied environmental impact) • Water efficiency • Resources Depletion • Energy Efficiency (primary energy, operational energy) • Material & Waste management	• Occupants' health and comfort (Indoor Air Quality Acoustic Comfort Visual Comfort Thermal Comfort) • Accessibilities	• Life cycle costs (capital cost, operational cost)

Table 1. *Sustainability dimensions, indicators, and their parameters (Bragança et al., 2007) (Bragança et al., 2010) (Mateus & Bragança, 2011).*

All sustainability dimensions are important and should be taken into account in building design to provide a balance between these aspects and this is possible with an integrated approach to building design. Improvement in the sustainability aspect and its parameter is a step forward toward green transition, especially in the construction industry. Focus on building sustainability performance is necessary to achieve the EU climate targets so there should be building performance assessment and evaluation systems to enable recognition of sustainable and green buildings.

Around 85% to 95 % of existing buildings in Europe will be still functional till 2050 and they are not energy-efficient constructions so building renovation has a big potential for achieving the EU goal for climate neutrality by 2050 and also have environmental, social, and economic impacts like healthier homes, more energy efficiency, and less emissions in buildings, and also creating more jobs in the sector.

Each year, only 11% of the buildings get renovated and the result for better energy performance buildings is just 0.2% of buildings per year which shows a need for better performance in this field (*COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A Renovation Wave for Europe - Greening Our Buildings, Creating Jobs, Improving Lives*, 2020).

Building performance is a broad topic, has different aspects, and can be a measure of energy efficiency, environmentally friendly material use, provision of a healthy and comfortable environment for occupants, acoustic performance, indoor air quality, etc, (*Building Performance*, 2022).

There are different approaches in order to predict building performance aspects like building performance simulation (BPS) which uses a computer-based model in simulation software to analyze the performance indicators like energy demand, indoor environmental quality, renewable system performance, etc. (‘Building Performance Simulation’, 2023).

The use of BPS in the early design phase by architects and engineers for building assessment performance is essential and also helpful for the decision-making process, since design parameters, like geometry, orientation, and material selection, etc. can affect a building's performance enormously, and taking action in the early stages is more influential and also cost-efficient as compared to later stages of the design (Figure 4) (Touloupaki & Theodosiou, 2017).

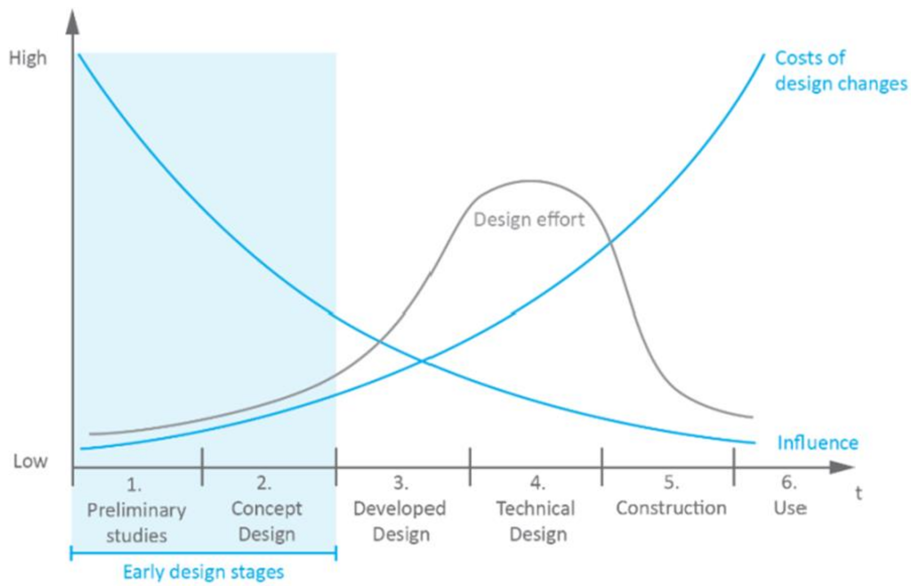


Figure 4. *Influence of the early design stages 'Paulson curve' (Paulson Jr, 1976).*

Different simulation softwares are used to calculate the building performance in various aspects but the focus is mostly placed on performance assessment in isolation and not performance optimization holistically during decision-making at the early stage. Fortunately, during the last decades, the focus has been changed to support the optimization procedure, and the assessment in the conceptual phase of the design becomes more integrated (Touloupaki & Theodosiou, 2017).

It is time-consuming to test every selected parameter in the conceptual design phase using traditional ways but following parametric design principles enables the designer to explore and make geometries by changing different parameters.

They are different softwares for parametric modeling but the most common and powerful one is Rhinoceros 3D, a computer-aided design (CAD) application, which uses a plugin called Grasshopper, a visual programming language, ('Grasshopper 3D', 2023) (AksiN & Selçuk, 2019) and it is possible to integrate building performance analysis with parametric modeling in them which is not possible in many other ones. (Aksamija, 2018) It can provide outputs like energy demand, thermal/visual comfort map, etc. with the use of different plugins and inputs (AksiN & Selçuk, 2019). It is possible to examine the effect of different parameters on building performance aspects, compares various design iteration and configurations, and even optimizes design choices, and the model gets updated automatically as per changes. Therefore, there is no need for re-drawing, going back and forth in different softwares, and importing or exporting the model in separate applications to get the required results (Fu, 2018) (Aksamija, 2018).

Although architects are concerned about the environmental impacts of their designs and decisions, most assessment methods focus on validations at the later stage. This results in a costly process with a low influence to make changes, so these methods are not suitable for the early design stage.

There are tools like “IEQCompass”, which try to asses indoor environment quality in an integrated way in the conceptual phase (Lasse Rohde et al., 2021) and there are studies that focus on the evaluation of energy efficiency and IEQ criteria to evaluate the importance of a holistic perspective in building performance improvement in the later stage (Jain et al., 2020).

A study done by Torben Østergårda and Rasmus L. Jensena - 2016, states that building simulations are mostly done at the end stage of design and not the early stage when important decisions are being made with high influence on the overall building performance. Therefore, they aimed to develop a simulation framework for early design stages, by comparing different currently used softwares by architects and engineers for building simulation to investigate their features and limitation with criteria of complexity, interoperability (linkage between CAD software and building performance simulation (BPS)), handling of different objectives, and supporting parametric simulation to find out the ones fulfilling these requirements (Table 2).

Architects as the most influential in early-stage design use CAD software for building design. There are different methods to connect CAD to BPS: an integrated method (calculation is integrated into CAD environment), a run-time interoperable method (link is through tools or programming interface), a file exchange method (use of a common file that is readable for both tools) and a standalone method (user interprets the result from tools individually) (Table 5) (Østergård et al., 2016a).

	Software	Design Stage			Interoperability	complexity	Objectives				Parametric Simulation	
		Conceptual	Preliminary	Detailed			Energy	Thermal	Daylight	LCA	Cloud	Integrated features
BPS (own engine)	Bsim		+	+	Standalone	High	+	+	+			
	Energyplus(E+)			+	Standalone	High	+	+				+
	IDA-ICE		+	+	File exchange	High	+	+				+
	IESVE		+	+	File exchange	High	+	+	+	+		
	Radiance		+	+	Standalone	High			+			+
	Velux Daylight Visualizer	+	+	+	File exchange	High			+			
BPS (external engine)	Daysim	+	+	+	Run-time	Radiance			+			
	Openstudio(OS)		+	+	File exchange	Radiance, E+	+	+	+		+	+
	DesignBuilder		+	+	File exchange	Radiance, E+	+	+	+			
Plug-in	Diva for Rhino	+	+	+	Run-time	Radiance			+			
	Honeybee(HB)	+	+	+	File exchange	(OS), Radiance, E+	+	+	+			+
	Grasshopper(GH)	+	+	+	File exchange	Algorithmic modeling	+	+	+			+

Table 2. *Building performance simulation (BPS) softwares Comparison (Østergård et al., 2016a).*

The existence of a tool or method that takes into account a wider range of building performance criteria in the early stage is missing due to different reasons like lack of knowledge, time-consuming model making, lack of simulation software, etc. There is a need for a method that is able to assess energy demands, indoor environment quality, and carbon emissions integrally, which has been less paid attention into the early design stage (Bernett & Dogan, 2019), and parametrically, which allows for proactive actions after different alternatives' comparison and timely feedback (Østergård et al., 2016a).

According to Batueva and Mahdavi (Batueva and Mahdavi, 2014), less than 8% of the 400 energy simulation software listed by the U.S. Department of Energy have potential in early design stage analysis. Architects are more fond of tools that are informative and can guide them in decision-making and find a balance and trade-off between different sustainability aspects in design alternatives to make conscious decisions in the early stage of design (Østergård et al., 2016a).

Architects need to know what is the effect of design parameters in a project on the different aspects of sustainability like indoor climate, energy use, and carbon footprint and also its compliance with the required standards from European to national, etc. If the "right" design alternative is chosen, sufficient daylight can be provided without causing thermal and visual discomfort like overheating or glare, also energy demand can be decreased and with choose of sustainable materials in design, the carbon footprint can be minimized so there is a link between the different aspects of sustainability that cannot be assessed in isolation and should be looked at in a more integrated way (Bernett & Dogan, 2019).

1.2 Problem formulation

For architects to design buildings that are efficient, comfortable, and healthy for both humans and the planet, there should be access to methods that are easy to use, have a holistic understanding approach to building design, and incorporate energy, comfort, and environmental aspects to have an overall view and be able to see the impact of their choices.

Architects are facing two challenges to design more sustainably and be able to see and investigate the impact of their design choices on the environment and building occupants to decide more consciously.

1. Indoor environment quality, energy usage, and carbon emissions are connected and can affect each other in contracting ways for example increasing window size for more daylight can increase cooling demand and affect thermal comfort negatively so to design sustainability and enhance building performance integrally, it is a necessity to analyze these aspects simultaneously, integrated and not in isolation but as stated in the introduction chapter there is a gap in assessments methods of mentioned aspects to find out a tradeoff and balance between them.
2. There are no tools available to evaluate the environmental and social performance aspects of design in an integrated way in the "early-stage design" so there is a gap for the early assessment method in the design process and also taking advantage of parametric modeling potential to evaluate the effect of different design parameters on building performance.

Fortunately, there is a movement toward green building design in both academia and also different sustainability assessment schemes like English BREEAM - the BRE Environmental Assessment Method - the American LEED - Leadership in Energy and Environmental Design - WELL - The WELL Building Standard- and German DGNB - German Sustainable Building Council- which aims to integrally assess and certify the sustainable building performance (Touloupaki & Theodosiou, 2017). These certificates assess the building performance when the building is ready and running with more focus on certifying and monitoring and not during the design stage when architects need to choose the best design variation for a more sustainable design.

As the scope of this project allows, we aim to investigate the building performance in regard to mentioned indicators in Table 3.

<table>
<tr><td colspan="4">Indicators and Parameters to assess in this study</td></tr>
<tr><td colspan="2">Environmental Performance</td><td colspan="2">Social Performance</td></tr>
<tr><td rowspan="2">Carbon Emissions</td><td>Embodied Carbon Emission</td><td rowspan="2">Indoor Environment Quality</td><td>Thermal Comfort</td></tr>
<tr><td>Operational Energy Consumption Emission</td><td>Visual Comfort</td></tr>
</table>

Table 3. *Indicators and Parameters to assess in this study (Author, 2023).*

In order to find answers to the existing gaps a main question and two sub-questions are raised:

1.3 Research Question

Main research question:

How can architects meet the challenges of designing more sustainable buildings? And at the same time how can architects make the sustainable consequences of their design choices visible and also easy to play with the different parameters?

Sub-questions:

1. *Are there any trade-offs between environmental building performance (both embodied and operational) and indoor environment quality in new construction?*
2. *How can the use of parametric design principles in the early stage of design impact building performance quality?*

There are three objectives in this study. Firstly, the balance between building performance parameters should be identified in an integrated way as the relation between them is complex, Secondly, the importance of decision-making in the early stage design should be examined as it has effects on the building performance Thirdly, appropriate tools and methodology should be used in the process for a high building performance.

To cover the main aspects of the problem, two actions were followed:

1. Integrated assessments

2. Parametric design tools in early stage design.

Below is Figure 5. That shows how we have structured this study.

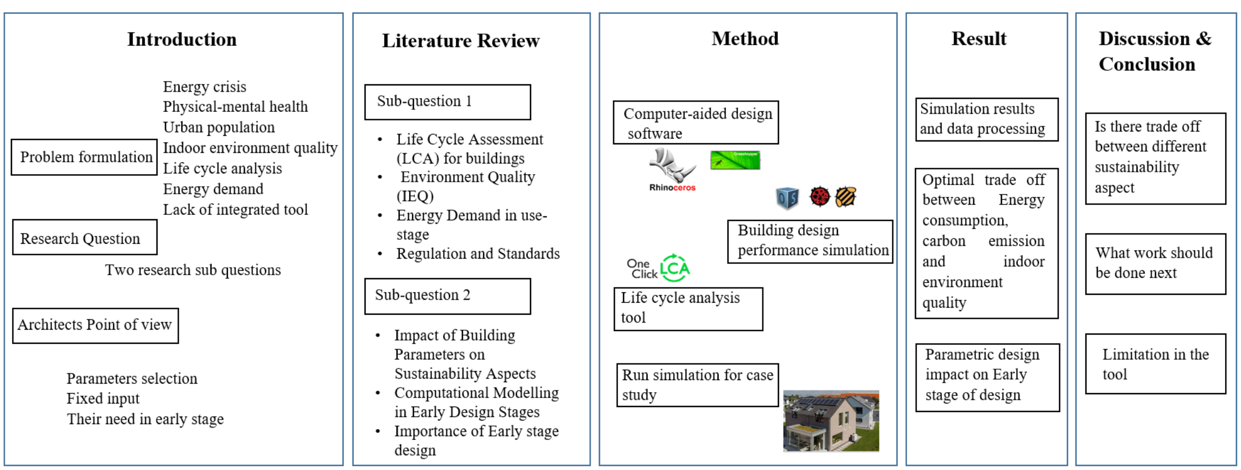


Figure 5. Thesis design structure

1.4 Architects' Point of View

VELUX interviewed 24 architects from 3 different countries to investigate architects' opinions about the most important parameter or feature in a platform that can enable them to evaluate three categories of IEQ, EP, and LCA in the stage in which they are making initial decisions. They were also asked how they can design more sustainably and which tools they use to do so. The company aims to know whether there is a need for a tool to help architects to make better decisions in the early stage and if yes what are the main functionalities (VELUX internal report-2022).

Architects believe they waste a lot of time to get to the decisions they make in the early stage going forward to the next stage because they have to wait for the other consultants and specialists to do the calculation for energy performance, daylight, acoustics, etc., and to let them know whether they are on track or not. This makes the process long and inefficient for architects with a lot of back-and-forth emails and phone calls. They state that they just need to know the overall performance of their design variables and be able to see the impact of their designs quickly to choose the most appropriate one and continue the design development which a detailed energy or indoor environment quality assessment can be done in it (VELUX internal report-2022).

Architects see the need for a tool or framework to guide them during the decision-making phase. This tool could provide feedback on performance parameters like daylight, thermal comfort, and energy use integrally. They claim the already digital plug-in calculation tools usually offer only estimation on one/a few aspects of the building design and are often too time-consuming. Currently, they do not use simulation tools for the early stage of their design, and during the design development phase, they have to send their design to engineers for building performance assessment and wait for results which makes the process long and time-wasting (VELUX internal report-2022). Below two of the questions architects were asked during the interview are presented.

Why do you have to do the iterations again and again? *"Results and the calculations will change, and we don't know necessarily because we don't have the knowledge of what changes in our design will give us in terms of numbers. So, we have an understanding but we don't specifically know"* (Architect from the UK, VELUX internal report-2022).

How do you feel about the consultant's accumulation? *"There is a dissolution of responsibilities. We can no longer have a clear line of thought when we need to ask so many people. Our mission slows down and our responsibility is dissolved"* (Architect from France, VELUX internal report-2022).

So the interview results show architects see value in using integrated design tools because they need a simple tool enabling them to evaluate the building performance in the early stage and get advice and guidelines numerically, or visual results by labeling or color coding to support a smoother and quicker work process (Velux internal report-2022).

2. Literature review

In this chapter, the performance parameters, and their standards are presented and further explained based on a literature review. Moreover, important parameters that are taken into account during the initial design phases are described, together with the benefits of integration of the computational modeling and evaluation of those parameters on a building level.

2.1 Life Cycle Assessment (LCA) for Buildings

LCA is a tool for the assessment of the potential environmental impact of a product, service, or process throughout all stages of its life (‘Life-Cycle Assessment’, 2023). It is also used for the environmental assessment of buildings in the construction sector where building elements and/or building different stages of life can be evaluated. (Birgisdottir, H., & Rasmussen, F. N. 2016).
There are regulations for the application of LCA analysis in the building design process and architects and planners as influencers in the sector have an important role to reduce the environmental impact of their design by using the tool.
The building life cycle is divided into 5 stages (Figure 6) which are the product stage, construction, use stage, end of life, and benefits. The five stages are divided into modules (Table 4), which include A1-A3, A4-A5, B1-B7, C1-C4, and D.

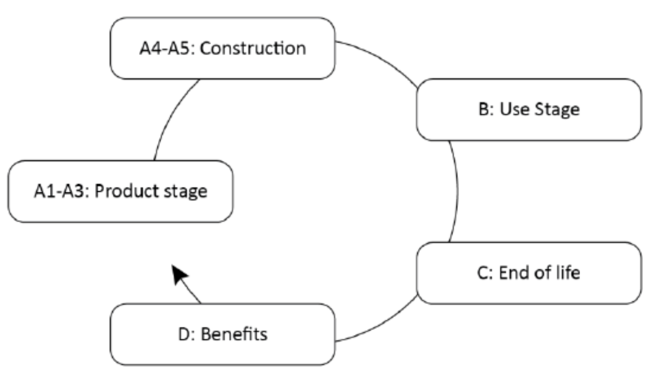


Figure 6. *Stages of building life cycle. (EN 15978:2012)*

A1-A3 module, also called cradle-to-gate, is about material production and is also a necessity (EN 15804:2012, p.16) for all environmental product declarations. EPDs is a report about the environmental impact of a product or service during its life cycle which is valid for 5 years but B1-B7 modules are voluntary and mostly not included in the EPDs (EN 15804:2012, p.44), and can be helpful for comparison between different products (http://www.environdec.com/).
Data accessibility and certainty are high for this module since manufacturers are aware of each step of the process (EN 15978:2012) (Hollberg, 2017).

Product			Construc-tion		Use Stage							End of Life				Benefits and loads beyond the system boundary	Life cycle stages
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D	Module
Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	Re-use, recovery and recycling potential	Process

Table 4. Life cycle modules (Made by Author Based on EN 15978:2011)(CEN TC350 standards)

LCA analysis requires environmental data that can be found in different forms of data banks including datasets of generic, average, and predefined EPDs. Some of these data banks are listed in Table 5, and in order to be able to define their environmental impacts, EN 15804:2012 has set categories with different parameters like Global warming Potential, Ozone Depletion Potential Acidification Potential, etc… the complete table is listed in the Appendix.

Name	Type of data	Country	Publisher	Website
Ökobau.dat	specific, average, generic	Germany	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety	http://www.oekobaudat.de/en.html
KBOB "Ökobilanzdaten im Baubereich"	generic	Switzerland	Koordinationskonferenz der Bau- und Liegenschaftsor-gane der öffentlichen Bauherren (KBOB)	http://www.eco-bau.ch/
Baubook	specific, average, generic	Austria	Baubook GmbH	https://www.baubook.info/
The Athena Institute database *	average, generic	Canada	Athena Institute	http://www.athenasmi.org/our-software-data/lca-databases/
Leitfaden	average, generic	Luxembourg	Centre de Ressources des Technologies pour l'Environnement (CRTE)	http://www.crtib.lu/Leitfaden/content/DE/116/

Table 5. *Data sources for building materials (Hollberg, 2017).*

According to the need, goal, and scope of each project, the LCA study can be done with different levels of detail. Three study types with different detail levels are specified by EebGuide which are screening, simplified, and complete LCA. For example, in the early stage architects and designers might need a simplified tool to justify his/her design but in the later stage, a more detailed and complete one is required (Wittstock et al. 2012, p.30).

2.1.1 Embodied and Operational Emissions

Embodied emissions, expressed as kg CO2 per year, are the total GHG emissions produced from some modules of the building life cycle, and operational emissions, expressed as kWh/m2/yr, are the emissions from the energy used in B6-B7 modules (Table 6) and both contribute to building climate impact.

Traditionally, operational phase emissions outweighed embodied emissions but this is changing due to more focus and restriction on energy consumption (Fufa et al., 2021). The result of a study done by Chastas et al. (2016) for buildings from 1977 to 2016 shows that embodied energy was between 6% to 25% higher than operational energy in traditional buildings. With the transition towards energy-efficient buildings, embodied energy has increased, between 26% to 57%. Due to the fact that more quality materials are being used for insulating housing to reduce heat losses and subsequently, energy consumption, embodied energy emissions have increased, so the focus should be on improving the overall building performance with an integrated approach towards LCA analysis, the carbon emission result for buildings cannot be shown either for operational energy carbon emission or embodied one but it should be an aggregation of both values to consider all the aspects in energy consumption. (Chastas et al., 2016) (Persson, 2022).

Product			Construc-tion		Use Stage							End of Life				Benefits and loads beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	Re-use, recovery and recycling potential
Initial embodied impact					Recurrent embodied impact					Operational impact		End of life embodied impact				

Table 6. *Embodied and operational emissions in the building life cycle modules (Made by Author based on Fufa et al., 2021).*

2.2 Indoor Environment Quality (IEQ)

Since people spend most of their time indoors, the quality of the indoor environment is important and has a direct effect on occupants' health, comfort, and well-being. Poor IEQ can cause different issues like sick body syndrome, dryness, asthma, allergies, etc (Ganesh et al., 2021). IEQ is affected by different factors as shown in Table 7, and in this study, we are just focusing on visual and thermal comfort factors.

Indoor Environment Quality Factors			
Thermal Comfort	Indoor Air Quality	Acoustic Comfort	Visual Comfort

Table 7. *Different indoor environmental factors (Fantozzi & Rocca, 2020a).*

2.2.1 Visual Comfort and Daylight Availability

Daylight has physiological and physical effects on humans and can benefit people's health, well-being, and performance (Al Omari, 2016), it can improve mood and reduce tiredness and eyestrain (Robbins 1986) it can also help decrease the electrical lighting consumption demand, but at the same time, it can cause visual discomfort like glare or thermal discomfort like overheating. In order to evaluate visual comfort, there are four categories identified 1. Amount of light 2. Color rendition 3. Glare and 4. Daylight availability (Table 8) and each group have specific indicators which describe them (Fantozzi & Rocca, 2020b).

The building design is important to provide occupants with enough natural daylight without compromising on comfort factors. In order to assure daylight availability, there are assessment methods that will be explained in the coming chapters.

Visual Comfort Indicators	
1. Amount of light	3. Daylight Availability
2. Glare control	4. Color rendition

Table 8. *Indicators affect visual comfort (Fantozzi & Rocca, 2020c).*

Each of the indicators had its specific metrics in order to make the assessment possible for example illuminance is the most used metric for the amount of light assessment, daylight factor (DF), and daylight autonomy (DA) are the most used ones for daylight availability quantity assessment, and unified glare rating (UGR) is the metric to assess glare (Fantozzi & Rocca, 2020c).

2.2.2 Thermal Comfort

As stated by The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) thermal comfort is very subjective, depends on every person's expectations, and is a state of the mind that reaches thermal satisfaction which can be influenced by different factors shown in Table 9, the first fourth factors depend on the environment and the other two are person dependant factors and that's the reason they are variation in thermal satisfaction from person to person (ANSI/ASHRAE Standard 55) (Fantozzi & Rocca, 2020a).

Thermal Comfort Indicators		
3. Air-speed	3. Air temperature	5. Metabolic rate
4. Humidity	4. Mean radiant temperature	6. Clothing insulation

Table 9. *Thermal comfort factors (‘Thermal Comfort’, 2023).*

There is a risk of overheating in the buildings since they are getting more airtight with better insulations for better energy performance. Air temperature and mean radiant temperature measurements show the operative temperature value which enables us to calculate overheating hours and make sure that comply with standards.

2.3 Energy Demand in the use stage

As the construction sector has a huge contribution to energy consumption and CO2 emissions, energy demand and supply are very important matters and play an important role in the green transition. Residential buildings account for almost 60% of the total emission in the sector and the aim is to reduce building energy demands through building design and performance efficiency and also the use of renewable energy sources as much as possible to be able to achieve the goal of being carbon neutral by 2050 (Santamouris & Vasilakopoulou, 2021).

2.3.1 Heating, Ventilation, and Air Conditioning (HVAC) and Lighting Demand

HVAC, which is a necessity for maintaining the occupant's comfort, has a big share in energy consumption worldwide (Figure 7) and accounts for almost 30 % of total energy use in residential buildings and it depends on different factors like climate, wealth, occupancy pattern, unit size, etc. (González-Torres et al., 2022) so it plays an important role in energy saving and reaching the goal set by the EU to reduce final energy use by 11.7% by 2030 to fight climate change and the EU energy dependencies (Abnett, 2023).

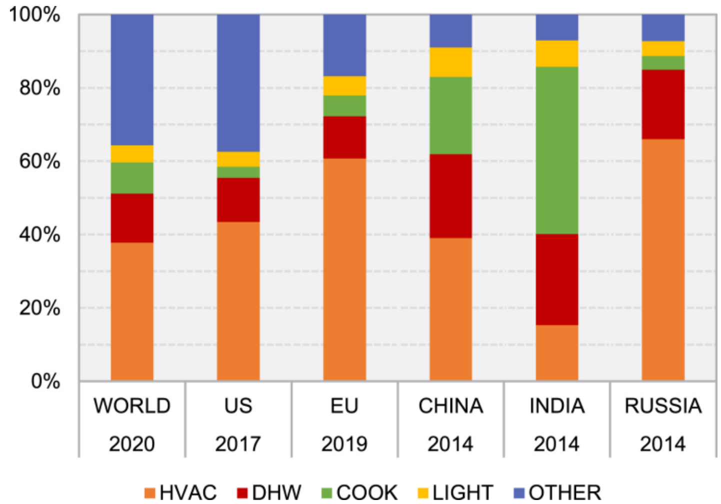


Figure 7. *Share of energy use for different services (González-Torres et al., 2022).*

In order to take action for energy efficiency and reduction in buildings, designers need to be able to estimate and predict buildings' energy performance which is a complicated matter since it is affected by different parameters. Building energy simulation enables the designers to estimate the energy demand and use in buildings in the early stage, enabling them to investigate the effect of different building parameters like facade design, wall-to-floor ratio, material selection, etc… which affect the energy load in buildings (Fumo, 2014).

2.4 Standards definition and functions

There are thousands of standards today used as a common language for communication and many of them are developed through systems like CEN, CENELEC, ETSI, ISO, etc. Standards can be national, regional (European), and international. Standards provide values for both society and businesses.

European standards are developed by CEN (the European Committee for Standardization), CENELEC (European Committee for Electrotechnical Standardization), and ETSI (the European Telecommunications Standards Institute), these standards start with EN like EN 16789 and they should be adopted as the national standard by countries that are members of these organizations to have common standards for the region, then the national prefix e.g DS, BS, etc will be added before the European standard for example, DS_EN 16798 for Denmark.

ISO (International Organization for Standardization) with 160 country members develops and publishes international standards that can be adopted as national standards by the members and will be for example EN ISO 13590.

Standards are voluntary measures and can pave the way for regulation like suggesting a minimum/maximum “u value” or “g value” for materials but when they are referred to by

legislation they become mandatory, regulations are mandatory and different acts should comply with them.
In order to make harmony within Europe standards, the European Commission mandates the European Standardisation Organisations to develop standards that support European legislation and assure the requirements for quality, safety, health, and environment which are then called harmonized standards (Hagelund, 2015).

2.4.1 Required Standards in this Study

EN 15643 as a European Standard provides guidelines for the environmental, social, and economic, three pillars of sustainability, performance assessment of both new and existing construction, and is developed into three standards for the assessments of each aspect (Table 10) (EN 15643-2021).

Framework	Sustainability Assessment		
	EN 15643		
Assessment	EN 15978-1	EN 15978-2	EN 15978-3
	Environmental Performance	Social Performance	Economic Performance

Table 10. *Standards for Sustainability of Construction Works (EN 15643-2021).*

2.4.1.1 Indoor environment quality assessment methods

Standard EN 16789-1, which is a revised version of EN 15251:2007, is used for both design and assessment of energy performance in buildings while assuring the requirements for indoor environmental quality and specifies the parameters which should be used as inputs in calculations (EN 16798-1_2019).

IEQ has been divided into 4 categories (Table 11) as per occupants' level of expectations different criteria are set for each level in the standard. In this study “Medium” as the normal level is considered (EN 16798-1_2019).

Category	Level of Expectation	
IEQ1	High	Use spaces with special requirements, like the disabled, the sick, etc
IEQ2	Medium	Normal level for new buildings and renovations
IEQ13	Moderate	An acceptable level for exciting buildings
IEQ14	Low	Cause discomfort but not health risk

Table 11 *Four Categories for IEQ (Churazova, 2018) (EN 16798-1_2019).*

DIN 4108-2 is the national standard for buildings in Germany which is part of the national energy saving regulations (since 2020 GEG – Gebäudeenergiegesetz), there are three methods proposed in this regulation to check the areas in the house with the highest thermal load in the summer house to prevent overheating. There are three methods proposed, method no. 3 uses thermal building simulation (performance based) for complying with the standards.
The operative temperature value is the building area is set as the criteria for thermal comfort assessment. Table 12 below shows the reference values for the internal operative temperature and overheating heating level in the summertime for three different regions in Germany.

Summer climate region	Reference value b,op of the internal temperature °C	Requirement value Overtemperature degree hours Kh/a	
		Residential buildings	Non-residential buildings
A	25	1 200	500
B	26		
C	27		

Table 12. *Reference values for the internal operative temperature and overheating heating level in the summertime or climate region A, B, and C (DIN 4108-2:2013).*

The location for the selected case study is Günzburg- Germany which comes under climate region B as per Figure 8. Below shows.

Figure 8. *Different climate regions in Germany (DIN 4108-2:2013).*

For climate B, the internal temperature is 26 degrees Celsius, and the allowed overheating hours (more than 26 degrees Celsius) is 1200 Kelvin Hours per year (Table 12).

Daylight Provision Assessment

EN 17037_2018 is the European standard for assessing daylight availability and visual comfort in buildings which are implemented as a national standard in Germany.

This standard helps designers to assess daylight availability and also ensure there is enough indoor illuminance in a space. This standard specifies metrics that are necessary to consider for daylight availability assessments and the way to calculate and verify them.

In order to assess daylight provision in an indoor room throughout the year, two criteria and methods are explained in EN 17037_2018 and three metrics of daylight factor (DF), daylight autonomy (DA), and spatial daylight autonomy (sDA) are defined for calculation use (*DS_EN 17037_2018.Pdf*, n.d.).

DF is the ratio of received illuminance on a point indoor (Ei) to the outside illuminance (Eo) under an unobstructed overcast sky and is presented in percentage DF = (Ei / Eo) x 100% (Reinhart et al., 2006).

DA is an annual daylight metric that represents the percentage of the time when occupants are in the space and minimum target illuminance is provided in that space by the daylight alone (Reinhart et al., 2006).

sDA is a metric to measure daylight provision and sufficiency in a space. It is the percentage of the floor area that receives a target illuminance for 50 % of the time occupants are there in a year (Lm, 2013).

Method 1. Based on the daylight factor.

A target and minimum target DF value should be achieved on a reference plane for 50% of the daylight hours (*EN 17037: 2018*). As Table 13 shows DF in the Berlin-Germany location is 0.7 % with minimum target illuminance of 100 lux and 2.2 % with a target illuminance of 300 lux.

Nation	**Capital** [a]	**Geographi cal latitude** φ [°]	**Median External Diffuse Illuminance** $E_{v,d,med}$	***D* to exceed 100 lx**	***D* to exceed 300 lx**
Germany	Berlin	52,47	13 900	0,7 %	2,2 %

Table 13. *DF Values for 50% of the daylight hours (*EN 17037: 2018*).*

Method 2. Based on the illuminance level with the use of climate data.

A target and minimum target illuminance value on a reference plane should be achieved.

As Table 14 shows a minimum target illuminance of 300 lux in 50 % of the plane area for 50% of the daylight hours and also a minimum target illuminance of 100 lux in 50 % of the plane area for 50% should be achieved in order to meet the criteria set for daylight provision (*EN 17037: 2018*).

Level of recommen-dation for vertical and inclined daylight opening	Target illumi-nance E_T lx	Fraction of space for target level $F_{plane,\%}$	Minimum target il-luminance E_{TM} lx	Fraction of space for min-imum target level $F_{plane,\%}$	Fraction of day-light hours $F_{time,\%}$
Minimum	300	50 %	100	95 %	50 %
Medium	500	50 %	300	95 %	50 %
High	750	50 %	500	95 %	50 %

Table 14. *Recommendation for target illuminance on a reference plane for vertical and inclined openings (*EN 17037: 2018*).*

Method 1. is not a dynamic approach for daylight availability assessment and just shows the minimum required daylight since DF is not a dynamic metric for daylight performance evaluation because it does not consider real-time, day, season, or real sky conditions and just considers overcast sky which is the worst case scenario but this method is commonly used because it is easy to calculate and communicate the result for designers (Reinhart et al., 2006).

Method 2 is a dynamic approach that uses building location and climate data for external solar radiation on different days, months, or seasons for the time step of the whole year.

In order to calculate DF and sDA there is a need for a 3D model as a representative of the area for the performance evaluation through the use of different software with the ability to calculate daylight performance (Reinhart et al., 2006). This part will be done in the case study analysis with the reference model in Germany.

2.4.1.2 Energy consumption assessment Methods

Energy consumption is dependent on many factors including building operation system, design, and quality of the indoor environment, and also set criteria for these factors for example setpoints and setbacks for heating/cooling systems which can change energy demand significantly. It should make sure that buildings meet the minimum requirements for building energy performance and factors like thermal characteristics, heating/cooling system, ventilation, lighting, hot water supply and internal loads, etc should be taken into account as it is stated in The Energy Performance of Buildings Directive (EPBD) (*Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings*, 2010).

The Building Energy Act (GEG) categorizes residential buildings into energy efficiency classes (Table 15), the best class is A+ with final energy consumption of 30 kWh/m2/year, and the worst class is H with final energy consumption of more than 250 kWh/m2/year. This classification can help the designers to know where their design stands when they calculate the final energy consumption in the building (*GEG (German Energy Act, 2020*).

energy efficiency class	final energy [kilowatt hours per square meter building area and year]
A+	ÿ 30
A	ÿ 50
B	ÿ 75
C	ÿ 100
D	ÿ 130
E	ÿ 160
f	ÿ 200
G	ÿ 250
H	> 250

Table 15. *Energy efficiency classes in residential buildings (*GEG (German Energy Act, 2020*).*

There are also requirements about technical design for a reference residential building in GEG, that gives minimum or maximum values for different characteristics like heat transfer coefficient, glazing transmittance, and thermal bridge allowance, etc, for different building components like walls, windows, roofs, HVAC systems, etc (*GEG (German Energy Act, 2020*). Details about these requirements are listed in the Appendix.

2.4.1.3 Carbon footprint assessment methods

Since the focus has been mostly on operational energy in buildings, embodied carbon emission has been neglected and as buildings become more energy efficient, regulation has started including all the whole life carbon emissions in the buildings. Some countries have set LCA regulations that are already in force and some are going into force by 2023 like Denmark and Finland in 2024 (*Construction-Carbon-Regulations.Pdf*, 2022).
Germany does not have any regulation set or going into force so far, It only has voluntary building certifications like DGNB and BREEMA, national LCA methodology which is based on DIN EN 15978 standards which cover A1-A5, B4, B6, and C1-C4 stages and at the product level, Germany follows EUs regulations. ÖKOBAUDAT is the standard material database used in Germany (*Construction-Carbon-Regulations.Pdf*, 2022).

2.5 Impact of Building Parameters on Sustainability Aspects

It is vital to find out which parameters are the ones with the most impact on the building performance and needs for analysis in the early stage in architects' opinion. This affects architects' choice in selecting design alternatives coming out of different design parameters.
Results from Architects' interviews show some of the important parameters and the most investigated ones by architects like thermal mass, glazing type, and glazing properties which are chosen as parameters in this study as well.
Selected parameters have an impact on all three building performance aspects of indoor environment quality, carbon emissions, and energy consumption in the life cycle of a building and should be investigated to have an integrated overview of each variation in design to find the optimum balance between them (architects interview, 2022). The importance of chosen parameters is also explained in the section below which is extracted from the different literature studies investigating essential design parameters in early-stage design.

2.5.1 Thermal Mass

Ability of materials in absorbing, keeping, and emitting heat is referred to as “thermal mass” and heavyweight materials like concrete have higher thermal mass than lightweight materials like timber. Thermal mass can affect the indoor thermal quality, heat gain or loss, and embodied and operational energy consumption in the building so the selection of the right materials for different climate zones in the early design stage is important to prevent overheating, high energy demand, and high carbon footprint (Zilberberg et al., 2021) (Balaras, 1996).

2.5.2 Glazing Size

The Glazing size influences the amount of daylight that comes inside the building and also affects indoor thermal comfort, for example, a big window size can cause overheating or heat loss which will affect the energy demand for cooling or heating in the building so it is important to pay attention to glazing size from the early stage to provide a balance between visual and thermal comfort with low energy demand (Hee et al., 2015).

Glazing area is mostly represented in the window-to-wall ratio (WWR) or window-to-floor ratio (WFR) and there is a limit in window size in order to provide enough daylight and decrease lighting energy cost so it is important for designers to know what is the appropriate WWR or WFR in their design and how to affect the other building performance aspects (Thalfeldt et al., 2013).

2.5.3 Glazing Properties

Windows in buildings as part of the facade with direct contact with the outside are important in the design process and the glazing properties of the windows can affect building performance enormously in terms of daylight, thermal comfort, and energy consumption. The main three glazing properties are explained below.

The solar heat gain coefficient (SHGC) is a thermal property of the glazing and is the fraction of solar radiation coming inside through the glass. SHGC is a value between 0 and 1 and a higher value means more heat is transmitted inside which is helpful in the wintertime to reduce the heating demand (Nils Petermann, 2010).

visible transmittance (Tvis) is the optical property and is a number between 0 and 1 and shows the fraction of visible light coming inside through the glazing, a higher value can decrease the use of artificial lighting in the building but it can cause glare at the same time (Nils Petermann, 2010).

Insulation value (U-factor) is a measurement rate for the amount of heat that is gained or lost through the glazing due to temperature differences between in and out, a higher U value shows better insulating abilities of glazing (Nils Petermann, 2010).

2.6 Computational Modeling in Early Design Stages

Computational design is a process that uses an algorithm to produce design variation and it has evolved throughout its time from 2D drafting to Machine learning (Figure 9) to make the design process faster and more efficient for architects with less iteration during design stages (*The Evolution of Computational Design (Detailed Guide - 2023)*).

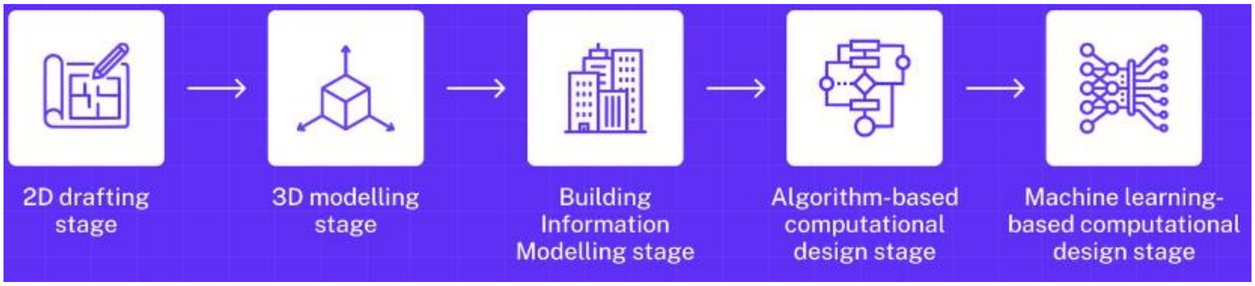


*Figure 9. The evolution process of computational design (*The Evolution of Computational Design (Detailed Guide - 2023)*).*

The fourth stage in the evolution, the algorithm-based computational design stage, enables users to set the parametric design principles in their design, and parametric design started from here.
There has been a problem between integrating building design tools with building performance simulations (BPSs) tools used by architects during design stages for building performance analysis and feedback which require lots of back and forth and remodeling (Negendahl, 2015).
Grasshopper is the most common tool for parametric modeling and they are plugins like Honeybee, Openstudio, etc, that link this tool to BPS to smoothen the connection between computer-aided design software (CAD) and building performance simulation (BPS) but this connection still needs to be improved for early-stage design to make the interaction between architectural models and simulation software easier and more flexible (Østergård et al., 2016a).

2.6.1 Benefits of Integrated Assessment

Building performance has different aspects like energy performance, environmental impact, and indoor environment quality, and each of these is influenced by many parameters that are linked to each other in different ways. In order to design high building performance buildings, Architects and designers should be aware of the differences in the multiple design alternatives in order to be able to choose the most appropriate design variation during the decision-making stage. This is possible with the use of parametric design and building performance simulation in an integrated way to allow users to evaluate different parameters simultaneously, get fast feedback to iterate their design and see the result at the same time (AksiN & Selçuk, 2019).

Chapter 3

3. Methodology

3.1 Simulation-based parametric software and plugins

To analyze the effect of different design variations on the building performance in terms of daylight, thermal comfort, energy use, and carbon emissions, building performance simulation software is used in this study. The selected case study 3D model has been made in Rhinoceros software and connected to the BPS environment through Grasshopper as a connecting plugin. Grasshopper also enables users to do the parametric study as it is the most used plugin for doing the parametric study (Apellániz et al., 2021). There is the possibility of adding many more plugins to Grasshopper to do daylight, energy, and thermal simulation (Table 2 - Chapter 1) and also LCA analysis and this enables us to have an integrated and parametric analysis at the same time which is the goal of this project (Østergård et al., 2016b).

3.1.1 Rhino and Grasshopper

Rhinoceros is a CAD software founded in 1978 by Robert McNeel & Associates (‘Rhinoceros 3D’, 2023). Grasshopper is a visual programming tool that works with Rhino to do parametric modeling (‘Grasshopper 3D’, 2023).

3.1.2 Ladybug and Honeybee

Ladybug and Honeybee are two open-source plugins for Rhino/Grasshopper and are used to do environmental studies. Ladybug uses EnergyPlus Weather data (.EPW), which is standard weather data made by the US Department of Energy (DoE)(Wintour, 2016), to provide meaningful 2D and 3D graphical results (Figure 10) for a better understanding of the simulation results which is beneficial for decision-making in the early stage of the design. It is possible to make a connection between environmental data analysis and design within the same model for architects (Sadeghipour Roudsari et al., 2013).

Honeybee provides a connection between Rhino/Grasshopper and Openstudio, Daysim, Radiance, and Energyplus for doing daylight and energy simulations (Figure 11) (Wintour, 2016) so it plays an important role as a BPS tool in the early stage design.

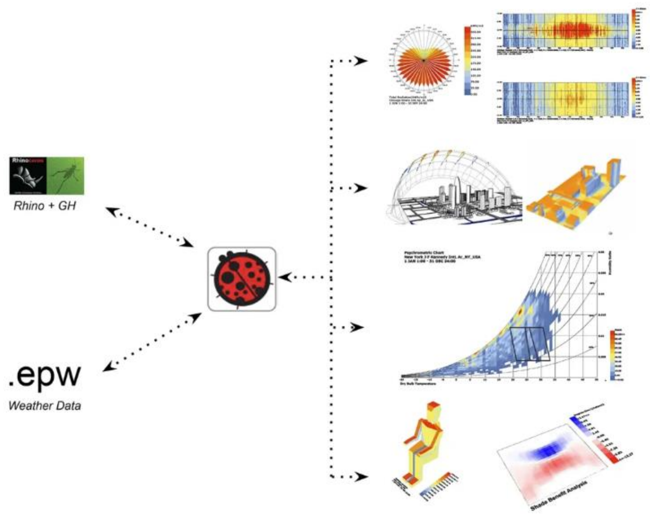


Figure 10. Ladybug connection between Rhino/Grasshopper and .epw and graphical visualization (Wintour, 2016).

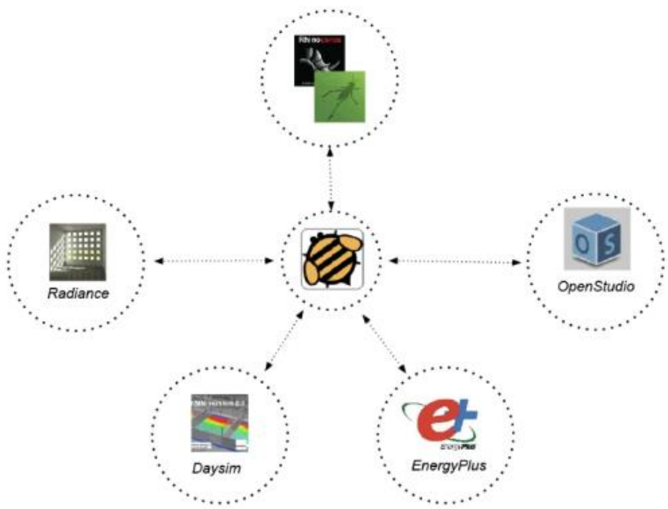


Figure 11. Honeybee and connection between Rhino/Grasshopper and different engines for environmental analysis (Wintour, 2016).

3.1.3 Openstudio

Openstudio is an open-source software tool that uses EnergyPlus and Radiance engines through a programming interface for doing energy simulations and getting feedback during the design stages and can be incorporated into Grasshopper which enables doing an integrated building energy performance study (Guglielmetti et al., 2011).

3.1.4 One Click LCA

Using Excel or similar platforms for doing LCA requires gathering and adding data manually into the software which makes it a time-consuming method (Apellániz et al., 2021). As explained in the earlier chapters, Rhino+Grasshopper is the perfect match for doing integrated environmental analysis and there is a need for a tool to be used in the same environment for carbon emission calculation. There are different tools and plugins available in the environment of Rhino+Grasshopper for doing LCA in a more automatic and integrated way, one of them is “Tortuga” which is very popular among the users but its material database is only connected to ÖKOBAUDAT, and has been updated many years ago. Another plugin is called “Bombyx” with a not user-friendly interface and a material database is only limited to Swiss ones (Apellániz et al., 2021). The third tool for doing LCA is “CAALA”, a commercial software, that provides a very comprehensive online platform for users with a very basic component in the plugin for Grasshopper with an only option for exporting material to the web page, and the database is mostly focused on ÖKOBAUDAT (Apellániz et al., 2021).
The final tool for doing a life cycle assessment in the Rhino+Grasshopper environment is “One Click LCA”, a tool that was developed to overcome the mentioned limitations by other tools. It has a more broad EPD database, better integrated into the Rhino+Grasshopper environment for doing visualization and optimization, and a more user-friendly interface that makes designers and architects more eager and interested to use LCA in the early stage of the design with a parametric approach (Apellániz et al., 2021).

3.2 Simulation reference model

The case study is located in Germany-Günzburg and is a single-family house with pitched roof and roof windows. There were three proposed locations of Denmark, France, and Germany by VELUX to do this simulation-based case study for the building performance investigation and comparison. The Danish case was already under investigation by the Artelia construction company and it was decided to evaluate the German case for this study. The French case study will be assessed in future studies by VELUX to achieve the comparison of the building performance for these three geographical locations.

The reference model is shown in the perspective view in Figure 12, the house size is almost 200 sqm2. The house contains a kitchen, living room, and dining area on the ground floor and has three bedrooms on the second floor (Figure 13 and 14).

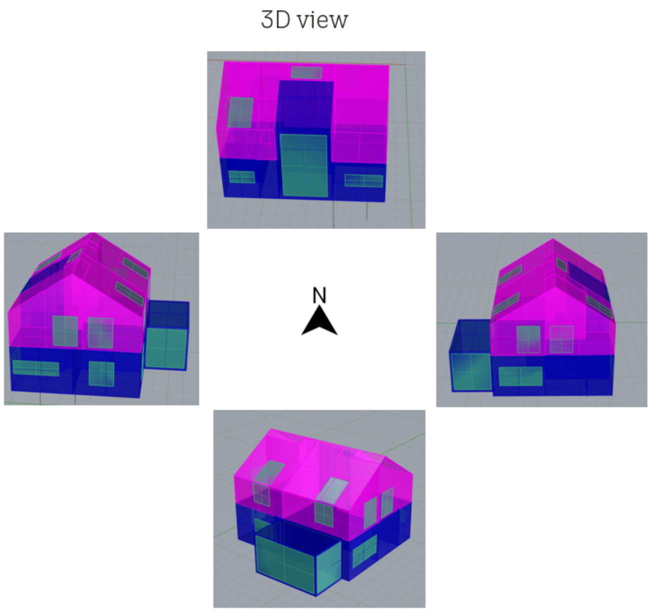


Figure 12. *Perspective view of the Reference case (Author-2023).*

Figure 13. *Reference house architectural plan - ground floor (Author-2023).*

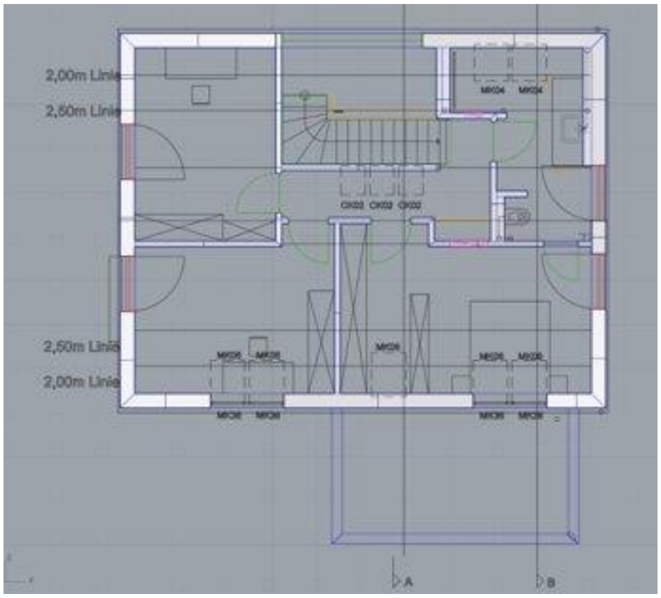


Figure 14. *Reference house architectural plan - first floor (Author-2023).*

This case study is used as a method to build a workflow, illustrate, analyze, and document the results of a specific case which is possible to make it general in the future. Also finding out what are the steps and challenges in each one during the whole workflow as a dynamic simulation of thermal and visual comfort, energy use, and carbon emissions calculation in an example building.

The surrounding context is not taken into consideration, such as trees, and buildings that provide shading potentially. However, a ground surface has been implemented in the Grasshopper script to accurately calculate the daylight admission in the building due to its reflectance.

3.3 Model Inputs

The important part of this chapter is the model preparation and insertion of the necessary inputs in order to get the correct result. There are some static parameters like the number of zones, occupancy schedule of the building, appliances loads and walls radiance values, etc., which are fixed and do not change and are necessary for the simulations. These inputs are presented and explained below.

3.3.1 Weather File

The first step is importing the weather data for the location of Günzburg-Germany (Figure 15) and the output from the component is an “epw” file which will be used as input for daylight and energy simulations. Weather data enables us to get the climate information of a specific location, which is important to do climate-based building performance analysis. In this study, the weather data file for Günzburg-Germany is downloaded from the https://www.ladybug.tools/epwmap/ which provides weather data files for different locations.

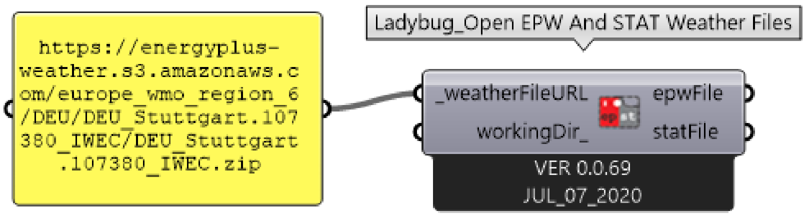


Figure 15. *Component to connect weather data to get "epw" file as output (Author-2023).*

3.3.2 Zoning

The second step is zoning which represents different zones in a house like a bedroom zone, kitchen zone, and living room zone. It is important to have simulation results for each zone separately because requirements are not the same for different zones. For example, there is more daylight needed in the living room than in the bedroom so we cannot consider the house as a large zone, therefore it should be divided into smaller zones. However, the zones of the buildings are not considered as a parameter since it is inevitable to evaluate the building without its zones. In this case study, there are fourteen zones in total, four on the ground floor and the rest on the first floor.

It is worth mentioning that the parameter of roof window size and glazing type that will be described below is more sensible in zones of the first floor.

In order to assess the performance criteria for each zone in a reasonable way, the location and the number of windows in each zone were distinguished and presented in the following table.

Ground floor's zones	Windows	Windows in more than 1 wall
Dining	X	
Entrance/corridor		
Lounge	X	X
Office	X	X
Mechanical		
Staircase	X (fixed)	
Kitchen		
Toilet G	X	
Greenhouse	X (fixed)	
First floor's zones	**Windows**	**Windows in more than 1 wall**
Toilet F	X	
Bedroom 2	X	X
Master bedroom	X	X
Bedroom 1	X	
Corridor		

Table 16. Position and distribution of windows in each zone on the ground and first floor

The orientation is considered as a significant parameter in passive solar architectural designs and it is known at the time of the site selection. Although the orientation of the current building is not a variable, it is an important player in the evaluation of daylight admission and overheating issues for each zone.

3.3.3 Facade Window Size

The facade window size was created based on the minimum ratio of 10% window-to-floor area as the building regulation suggests (Building Regulation 2018. Then this number has been converted to the value for the windows-to-wall ratio in the study. This means that different windows-to-wall ratios are generated for each zone since each zone has a different floor area. It was decided though to choose this specific percentage for the facade windows (based on the 10 percent glazing-to-floor ratio method) and not consider the facade window size as a parameter for this study as more simulation time would be required if more window ratios were investigated.

3.3.4 Schedules and Loads

The next step is to identify the occupancy schedules which show occupied and unoccupied hours in the house. As shown in Figure 16, the unoccupied hours are shown as “0” and fully occupied hours are represented by “1” with a different schedule for weekends and weekdays. Then, the values are connected to two other components to get schedules in value as output.

This is important information since the requirements are different for the periods that residents are or are not at home and to decrease energy demand for providing a high-quality indoor environment. Equipment loads are also effective in the house's energy demand, so there should be a value set for each electrical appliance in the house as well (Appendix).

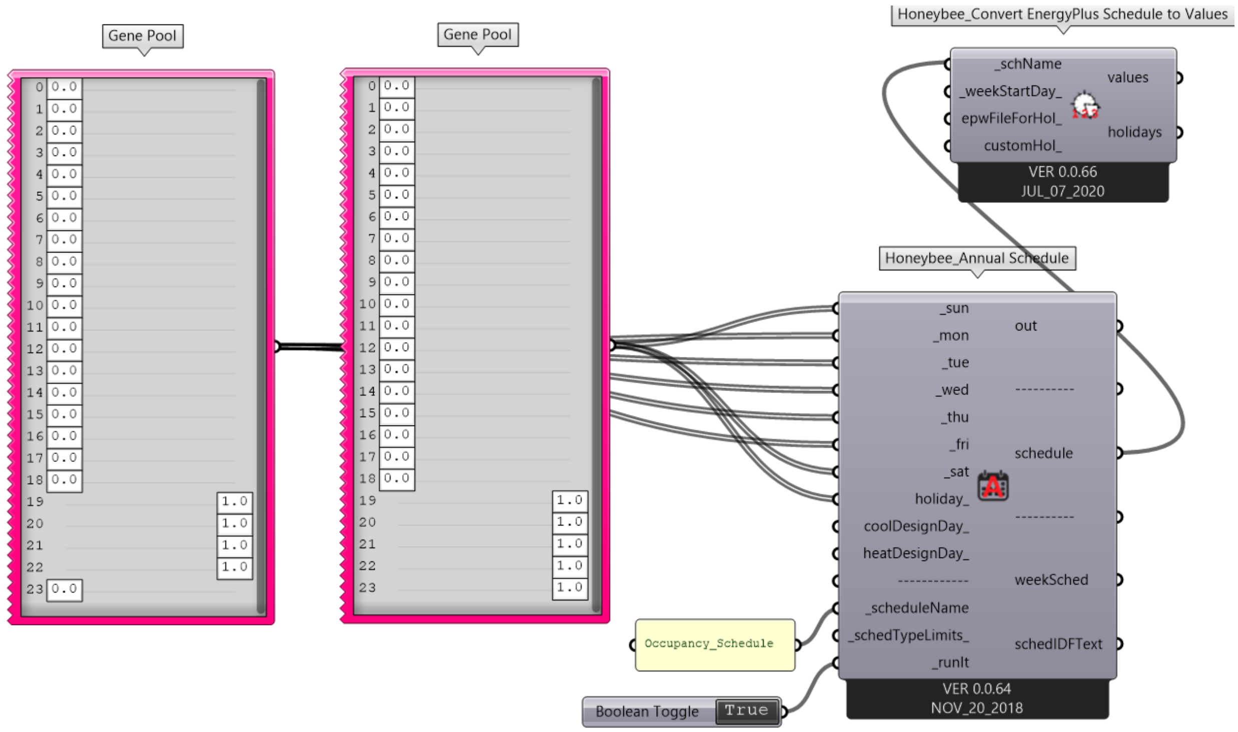


Figure 16. Setting occupied and unoccupied schedules (Author-2023).

3.3.5 Optical Material Properties

The next important and necessary input to be added, is radiance values for the different surfaces in the building for example radiance value for the walls, ceiling, etc., since it affects the occupant's visual comfort. These values are mentioned in Table 17 below.

Optical material properties	
Surface	Reflectance
floor	0,2
interior wall	0,5
ceiling	0,7
exterior wall	0,2
window sill	0,35
external ground	0,1

Table 17. Reflectance values of different surfaces (Jakubiec, 2022).

3.3.6 Heating, Ventilation, and, Air Conditioning (HVAC)

The mechanical system selected for this study is the “ideal air load”, a system that provides an ideal amount of air to each zone according to the zone loads to understand what is the thermal need of each zone and very useful for early stage design since there is no HVAC system set yet in this stage. But there is an option for change to other more detailed systems like VAV (Variable Air Volume), etc., which is possible with the use of the openstudio component in the Honeybee plugin.

The heating/cooling values as outputs in this system are the amount of heat that is needed or should be removed in space according to the setpoints or setbacks values in the system (*Ideal Loads Air System Default Mechanical Ventilation Setting*, 2016).

3.4 Investigated Parameters

As mentioned before, building performance is affected by different design parameters like façade opening size, windows properties, types of materials, etc., selecting any alternatives in these parameters provides many design variants which makes the designers choose between them and it is essential to choose the most appropriate one with the high performance as the ultimate goal. In order to find the most appropriate answer and justify the reason for choosing a design variant over the others, there should be a comparison between the options. In this study, we have selected some parameters which have the most influential impact on the building performance in the early stage which have been identified from analysis of the architect's survey.

Chosen parameters are thermal mass, roof window glazing properties, and roof window size, considering these parameters, there will be 18 design variants (Table 18) for each house zone. We will compare the design variants to see the effect of each parameter on the building performance quality in this study.

Construction Type	Roof window size	Roof window glazing type
Heavyweight (material: Brick) Lightweight (material: Timber)	None MK06 0.5 m *1.0 m 2MK06 0.1 m *1.5 m	GGL70-Double layer (U value:1.3 SHGC:0.46 VT:0.68) GGL66-Triple layer (U value:1.0 SHGC:0.44 VT:0.62)

Table 18. *Selected parameters in this study with their properties.*

3.4.1 Construction type

The fifth step is to define the thermal properties of used material in the building which has an impact on the energy consumption and thermal comfort of the residence.
Two types of heavy and light constructions have been selected in this study to compare the effect of each on different environmental parameters.
Table 19 shows the material properties of the external wall as they have the most square meter area in the design and the rest of the material can be seen in the Appendix part.

	Light external wall			
No	layers	Thermal conductivity [W/(mK)]	Density [kg/m3]	Special heat capacity [J/(kgK)]
1	plaster	0,16	1180	800
2	cement bound	1,6	1400	800
3	timber frame	0,12	470	1300
4	rockwool insulation	0,035	90	1030
5	wood fiber panel	0,1	625	2100
6	plasterboard	0,16	1180	800
	Heavy external wall			
	layers	Thermal conductivity [W/(mK)]	Density [kg/m3]	Speci□c heat capacity [J/(kgK)]
1	plasterboard	0,16	1180	800
2	brick	0,62	1395	800
3	woodfiber insulation	0,047	163	2100
4	plasterboard	0,16	1180	800

Table 19. *The material used for heavy and light construction (https://webtool.building-typology.eu/#bd) (Internal Excel sheets for common material used in Germany-2022).*

3.4.2 Roof Window Size

For the roof windows size, two specific VELUX roof windows, MK06 and SK08, are selected. Two scenarios are designed for the roof windows. The first scenario includes one single window of each type and the second scenario includes two of the same roof window of each type installed side by side to investigate the result of daylight and thermal comfort and also carbon footprint with more roof windows (Figure 17).

Figure 17. *Velux window product of MK06 and its location on the model.*

4.2.3 Roof Window Glazing Type

The properties for the facade window are fixed parameters but different properties are selected for the roof window (Table 20).

Window type	Tvis	SHGC	U-value
Façade window			
Façade window lowE	0,05	0,44	1,00
Roof window			
GGL 66 triple layer	0,62	0,44	1,00
GGL 70 double layer	0,68	0,46	1,30
GGU 66 triple layer	0,62	0,44	1
GGU 70 double layer	0,68	0,46	1,3

Table 20. *Facade and roof window technical values* (Aust Ggl Product Sheet 2022 Web.Pdf, *2022.)* *(*GGU_34_en-HQ_HQ.Pdf, *2022.)*.

3.5 Simulation cases

When the model is prepared for building performance simulation in the Grasshopper environment as explained before, we need to run the simulation for the three categories of energy, indoor environment, and LCA. In this section, the workflow for doing the simulation is explained (Figure 18).

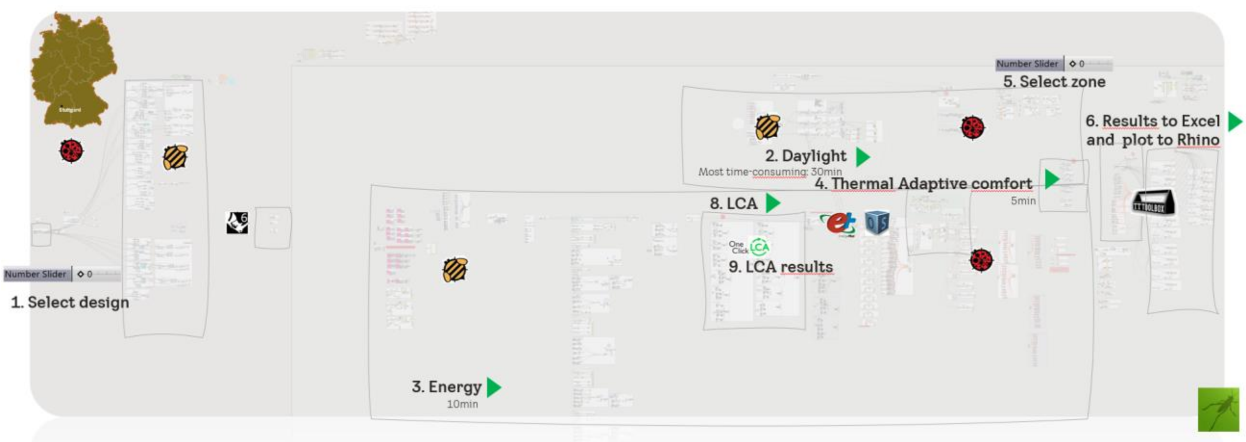


Figure 18. *Steps of the simulation workflow*

3.5.1 Daylight Simulation

For doing visual comfort analysis, the honeybee plugin is used and it is possible to get results for daylight factor and daylight autonomy which are essential for daylight availability assessment in each zone.

The main component used for the simulation is Figure 19 which uses different inputs like HBzones, weather file, analysis recipes that define test points, vectors, test meshes, etc to give outputs like DA, sDA, useful daylight autonomy in different ranges, etc.

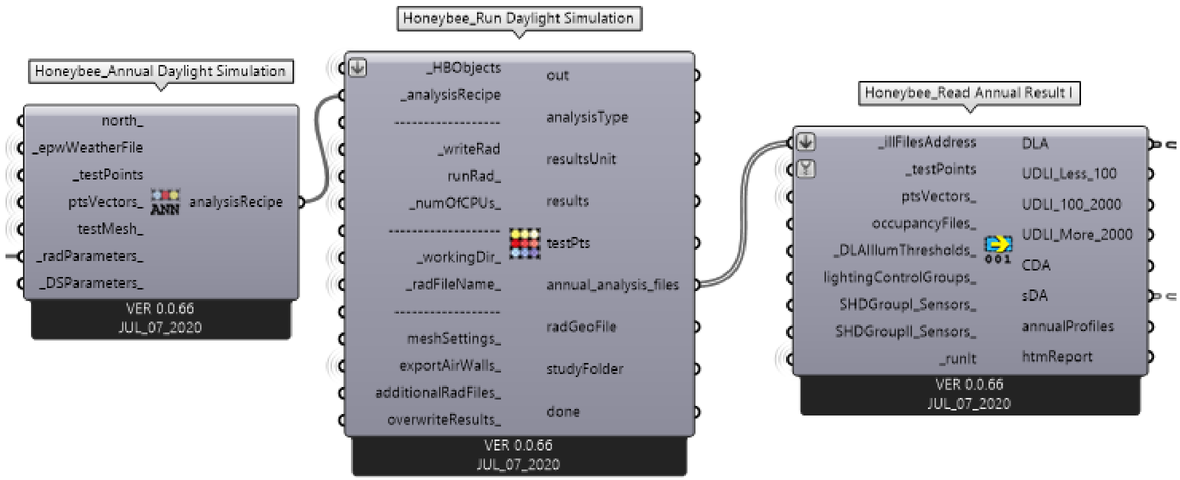


Figure 19. Inputs and outputs in running daylight simulation using Honeybee.

3.5.2 Energy and thermal comfort Simulation

For doing an Energy simulation, there are specific components that should be used in order to get the result. The engine "Eneryplus" is used to calculate the operational energy demand including heating, cooling, ventilation, and lighting in this case study. We can also calculate operative temperature and following that, overheating hours in this environment. The main component used for the simulation is Figure 20, which needs different inputs like HBzones, weather file, analysis period, etc. to give outputs like cooling, heating, lighting, air temperature, operative temperature, meanRadTemperature, solar gain, etc.

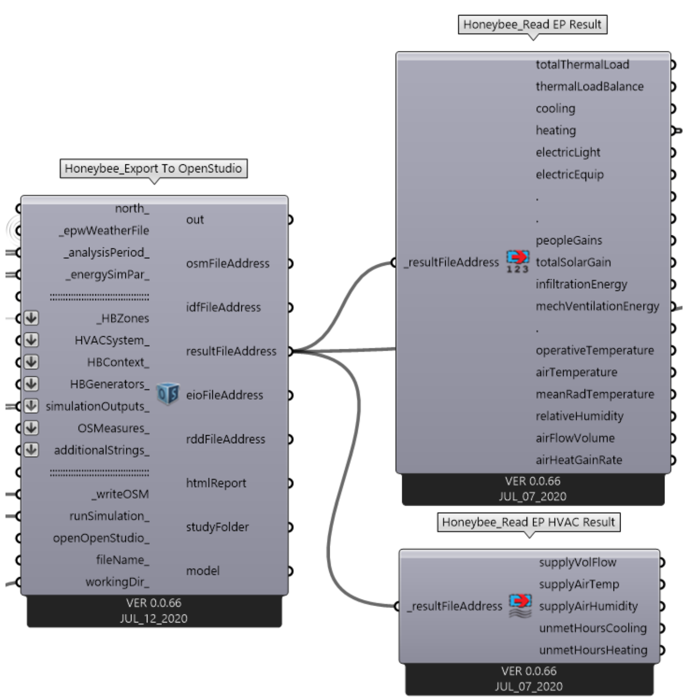


Figure 20. Inputs and outputs in running energy simulation using openstudio.

Operative temperature as output is used for calculating the overheating hours which if it exceeds the set number in the standard, cause thermal discomfort in the zone.

3.5.3 Calculating LCA

For calculating embodied carbon emission, a tool called one-click LCA is used which is the most appropriate tool for doing life cycle analysis parametrically and in the early stage design of the design as of now. There is a plugin available to connect the grasshopper environment to the one-click LCA online platform through the shown component below (Figure 21), by clicking “Button” to get connected to the cloud system.

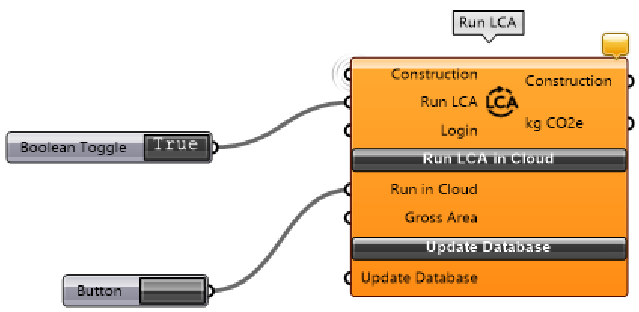


Figure 21. *The plugin is available in Grasshopper for LCA.*

The next step in doing the LCA is to find the material we need in the construction through the “select profile” component (Figure 22).

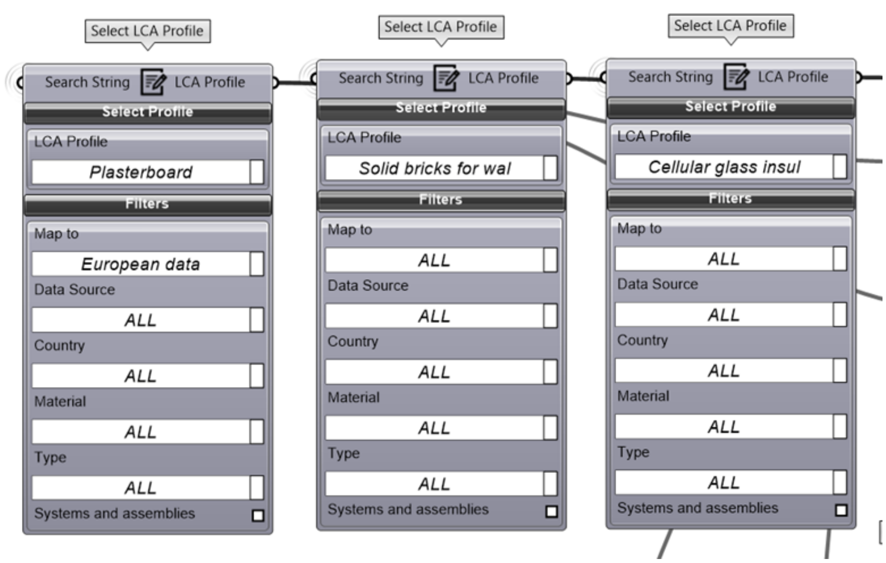


Figure 22. *Components for finding the desired material.*

Then we define the geometry, thickness, and quantity of the material with the help of the “Define material” component (Figure 23) then we connect all the material required for construction to the “Create construction” component (Figure 24) which will be finally connected to the run LCA component and get connected to the online platform (Figure 21).

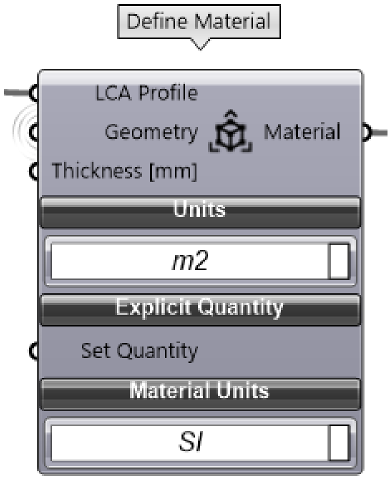


Figure 23. *Setting the quantity of material*

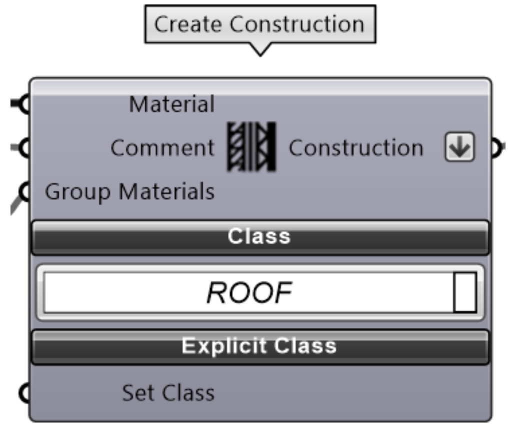


Figure 24. *Combining the material layers*

4. Results

There will be 5 case variants with different parameters investigated in this study to find out the relation between each in terms of building performance quality. As there are 14 zones in the house with many design variations, it is not possible to present all the data in this part so it is decided to present daylight and energy results for only two zones, bedroom no.2 on the first floor and lounge zone on the ground floor in this part and more result is available in the Appendix section.

4.1 Daylight and Simulation Result - Graph

In this part, the result of daylight simulation is presented for the entire house in the case "heavyweight_WWR0.1_2xMK06_GGL70double" which is a case with heavy thermal mass, a window-to-wall ratio of 0.1, and two roof windows with MK06 type (Velux window product type) and case "heavyweight_WWR0.1_0RW" which is a case with heavy thermal mass, a window-to-wall ratio of 0.1, and none roof window.
The presented results show the DA value for each sensor point of all the zones, also the sDA percentage as indices for daylight sufficiency evaluation on both the ground and first floor.

4.1.1 DA values and sDA percentage

Figure 27 shows the sDA of 100% for all the zones. Criteria for daylight availability is minimum target illuminance of 300 lux in 50 % of the plane area for 50% of the daylight hours (see the standard chapter) It means there is enough daylight in all zones on the ground floor (Figure 25) and due to presence of facade windows on one or both sides of the exterior walls.
On the first floor (Figure 26) the corridor zone with an sDA of 10% is not passing the criteria but the rest of the zones are passing it with an sDA of more than 50%.

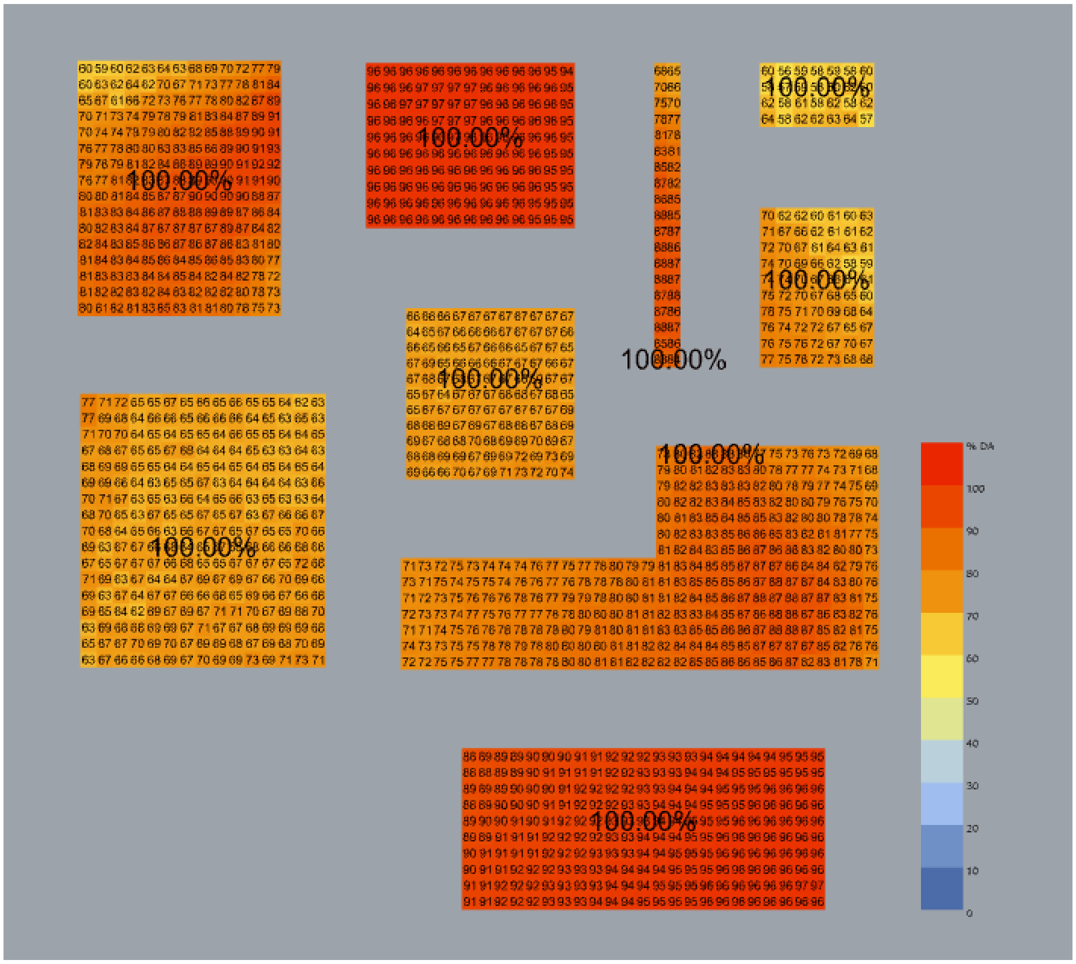


Figure 25. *DA values and sDA percentage of the entire house for the case “heavyweight_WWR0.1_2xMK06_GGL70double” - Ground floor*

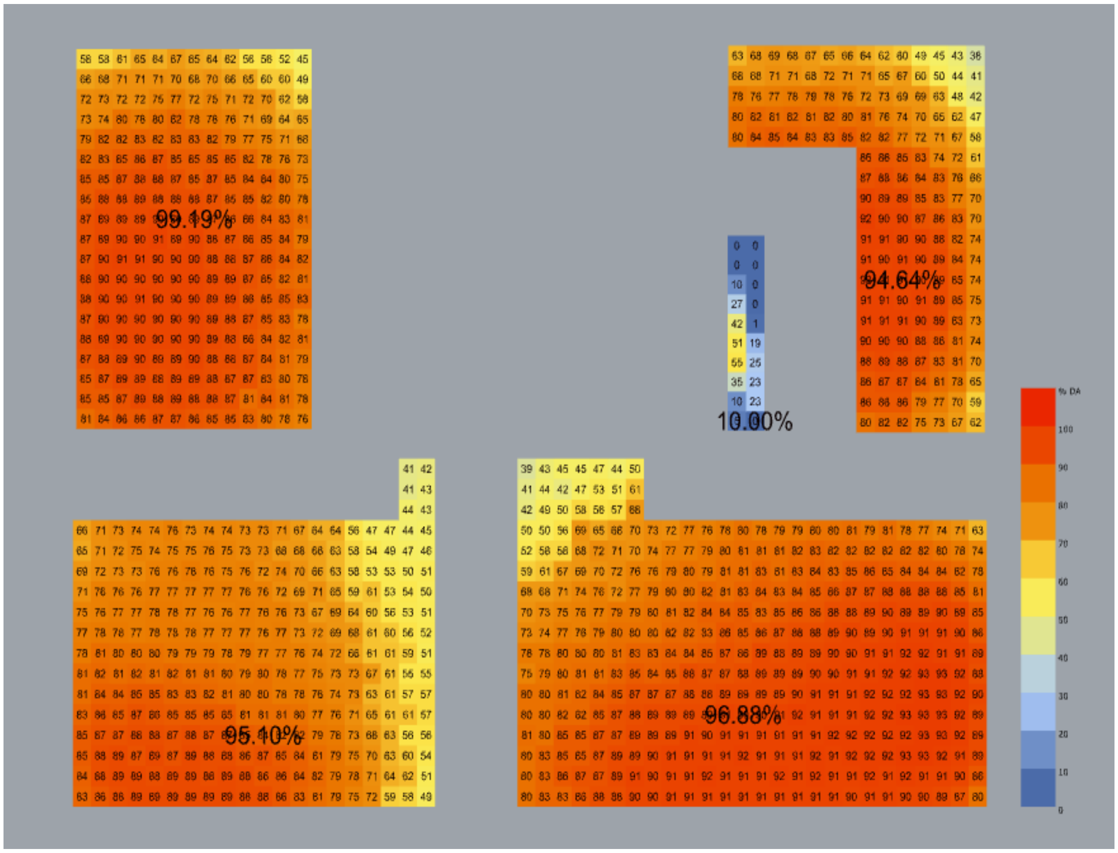


Figure 26. DA values and sDA percentage of the entire house for the case “heavyweight_WWR0.1_2xMK06_GGL70double” - First-floor

Daylight simulation result for the next case of “heavyweight_WWR0.1_0RW” for the ground floor (Figure 27), shows all the zone are passing the criteria with sDA more than 50% and it was quite obvious because lack of roof windows does not affect the daylight efficiency on the ground floor.

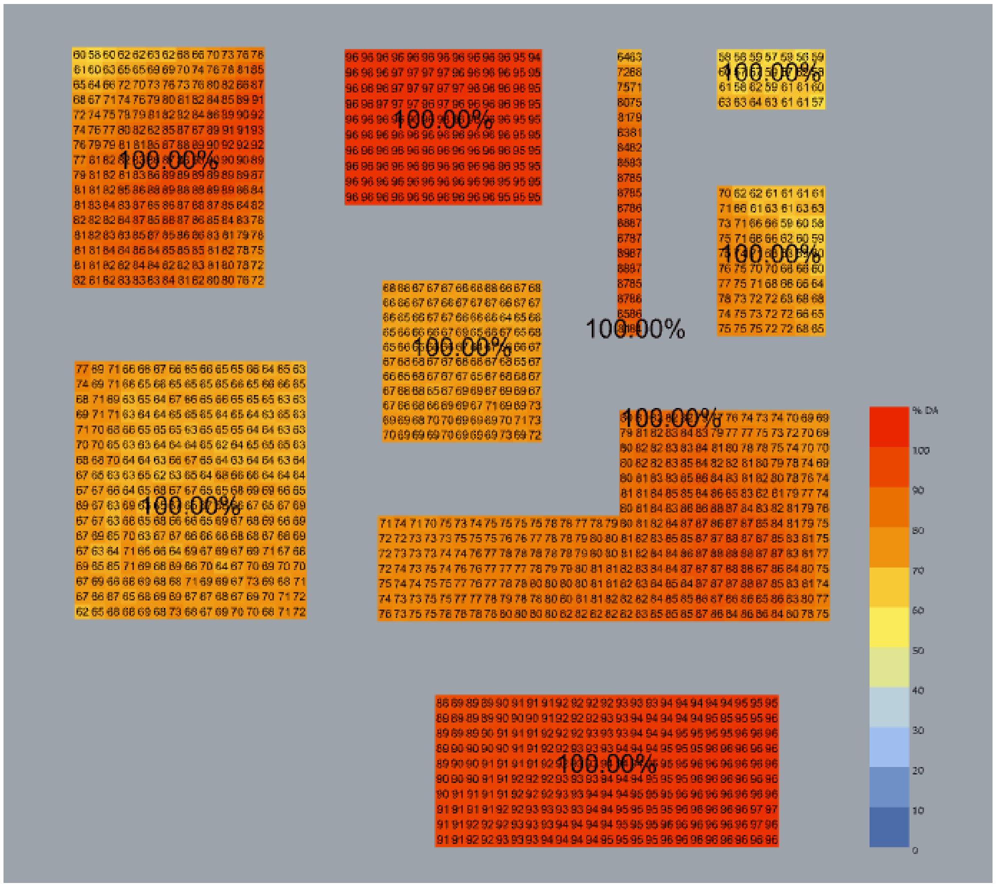


Figure 27. DA values and sDA percentage of the entire house for the case "heavyweight_WWR0.1_0RW"

The scenario is different for the first floor (Figure 28), because in this case there are no roof windows placed which has caused criteria failure in all the zones with sDA below 50% except master bedroom.

This result shows adding roof windows in this case can be a good solution for daylight sufficiency but it might cause overheating in the zones. Therefore, the results for overheating hours should have checked before taking any decisions.

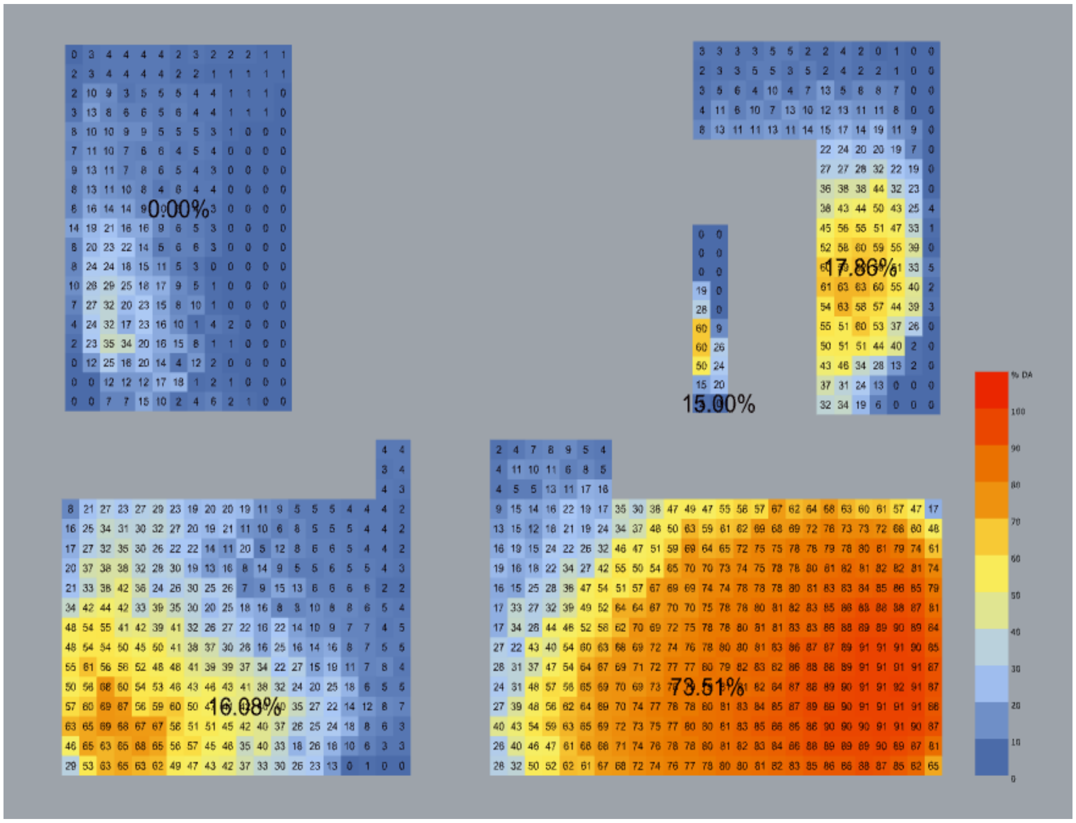


Figure 28. DA values and sDA percentage of the entire house for the case "heavyweight_WWR0.1_0RW"

4.2 Energy and Thermal Comfort Simulation Result - Graph

The graphs in the energy simulation part include an Energy Balance bar chart of the entire house during the whole year, heating/cooling load map for all the zones to compare the load in different zones. Operative temperature graph for a specific zone in one scenario and compare it with a different scenario.
The result will be presented for the case "heavyweight_WWR0.1_2xMK06_GGL 66" and a comparison with the case "heavyweight_WWR0.1_0RW"

4.2.1 Heating Load Zone Color Graph
Figure 29 shows the heating graph for all the zones. It presents the zones with the most heating demand, for example, on the ground floor (left side) entrance, mechanical room, and staircase have the most load need, and, the corridor, toilet, and master bedroom on the first floor (right side) are with the ones with the most need. It is a helpful graph to have an overview of what is happening in each zones in terms of heating demand.

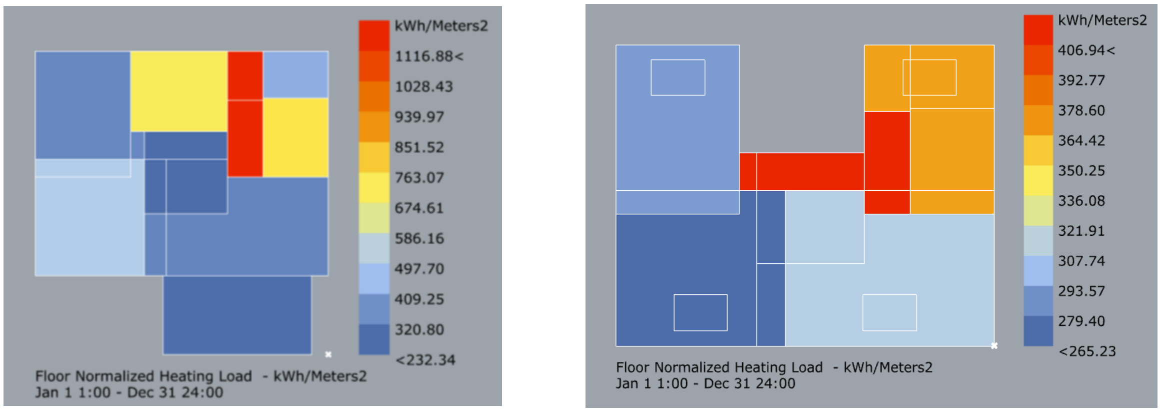


Figure 29. shows the heating load in all the zones in the house, ground floor (left)and first floor (right)

4.2.2 Operative Temperature-Hourly Graph

Below Figure.27 is the hourly operative temperature for bedroom no.2 during the entire year for each hour of the day. It is a good way to get an overall view of a zone in different case scenarios. For example, Figure 30 shows the operative temperature of the same bedroom no.2 but for the case heavyweight_WWR0.1_0RW (Figure 31), clearly has a lower operative temperature during the day specifically summer time and there is more chance of overheating when the operative temperature goes above 26degree for 1200 degree hours.

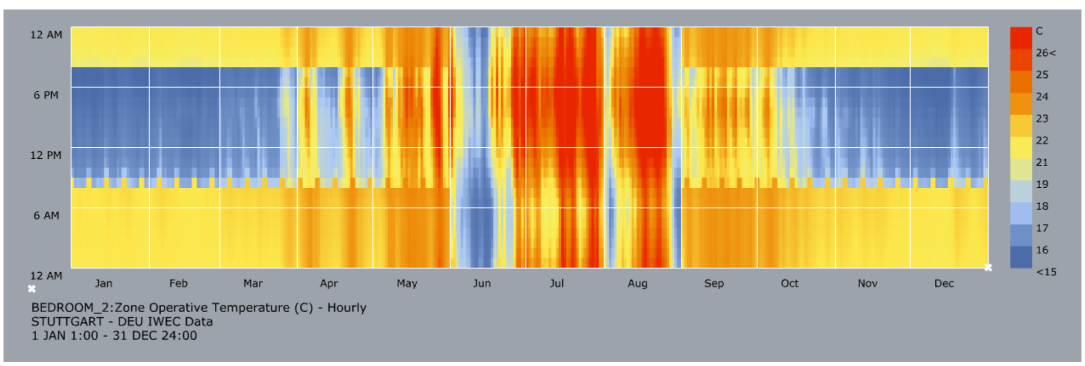


Figure 30. operative temperature for bedroom no.2

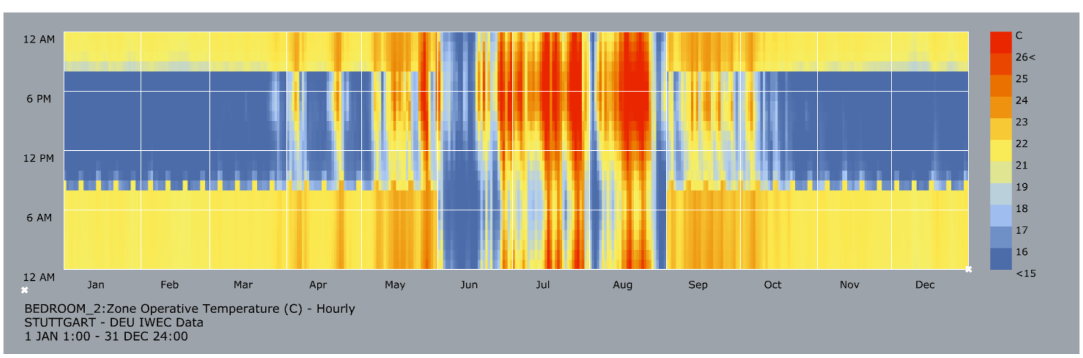


Figure 31. operative temperature for bedroom no.2-comparison case

4.2.3 Energy Balance Bar Chart - Graph

Figure 32 shows the energy balance bar chart for bedroom no.2 below in the case “heavyweight_WWR0.1_2xMK06_0.68”

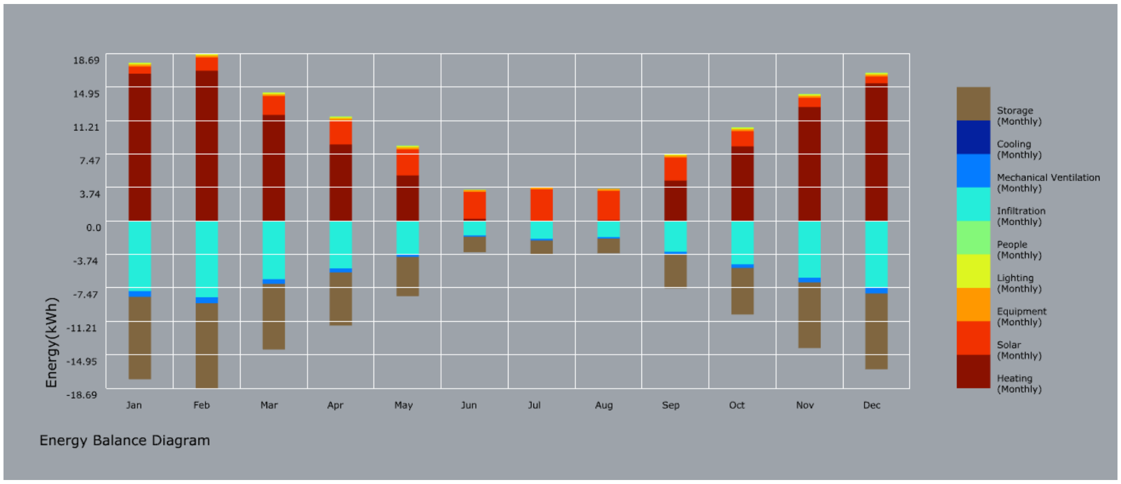


Figure 32. *Energy balance bar chart for bedroom no.2 for the case. heavyweight_WWR0.1_2xMK06_GGL70double*

The figure shows what are the heating sources in the zone (+values) which can be from solar gain, people, heating system, lighting, etc., and opposite to that what are the heating losses (-values) from infiltration, ventilation, etc. and there should be a balance for it during the whole year. The storage part shows the heat that is trapped in the thermal mass and it tries to balance the gains and losses in the zone. It is a good graph to check if the HVAC system is giving the right result after the simulation.

4.3 LCA result

Life cycle analysis has been done for 4 cases out of 5 (Table 21) because there were no EPDs for glazing type GGL66 triple-layer yet. There are EPDs available for GGL 70 double-layer. Although this information can guide in selecting the better design variation because Triple glazing windows has more GWP than double layer with the same properties.

Case no	Case Name
1	GFR10%_RW_heavyweight_WWR0.1_MK06_GGL66triple
2	GFR10%_RW_heavyweight_WWR0.1_MK06_GGL70double
3	GFR10%_RW_heavyweight_WWR0.1_2xMK06_GGL66triple
4	GFR10%_RW_heavyweight_WWR0.1_2xMK06_GGL70double
5	GFR10%heavyweight_WWR0.1
6	GFR10%lightweight_WWR0.1

Table 21. *Number of cases for LCA.*

Below are results in the form of pie graphs for different stages, different building elements and construction materials layers.
the life cycle overview of global warming for each case.

Figure 33, is life cycle overview of global warming for the case “heavyweight_WWR0.1_0RW” GWP value for this case: 9.06 kg CO2e / m2 / year. (result come from one click LCA online platform)

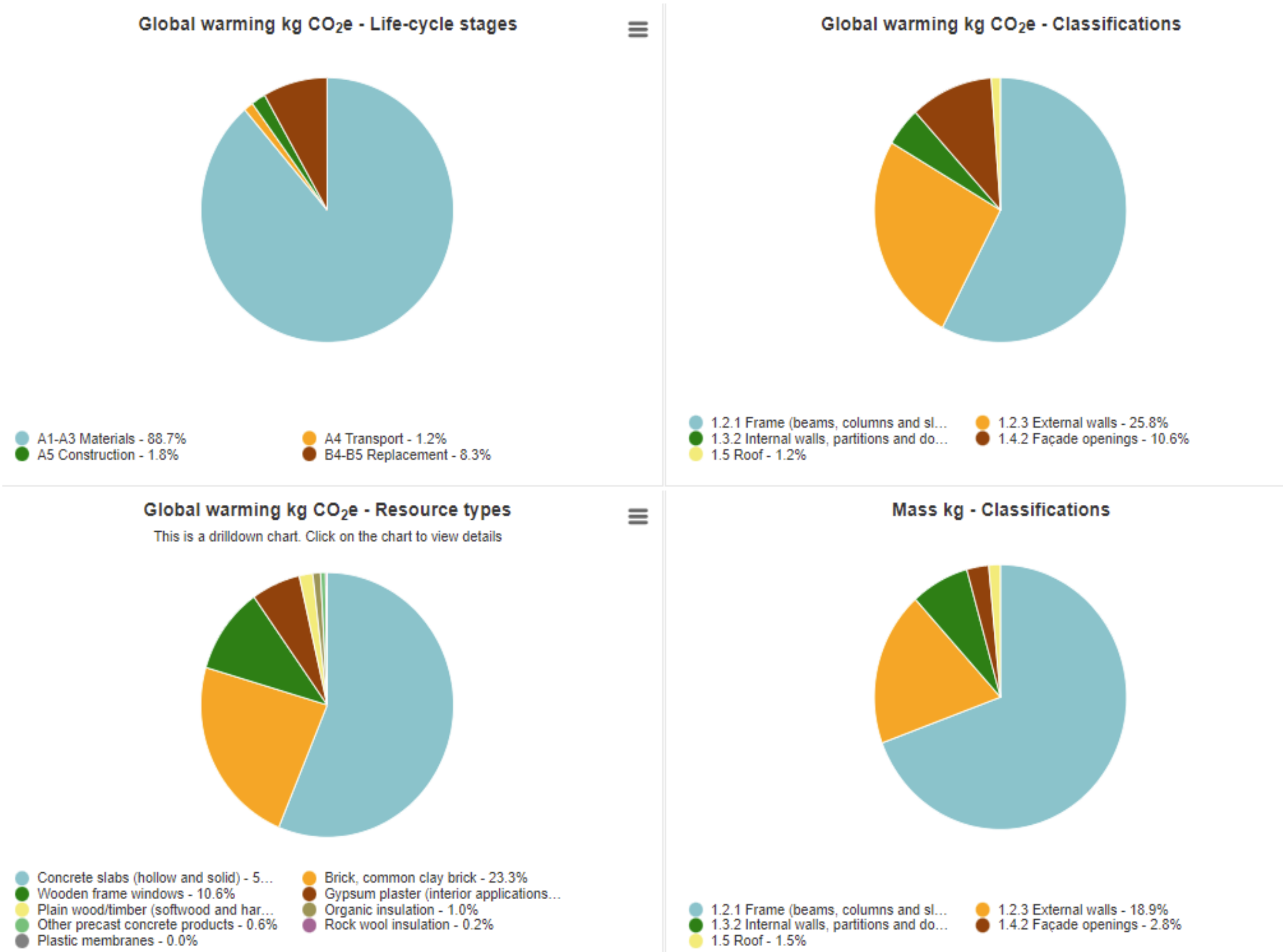


Figure 33. Life cycle overview of global warming-case 2

Below is the life cycle overview of global warming for the case “lightweight_WWR0.1_0RW” (Figure 34). GWP value for this case: 3.82 kg CO2e / m2 / year (result come from one click LCA online platform)

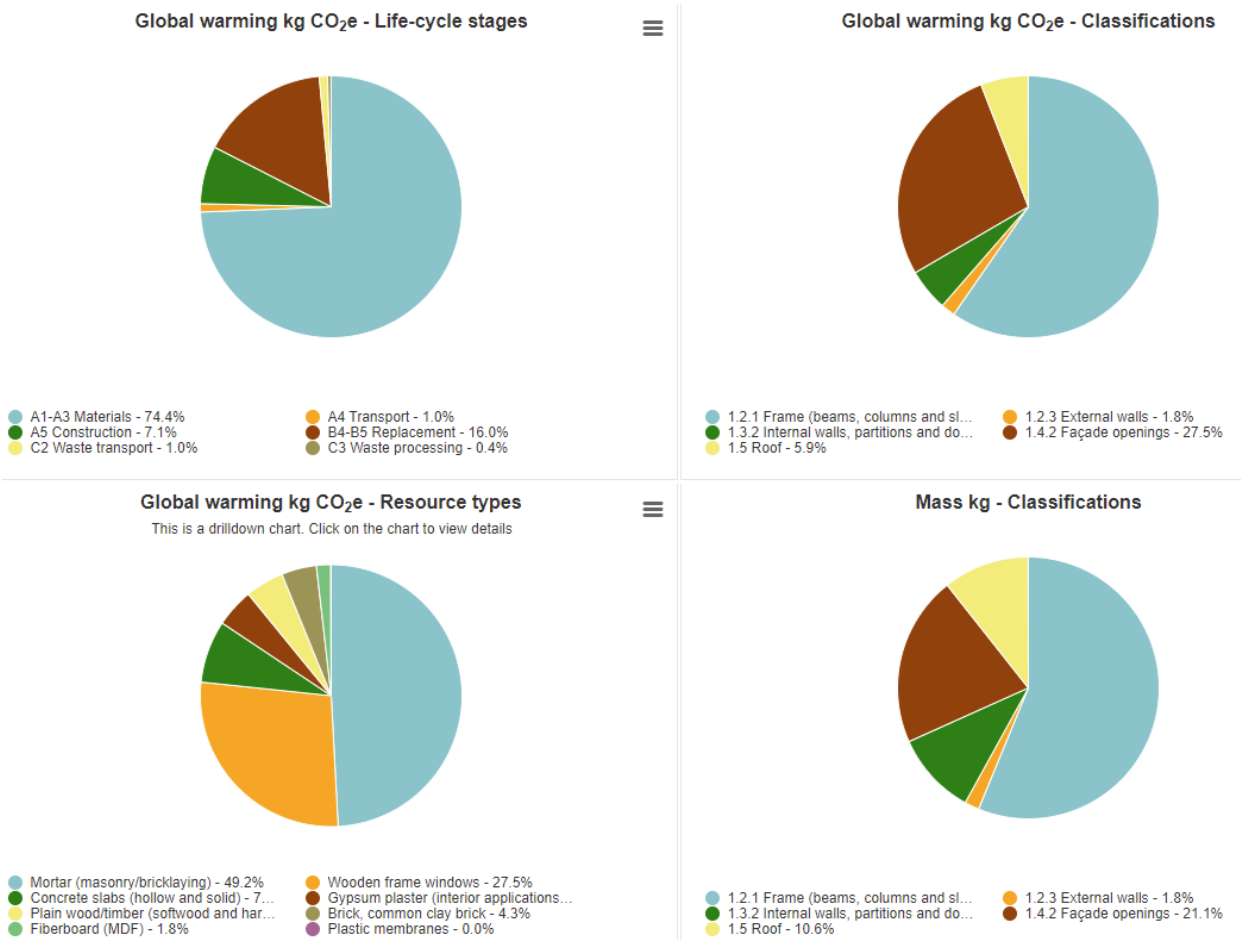


Figure 34. Life cycle overview of global warming-case 6

Below is the life cycle overview of global warming for the case GFR10%_RW_heavyweight_WWR0.1_2xMK06_GGL70double (Figure 35). GWP value for this case:10.17 kg CO2e / m2 / year (result come from one click LCA online platform)

Figure 35. Life cycle overview of global warming-case

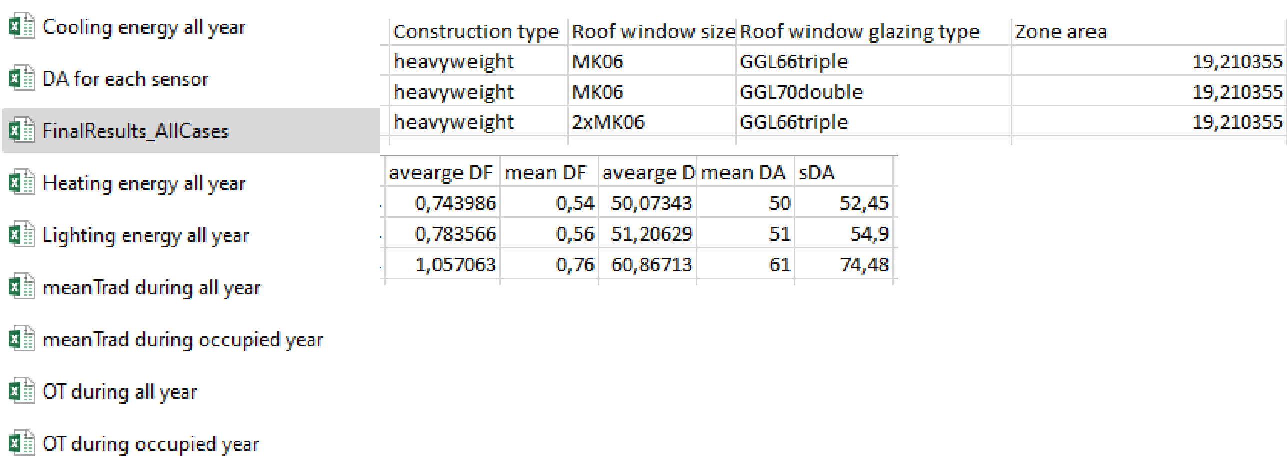
Table 21. below shows the GWP results in all analyzed cases.

Case no	GWP
1	<9.26 kg CO2e / m2 / year
2	9.26 kg CO2e / m2 / year
3	>10,17 kg CO2e / m2 / year
4	10,17 kg CO2e / m2 / year
5	9.06 kg CO2e / m2 / year
6	3.82 kg CO2e / m2 / year

Table 22. GWP results for 6 cases.

4.4 Result in Excel sheets

To be able to compare different environmental parameters like overheating, energy demand, and daylight efficiency for different cases, data should be extracted in Excel and find out the cases with the most balance trade-off between parameters. As it is shown in the Figure 36 below numerical data for each case has been extracted from the script for the comparison.
This data will be used in Tableau software for making comparison graphs.



Construction type	Roof window size	Roof window glazing type	Zone area
heavyweight	MK06	GGL66triple	19,210355
heavyweight	MK06	GGL70double	19,210355
heavyweight	2xMK06	GGL66triple	19,210355

avearge DF	mean DF	avearge D	mean DA	sDA
0,743986	0,54	50,07343	50	52,45
0,783566	0,56	51,20629	51	54,9
1,057063	0,76	60,86713	61	74,48

Figure 36. The way results are getting saved in the Excel sheet

Chapter 5

5. Discussion

5.1 Limitations

One of the limitations during the process was the software license which took time to apply for access from the university and also the installation process was time-consuming as well. Some plug-ins like one-click LCA do not give full access to all services if you are using a student license and not a business license so some features or options were not available for visualization or localization of the chosen materials. Initially, I decided to simulate more than 100 cases as per the number of parameters I chose at the beginning but due to time limitations for simulating all, I decided to select 5 cases and compare the result. If time was not a limitation, it’s possible to simulate all the cases since the user for example an architect needs to know what is the effect of chosen design alternatives to be able to choose between them. The study aims to show the workflow for the process, therefore simulating fewer cases does not cause any harm.

One of the main aims of this tool is to be easy and fast but because developing the final product is time-consuming and it is not completed by the end of this thesis it has not been possible to validate the easiness and speed of the tool.

So the already-made script is not fast and easy to run now and needs an expert to run it since it is in the development stage yet. When it comes in the form of a tool, for example, a plug-in that can be installed in different architectural software or an online platform that is connected to architectural software with an option to change the design parameters and see the comparison result. This part comes under tool development which is happening in collaboration between Velux and a tool-developing company, the written script will be used as the main data source behind this tool.

Another goal for this tool is to be integrated and contain all three environmental aspects of carbon emissions, indoor environment, and energy use that have been taken care of in the already developed script.

Due to climate change and temperature increases in the future, the low-energy houses constructed today may be overheated in the future with bad quality indoor thermal comfort so there should be more focus on natural ventilation, material choices, and properties like U value and G value, therefore the developed tool should be able to comply with the new situation and requirements.

The weather data “epw file” provides information about dry bulb temperature, hourly heating/cooling degree hours, humidity, wind speed and direction, latitude, etc., for the building performance simulations but this file should get updated as the climate changes, this tool should be able to integrate future climate changes which have an impact on the definition of building

performance in terms of indoor environment quality in order to be a valid tool for giving feedback and guiding designers during their design phases.
Another important point that needs to be raised here is the product EPDs which are not covering all the life cycle analysis stages for carbon emission calculations. Most of the EPDs do not consider the “use phase” which includes use, repair, maintenance, replacement, and refurbishment. With the new regulations set by the EU with an “Ecodesign approach” and the main focus on the circularity of a wide range of products from textile to construction, etc, the use phase needs to be included in the products' EPDs. This is important for having a more realistic number for the carbon footprint calculation (*REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL.Pdf*, 2022).
As of now designers do not pay attention to the circularity of materials they choose since there is no information available about aspects like reparability, durability, reusability, etc. and this needs to be changed with the help of new upcoming regulations that will change the focus more towards circularity in products. It is the same story for Velux as a window manufacturer and sale company to deal with the new requirements specific to the windows which will be in place within some years, Velux needs to have this in mind and have more focus on updating their product data in the use phase as well.
The focus of this study has been on new construction for residential buildings and it would be more complete if the criteria set in the tool were complied with both the non-residential buildings and also renovation projects since a lot of construction work needs renovation in Europe. The standard criteria are not the same for different aspects of these construction categories.

5.2 Future work

Script written in Grasshopper is not the final product and needs to be transformed into a tool that can be in the form of a plug-in for different software that architects are familiar with, an online platform that can connect architects' designs to environmental analysis, etc… The already-made script is like the backbone of the ultimate tool like in any other application that has some programming behind but the importance is to be easy and fast to use, which is possible in the tool interface and also with shortening and optimizing the workflow in the script.
Some features are missing in the script which needs to be added, features such as natural ventilation, indoor air quality, view to the outside, adding shading to the windows, acoustic, and also compliance with standards in more countries than Denmark and Germany which are included in the script for now.
The script also needs to be automated in running the simulation, and this is possible with the help of Python language for writing the code for this command. Right now it’s possible to run the simulation for every zone of the house and save the data before going to the next zone manually but this process is time-consuming and needs to be done automatically.
Another step that should be taken in the future is customizing the study model to any house with different sizes and zone numbers and not a specific case of a family house in Germany as in the current scenario because architects need to be able to test any design alternatives they have for different projects.
Another important future step is to be validated and tested by different architectural companies like “Hening Larsen” or “Rambol” etc, with experience and expertise in the computational design field. Architects in these firms will be using this tool and give us feedback on its performance like result quality, the speed for simulations, how easy it is to use, and to what extent the interface is friendly to use. Then afterward it needs to be further modified as per the feedback.

The script needs to be updated when there is a new standard coming or there are changes in already existing ones for a better building performance quality. Also in the LCA process if there is an update in product EPDs that is happening in the coming years the script needs to be updated accordingly.
The optimization workflow should also be added to this tool which is not there yet. The optimization part helps architect to find the best design alternatives among all the options they might have which may depend on the number of parameters they have. Architects cannot check in case there are hundreds of design options one by one and choose between them. In the optimization process, this tool can find the best solution for them, for example, a case with GWP value, overheating hours, special daylight autonomy, etc. within an acceptable range for it.
A very good way of presenting the trade-off between the environmental parameters is the radar graph Figure 37. It is possible to rank every parameter from 1 to 4 or A to D and see the comparison between different cases. Due to the time limitation to find out the resources on how to categorize the result into the best to worst cases, it was not possible to present the result in the radar graph but it can be something to do in the future for more comprehensive result analysis.

	Case 1	Case 2
Energy	2	4
Thermal comfort	1	5
Daylight	2	2
LCA	3	1

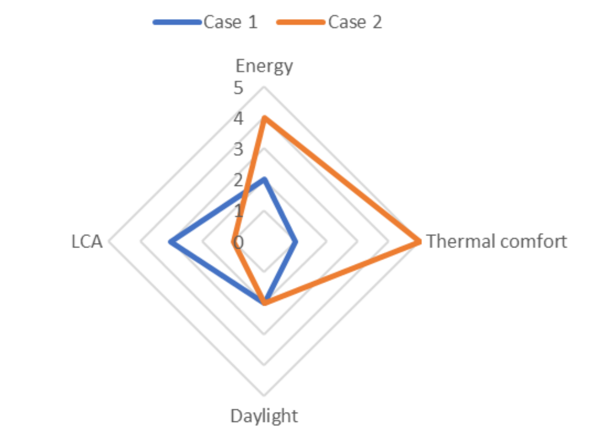


Figure 37. Radar graph with categories from 1 to 4.

Chapter 6

6. Conclusion

1. Are there any trade-offs between building energy performance (both embodied and operational) and indoor environment quality in new construction?

In order to find answer to this question, pass/fail analysis has been done for the 5 case variants. Cases are compared on the base of compliance with sDA percentage, and overheating degree hours (based on German standards) and better LCA result.
The below graphs (Figure 38 & 39) are used for showing which cases for different zones are passing/failing the three criteria.

The cases which are located on the top left side of the graph (Figure 38 & 39) are the ones passing the two criteria of daylight and thermal comfort.
As per Figure 38 shows, all the zones with the 5 case scenarios, are good design alternatives in term of daylight and thermal comfort except one zone.
The zone represented in pink color (Figure 38) is the greenhouse zone which is passing the daylight criteria but not the thermal comfort.

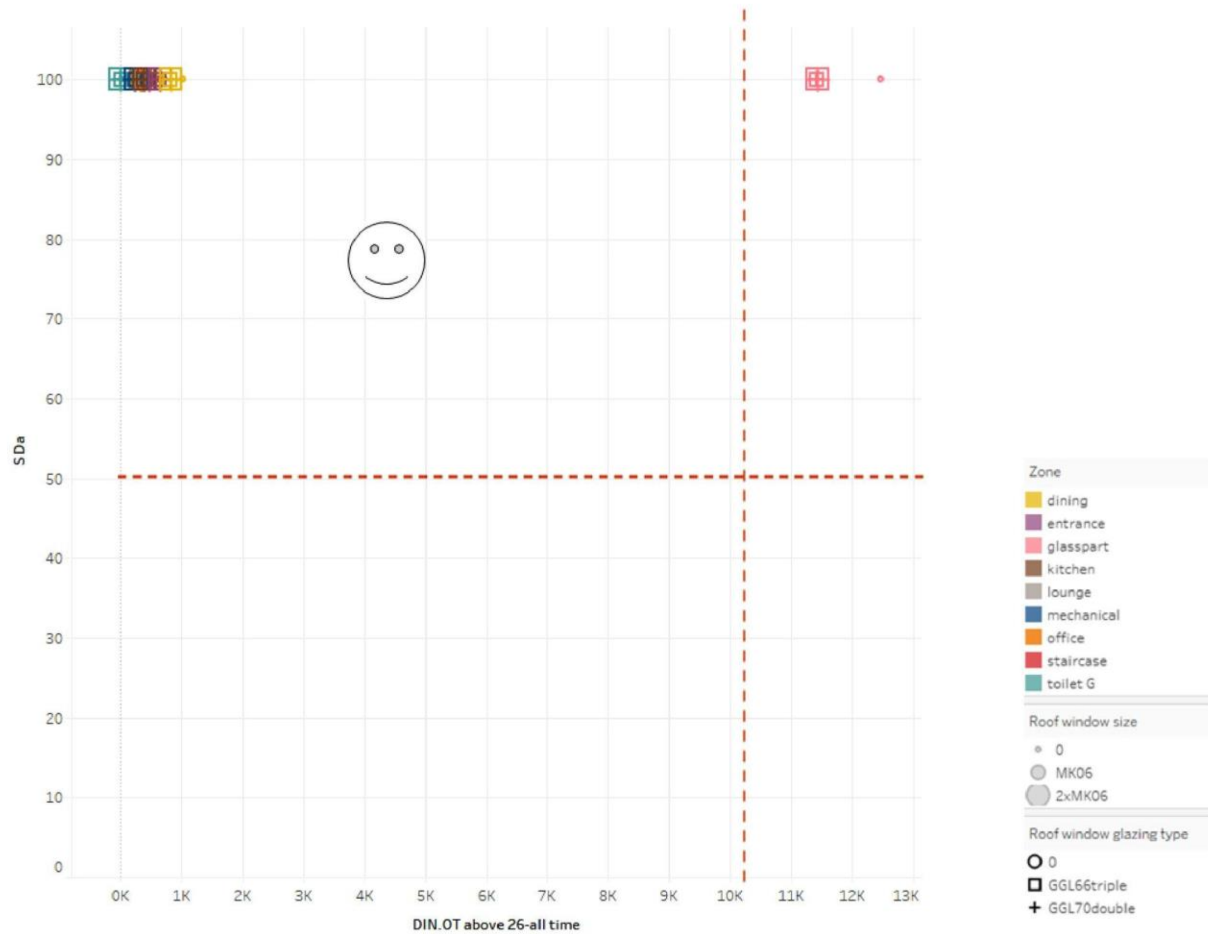


Figure 38. Cases that pass both criteria of sDA and OH hours - ground floor

On the other hand, on the first floor (Figure 39) there are cases for different zones which are failing the daylight criteria. For example, in bedroom 2 (represented in orange color) 3 case variants are not acceptable for daylight availability (bellow the sDA line).

Figure 39. Cases that pass both criteria of sDA and OH hours - first floor

And in bedroom no 1 (blue color) there are 4 cases passing the both criteria and the difference between these cases is in roof window size and glazing properties. In order to be able to choose between these four options, the LCA result should be considered. LCA result (Table 23) shows case variant no 2 with the better value as compared to the rest. So case variant no 2 is the best option for bedroom no.1 that passes all three criteria of daylight, thermal comfort.

At the same time case variant no.6 has the best value LCA but failing the daylight criteria. So It is important to analysis the case variants in an integrated way to consider all the three environmental parameters.

Case no	Case variant	GWP
1	GFR10%_RW_heavyweight_WWR0.1_MK06_GGL66triple	>9.26 kg CO2e / m2 / year
2	GFR10%_RW_heavyweight_WWR0.1_MK06_GGL70double	9.26 kg CO2e / m2 / year
3	GFR10%_RW_heavyweight_WWR0.1_2xMK06_GGL66triple	>10,17 kg CO2e / m2 / year
4	GFR10%_RW_heavyweight_WWR0.1_2xMK06_GGL70double	10,17 kg CO2e / m2 / year
5	GFR10%heavyweight_WWR0.1	9.06 kg CO2e / m2 / year

Table 23. *Design variants comparison for LCA*

It is possible to find the tradeoff between environmental parameters for all other zones with different case variants as it was done for the bedroom no.1 in this study.

Using both visual simulations presented in the result chapter and the graphs, provide guidance for designer to choose the best design variants.

2. How can the use of parametric design principles in the early stage of design impact building performance quality?

The method in this study is to avail the computational design potential that follows parametric modeling principles which have formed the script in this study (the workflow in the script has been explained in the model analysis section). The script has been written through the Grasshopper plugin in Rhino 3D modeling software environment.

The script performs in a way that can be modified and updated according to the different parameters it receives, then it runs the environmental simulations for all the design alternatives coming out of this process. As it is shown in Figure 40, it is possible to change different parameters with the help of a slider and as a result, different design cases get produced. All the cases will go through environmental simulations written in the script, and in the end, results for indoor environmental quality, operational energy demand, and global warming potential value as part of LCA can be extracted on a detailed level presented graphically or numerically in Excel.

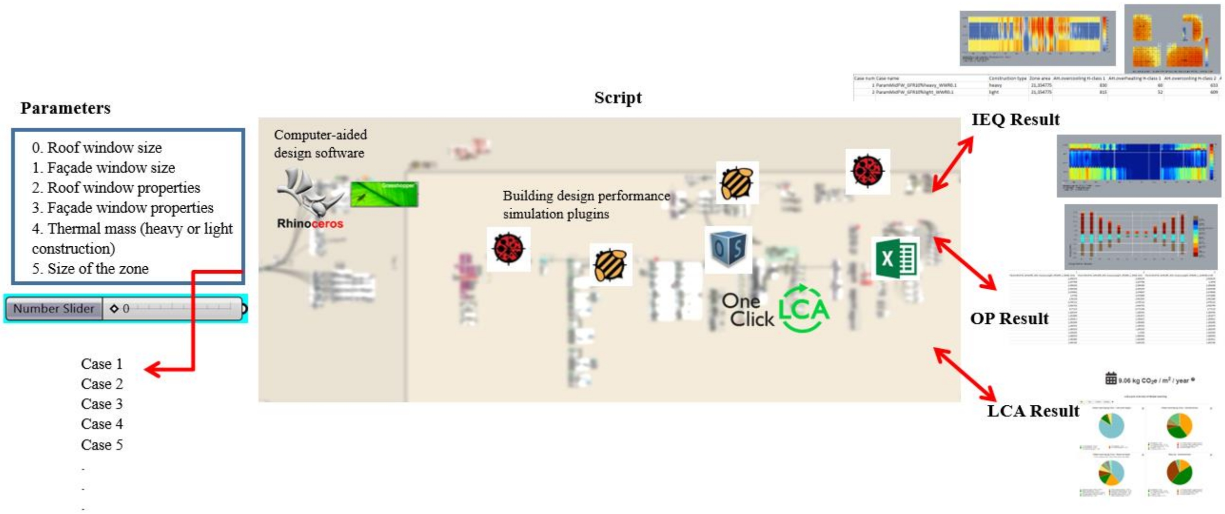


Figure 40. How architects can use the script with different parameters and get environmental results for easy comparison.

This tool can help architects in a way that enable them to choose different design parameters as per their design requirement and needs and to compare these different design scenarios at the early stage of their design, for example, if they want to compare the result in a zone which has either timber or concrete as the main construction, two roof window versus 4 roof windows, window to wall ratio for facade window of 10% or 25% and visual transmittance value of 0,62 or 0,68 for the windows, these all parameters can be set in the script and result for all three environmental parameters will be available for comparison both in visual ways like graphs showing yearly heating/cooling demand, solar gains in the zones, hourly operative temperature, daylight autonomy in different points in the zones, carbon emission for different material selected, etc. and also in form of Excel for more detailed comparison and making more customized graphs if needed.

This method helps architects for making more conscious design decisions at the initial design step in a more time-efficient way, instead of completing the conceptual design first and sending it to the engineers for the initial environmental analysis, waiting for the result from them, then implementing the needed changes according to the engineers' feedbacks into the design again. This process can go on many times till getting the appropriate result which wastes a lot of time and effort from both architects and engineers.

An architect from Germany say the same after being explained about this tool and being asked for his opinion about what is the added value for him if he could use this tool in his design process and he replies:

"The added value is that comparison as I can decide faster and easier, and I do not need to write an email or call somebody saying: What if… But being able to compare two different materials with each other and if I send it to an expert, they have to spend time looking at it. And this seems very practical. And in the conceptual phase where I have many different versions, I can choose easier." (Architect from Germany) (VELUX internal report, 2022).

Chapter 7

7. References

Abnett, K. (2023, March 10). EU strikes deal to curb energy use by 2030. *Reuters*. https://www.reuters.com/business/energy/eu-reaches-agreement-to-reduce-energy-consumption-eu-level-by-117-2030-2023-03-10/

Aksamija, A. (2018). *Methods for integrating parametric design with building performance analysis*.

AksiN, F. N., & Selçuk, S. A. (2019). USING PARAMETRIC ALGORITHMS WITHIN THE CONTEXT OF ENERGY OPTIMIZATION OF BUILDING SKINS. *Part B*.

Al Omari, K. (2016). The impact of daylight on occupant's satisfaction: In the Residential apartments of Amman, Jordan. *International Journal of Applied Environmental Sciences*, *11*(2), 551–557.

Apellániz, D., Pasanen, P., & Gengnagel, C. (n.d.). *A Holistic and Parametric Approach for Life Cycle Assessment in the Early Design Stages*.

Aust ggl product sheet 2022 web.pdf. (n.d.).

ANSI/ASHRAE Standard 55-2017, Thermal Environmental Conditions for Human Occupancy

Balaras, C. A. (1996). The role of thermal mass on the cooling load of buildings. An overview of computational methods. *Energy and Buildings*, *24*(1), 1–10.

Bernett, A., & Dogan, T. (2019, December). *Early Design Decision-Making Framework Based on Multi-Objective Building Performance Simulation Incorporating Energy, Carbon Footprint and Cost*. https://doi.org/10.26868/25222708.2019.210856

Bing Bing Guo. (2022). *How Does Your Indoor Environment Affect Your Mental Health and Well-being? | Delos*. https://delos.com/resources/blog/how-your-indoor-environment-impacts-mental-health/

Birgisdottir, H., & Rasmussen, F. N. (2016). Introduction to LCA of Buildings. (1 ed.) Trafik-og Byggestyrelsen.

Bragança, L., Mateus, R., & Koukkari, H. H. (2010). Building Sustainability Assessment. *Sustainability*, *2*, 2010–2023.

Bragança, L., Mateus, R., & Koukkari, H. H. (2007). *Perspectives of building sustainability assessment*.

Building performance. (2022). [Guidance]. https://www.designingbuildings.co.uk. https://www.designingbuildings.co.uk/wiki/Building_performance

Building performance simulation. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Building_performance_simulation&oldid=1144156853

CEN-CENELEC. (2020). CEN-CENELEC. https://www.cencenelec.eu/

CO2 emissions from buildings and construction hit new high, leaving sector off track to decarbonize by 2050: UN. (2022, September 11). UN Environment. http://www.unep.org/news-and-stories/press-release/co2-emissions-buildings-and-construction-hit-new-high-leaving-sector

COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A Renovation Wave for Europe—Greening our buildings, creating jobs, improving lives, (2020). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0662

Construction-Carbon-Regulations.pdf. (n.d.).

Consumption in the construction industry. (2022). [Definition; Guidance]. https://www.designingbuildings.co.uk. https://www.designingbuildings.co.uk/wiki/Consumption_in_the_construction_industry

Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. (2010).

DS_EN 17037_2018.pdf. (n.d.).

DIN 4108-2 Thermal protection and energy economy in buildings -Part 2: Minimum requirements to thermal insulation.

E. Batueva and A. Mahdavi, "Assessment of a computational design environment with embedded simulation capability," in eWork and eBusiness in Architecture, Engineering and Construction - Proceedings of the 10th European Conference on Product and Process Modelling, ECPPM 2014, 2015, pp. 197–202.

EN 15978:2011, Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method, CEN, Brussels.

EN 15978:2012 Nachhaltigkeit von Bauwerken – Bewertung der umweltbezogenen Qualität von Gebäuden. European Committee for Standardization. CEN/TC 350.

EN 17037:2018/AC:2021 - Daylight in buildings

EN 15643:2021 - Sustainability of construction works - Framework for assessment of buildings and civil engineering works

Fantozzi, F., & Rocca, M. (2020a). An Extensive Collection of Evaluation Indicators to Assess Occupants' Health and Comfort in Indoor Environment. *Atmosphere*, *11*(1). https://doi.org/10.3390/atmos11010090

Fantozzi, F., & Rocca, M. (2020b). An Extensive Collection of Evaluation Indicators to Assess Occupants' Health and Comfort in Indoor Environment. *Atmosphere*, *11*, 90. https://doi.org/10.3390/atmos11010090

Fantozzi, F., & Rocca, M. (2020c). An Extensive Collection of Evaluation Indicators to Assess Occupants' Health and Comfort in Indoor Environment. *Atmosphere*, *11*(1). https://doi.org/10.3390/atmos11010090

Fu, F. (2018). Chapter Six—Design and Analysis of Complex Structures. In F. Fu (Ed.), *Design and Analysis of Tall and Complex Structures* (pp. 177–211). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-08-101018-1.00006-X

Fufa, S. M., Flyen, C., & Flyen, A.-C. (2021). How Can Existing Buildings with Historic Values Contribute to Achieving Emission Reduction Ambitions? *Applied Sciences*, *11*(13), 5978. https://doi.org/10.3390/app11135978

Fumo, N. (2014). A review on the basics of building energy estimation. *Renewable and Sustainable Energy Reviews*, *31*, 53–60. https://doi.org/10.1016/j.rser.2013.11.040

Ganesh, G. A., Sinha, S. L., Verma, T. N., & Dewangan, S. K. (2021). Investigation of indoor environment quality and factors affecting human comfort: A critical review. *Building and Environment*, *204*, 108146. https://doi.org/10.1016/j.buildenv.2021.108146

GEG (German Energy Act 2021_English).pdf. (n.d.).

GGU_34_en-HQ_HQ.pdf. (n.d.).

González-Torres, M., Pérez-Lombard, L., Coronel, J. F., Maestre, I. R., & Yan, D. (2022). A review on buildings energy information: Trends, end-uses, fuels and drivers. *Energy Reports*, *8*, 626–637. https://doi.org/10.1016/j.egyr.2021.11.280

Grasshopper 3D. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Grasshopper_3D&oldid=1138486436

Guglielmetti, R., Macumber, D., & Long, N. (2011). *OpenStudio: An Open Source Integrated Analysis Platform; Preprint*.

Guidance on Core Indicators for Sustainability and SDG Impact Reporting. (2022).

Hagelund, J. J. J. (2015). *A World Built on Standards – A Textbook for Higher Education*.

Hee, W. J., Alghoul, M. A., Bakhtyar, B., Elayeb, O., Shameri, M. A., Alrubaih, M. S., & Sopian, K. (2015). The role of window glazing on daylighting and energy saving in buildings. *Renewable and Sustainable Energy Reviews*, *42*, 323–343. https://doi.org/10.1016/j.rser.2014.09.020

Hollberg, A. (2017). *A parametric method for building design optimization based on Life Cycle Assessment*.

How COVID-19 made healthy indoor environments and wellness a priority | The Edge Vol 4. (2020). Cushman &

Wakefield. https://www.cushmanwakefield.com/en/insights/the-edge/how-covid-19-made-healthy-indoors-environments-and-wellness-a-priority

Ideal Loads Air System default mechanical ventilation setting. (2016, June 21). Ladybug Tools | Forum. https://discourse.ladybug.tools/t/ideal-loads-air-system-default-mechanical-ventilation-setting/1251

Jain, N., Burman, E., Robertson, C., Stamp, S., Shrubsole, C., Aletta, F., Barrett, E., Oberman, T., Kang, J., Raynham, P., Mumovic, D., & Davies, M. (2020). Building performance evaluation: Balancing energy and indoor environmental quality in a UK school building. *Building Services Engineering Research and Technology*, *41*(3), 343–360. https://doi.org/10.1177/0143624419897397

Jakubiec, J. (2022). Data-Driven Selection of Typical Opaque Material Reflectances for Lighting Simulation. *LEUKOS*, *19*, 1–14. https://doi.org/10.1080/15502724.2022.2100788

Lasse Rohde, R. L. Jensen, O. K. Larsen, K. T. Jønsson, & T. S. Larsen. (2021). *Holistic indoor environmental quality assessment as a driver in early building design*.

Life-cycle assessment. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Life-cycle_assessment&oldid=1140874481

Lm, I. (2013). Approved method: IES spatial Daylight autonomy (sDA) and annual sunlight exposure (ASE). *Illuminating Engineering Society. Https://Www. Ies. Org/Product/Ies-Spatial-Daylight-Autonomy-Sda-and-Annual-Sunlight-Exposure-Ase*.

Mateus, R., & Bragança, L. (2011). Sustainability assessment and rating of buildings: Developing the methodology SBToolPT–H. *Building and Environment*, *46*(10), 1962–1971. https://doi.org/10.1016/j.buildenv.2011.04.023

Negendahl, K. (2015). Building performance simulation in the early design stage: An introduction to integrated dynamic models. *Automation in Construction*, *54*, 39–53. https://doi.org/10.1016/j.autcon.2015.03.002

Nils Petermann. (2010). *Efficient Windows Collaborative* (No. 1024896; p. 1024896). https://doi.org/10.2172/1024896

OECD. (2019). *Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences*. OECD. https://doi.org/10.1787/9789264307452-en

Østergård, T., Jensen, R. L., & Maagaard, S. E. (2016a). Building simulations supporting decision making in early design – A review. *Renewable and Sustainable Energy Reviews*, *61*, 187–201. https://doi.org/10.1016/j.rser.2016.03.045

Østergård, T., Jensen, R. L., & Maagaard, S. E. (2016b). Building simulations supporting decision making in early design–A review. *Renewable and Sustainable Energy Reviews*, *61*, 187–201.

Paulson Jr, B. C. (1976). Designing to reduce construction costs. *Journal of the Construction Division*, *102*(4), 587–592.

Persson, L. (2022). *A comparison between embodied and operational carbon in a building envelope from a life cycle perspective*.

REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL.pdf. (n.d.).

Reinhart, C. F., Mardaljevic, J., & Rogers, Z. (2006). Dynamic Daylight Performance Metrics for Sustainable Building Design. *LEUKOS*, *3*(1), 7–31. https://doi.org/10.1582/LEUKOS.2006.03.01.001

Rhinoceros 3D. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Rhinoceros_3D&oldid=1149655294

Robbins, C. L. (1986) Daylighting Design and Analysis, New York: Van Nostrand Reinhold Company.

Sadeghipour Roudsari, M., Pak, M., & Viola, A. (2013, August 28). *Ladybug: A Parametric Environmental Plugin For Grasshopper To Help Designers Create An Environmentally-conscious Design*. 2017 Building Simulation Conference. https://doi.org/10.26868/25222708.2013.2499

Santamouris, M., & Vasilakopoulou, K. (2021). Present and future energy consumption of buildings: Challenges and opportunities towards decarbonisation. *E-Prime - Advances in Electrical Engineering, Electronics and Energy*, *1*, 100002. https://doi.org/10.1016/j.prime.2021.100002

—*SDG Indicators*. (n.d.). Retrieved 12 March 2023, from https://unstats.un.org/sdgs/report/2021/goal-13/

Thalfeldt, M., Pikas, E., Kurnitski, J., & Voll, H. (2013). Facade design principles for nearly zero energy buildings in a cold climate. *Energy and Buildings*, *67*, 309–321. https://doi.org/10.1016/j.enbuild.2013.08.027

The Evolution of Computational Design (Detailed Guide—2023). (n.d.). Retrieved 26 April 2023, from https://www.oneistox.com/blog/evolution-of-computational-design

Thermal comfort. (2023). In *Wikipedia*.

https://en.wikipedia.org/w/index.php?title=Thermal_comfort&oldid=1138115628#cite_note-Ashrae_55_Standard-1
Wintour, P. (2016, March 13). Ladybug & Honeybee. *Parametric Monkey*. https://parametricmonkey.com/2016/03/13/ladybug-honeybee/
Zilberberg, E., Trapper, P., Meir, I. A., & Isaac, S. (2021). The impact of thermal mass and insulation of building structure on energy efficiency. *Energy and Buildings*, *241*, 110954. https://doi.org/10.1016/j.enbuild.2021.110954

Wittstock, B. et al., 2012. EeBGuide Guidance Document Part B: BUILDINGS,

8. Appendix

	Light roof			
	layers			
1	clay roofing	0,8	2020	880
2	battens timber	0,04	180	2100
3	timber frame	0,12	470	1300
4	battens timber	0,04	180	2100
5	plasterboard	0,16	1180	800
	light floor to ground			
	layers			
1	floor screed	0,41	1200	800
2	timber frame	0,12	470	1300
3	battens timber	0,04	180	2100
4	plasterboard	0,16	1180	800

	Heavy roof			
No	layers			
1	concrete roof tile	0,84	2100	880
2	timber frame	0,12	470	1300
3	woodfiber insulation	0,047	163	2100
4	plasterboard	0,16	1180	800
	heavyfloor to ground			
	layers			
1	waterproof membran	0,022	50	840
2	concrete	1,63	2533	1000
3	rockwool insulation	0,035	90	1030
4	plasterboard	0,16	1180	800

	interior wall			
No	layers			
1	plasterboard	0,16	1180	800
2	timber frame	0,12	470	1300
3	plasterboard	0,16	1180	800
	interior ceiling/floor			
No	layers			
1	plasterboard	0,16	1180	800
2	concrete	1,63	2533	1000
3	plasterboard	0,16	1180	800

	Green house roof for light construction			
No	layers	Thermal conductivity [W/(mK)]	Density [kg/m3]	Special heat capacity [J/(kgK)]
1	waterproof membran	0,022	50	840
2	timber frame	0,12	470	1300
3	plasterboard	0,16	1180	800
	Green house roof for heavy construction			
No	layers	Thermal conductivity [W/(mK)]	Density [kg/m3]	Special heat capacity [J/(kgK)]
1	waterproof membran	0,022	50	840
2	concrete	1,63	2533	1000
3	plasterboard	0,16	1180	800

Figure 1.1. The material construction layers for different elements in the house.

Simulation cases	Construction type	Facade window size	Roof window size	Roof window glazing type
Case 1	Heavyweight	10%	None	None
Case 2	Lightweight	10%	None	None
Case 3	Heavyweight	10%	MK06	GGL66 triple layer
Case 4	Heavyweight	10%	MK06	GGL70 double layer
Case 5	Heavyweight	10%	MK06	GGU66 triple layer
Case 6	Heavyweight	10%	MK06	GGU70 double layer
Case 7	Heavyweight	10%	2MK06	GGL66 triple layer
Case 8	Heavyweight	10%	2MK06	GGL70 double layer
Case 9	Heavyweight	10%	2MK06	GGU66 triple layer
Case 10	Heavyweight	10%	2MK06	GGU70 double layer
Case 11	Heavyweight	10%	SK08	GGL66 triple layer
Case 12	Heavyweight	10%	SK08	GGL70 double layer
Case 13	Heavyweight	10%	SK08	GGU66 triple layer
Case 14	Heavyweight	10%	SK08	GGU70 double layer
Case 15	Heavyweight	10%	2SK08	GGL66 triple layer
Case 16	Heavyweight	10%	2SK08	GGL70 double layer
Case 17	Heavyweight	10%	2SK08	GGU66 triple layer

Case 18	Heavyweight	10%	2SK08	GGU70 double layer
Case 19	Lightweight	10%	MK06	GGL66 triple layer
Case 20	Lightweight	10%	MK06	GGL70 double layer
Case 21	Lightweight	10%	MK06	GGU66 triple layer
Case 22	Lightweight	10%	MK06	GGU70 double layer
Case 23	Lightweight	10%	2MK06	GGL66 triple layer
Case 24	Lightweight	10%	2MK06	GGL70 double layer
Case 25	Lightweight	10%	2MK06	GGU66 triple layer
Case 26	Lightweight	10%	2MK06	GGU70 double layer
Case 27	Lightweight	10%	SK08	GGL66 triple layer
Case 28	Lightweight	10%	SK08	GGL70 double layer
Case 29	Lightweight	10%	SK08	GGU66 triple layer
Case 30	Lightweight	10%	SK08	GGU70 double layer
Case 31	Lightweight	10%	2SK08	GGL66 triple layer
Case 32	Lightweight	10%	2SK08	GGL70 double layer
Case 33	Lightweight	10%	2SK08	GGU66 triple layer
Case 34	Lightweight	10%	2SK08	GGU70 double layer

Table 2.1. Design cases planned to run in the study.

Impact category	Parameter	Abbreviation	Unit
Climate Change	Global Warming Potential	GWP	kg CO_2-equiv.
Ozone Depletion	Ozone Depletion Potential	ODP	kg R11-equiv.
Acidification of soil and water	Acidification Potential	AP	kg SO_2-equiv.
Eutrophication	Eutrophication Potential	EP	kg PO_4^{3-}-equiv.
Formation of Photo Oxidants	Photochemical Ozone Creation Potential	POCP	kg CH_4-equiv.
Abiotic Resource Depletion*	Abiotic Resource Depletion Potential element	ADPe	kg Sb-equiv.
Abiotic Resource Depletion*	Abiotic Resource Depletion Potential fossil	ADPf	MJ

Table 2.2. Impact categories and their parameters (EN 15804:2012, p.33).

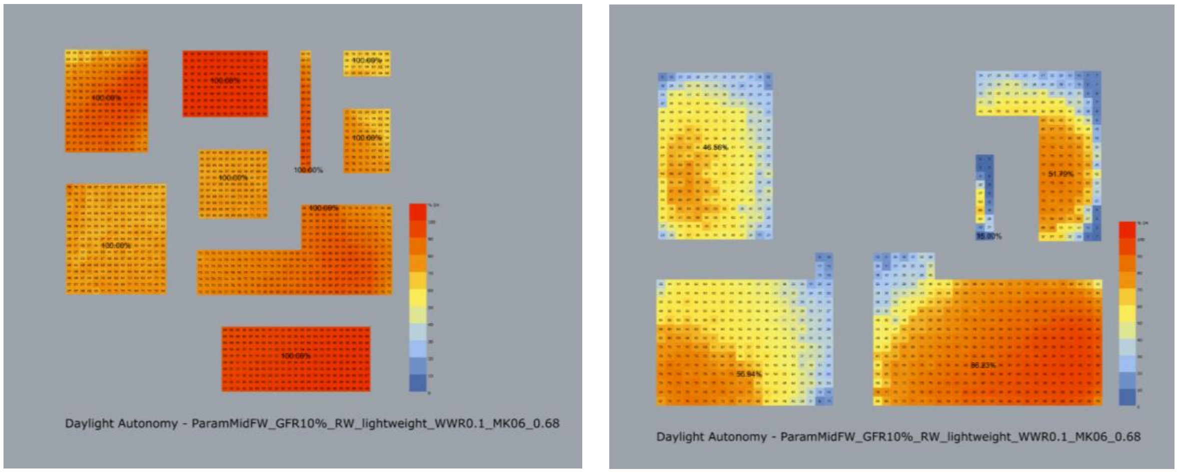


Figure 1.2 Daylight result for case GFR10%_RW_lightweight_WWR0.1_MK06_0.68

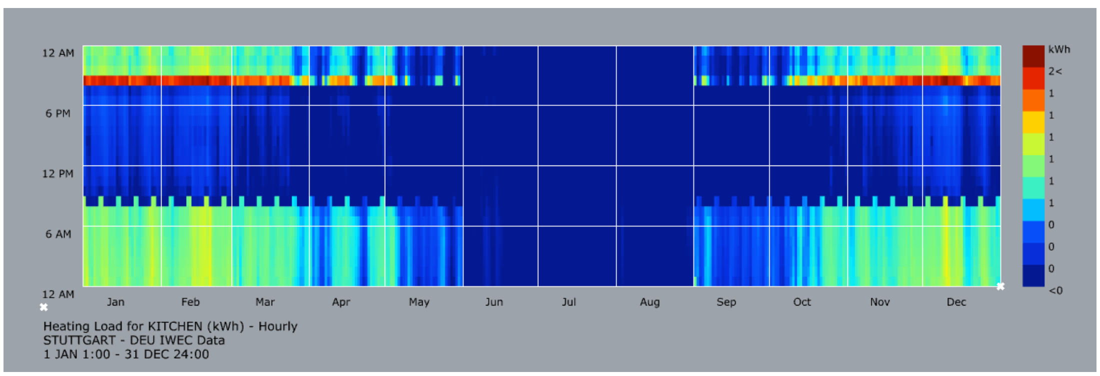


Figure 1.3 Heating energy temporal for case GFR10%_RW_heavyweight_WWR0.1_SK08 in kitchen

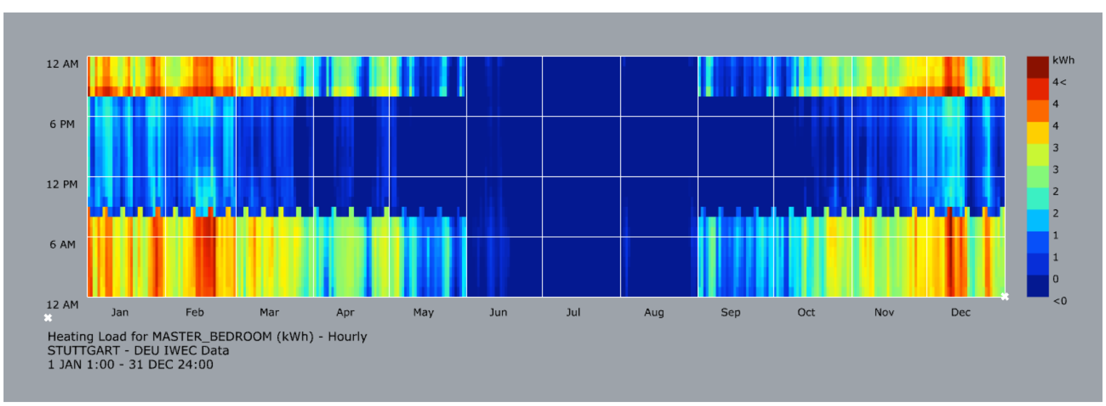


Figure 1.4 Heating energy temporal for case FW_GFR10%heavy_WWR0.1 in master bedroom

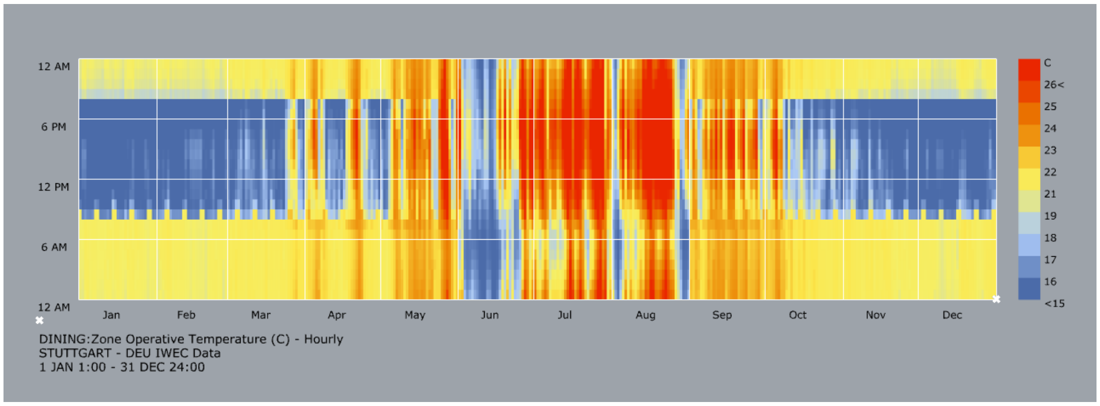


Figure 1.5. Operative Temperature for case FW_GFR10%_RW_lightweight_WWR0.1 in dining