COMPUTATIONAL OPTIMIZATION OF HEMPCRETE INTEGRATION: IMPROVING ENERGY PERFORMANCE AND MINIMIZING EMBODIED ENERGY IN A VARIETY OF BUILDING TYPES AND CLIMATES

By Dimitra Mountaki

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Thesis committee: Dr. Michela Turrin, Dr. Martin Tenpierik

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Abstract

The growing threat of climate change highlights the necessity for long-term solutions in the construction industry. Buildings account for a large share of worldwide energy consumption and carbon dioxide emissions, so there is an urgent need for creative techniques to improve energy efficiency and reduce their ecological footprint. This thesis focuses on this by creating a computational optimization workflow for incorporating hempcrete, a low-carbon construction material, into high-performance structures during the initial stages of design. This approach uses a multi-objective optimization process to offer optimal solutions adapted to various climates and building types, optimizing energy efficiency and daylight while limiting global warming potential. Architects and engineers can get greater performance and sustainability results by experimenting with different layout options and design parameters using parametric modelling, energy analysis, and optimization algorithms. The suggested workflow provides a systematic technique to facilitate decision-making during the key design steps, promoting hempcrete implementation and accelerating the shift to performance-driven architectural design in response to climate change problems.

Contents

1. Introduction

The research question and the problem statement are presented.

1.1. Background

The discovery of inexpensive cast iron triggered vast industrial and urban growth, resulting in the Industrial Revolution (Akpan et al., 2012). The research reports a substantial association between climate change and industrialization (Wadanambi et al., 2020a). The beginning of climate change can be traced down to the early stages of the 18^{th} century when the fossil-fuel-based technologies started arising and the human activities changed rapidly. The transition to the new age has as outcome the rapid increase of coal demand and later on of oil and natural gas, while simultaneously contributed to the ten-fold increase of the population. The global population is anticipated to overcome 12 billion by 2100, which in combination with the rising urbanization, is going to raise the energy demand (Department of Economic and Social Affairs, 2022). Hence, the rapid growth of energy demand will raise the current amount of carbon dioxide (CO2) and other greenhouse gas (GHG) emissions (Li & Lin, 2015).

According to the International Energy Agency report (IEA) for 2022, the building environment consumes 34 % of total final energy, followed by other industries (31%), and transportation (26%). 30% of overall energy demand is for operational purposes in the building industry, whereas 5% needed for building material manufacturing, such as steel, aluminum, concrete and so on (United Nations Environment Programme, 2022a). Similarly, 28% of CO2 emissions in the building sector are generated by operational energy. Global emissions from building material production are estimated to be 3.5 GtCO2 accounting for approximately 9% of total emissions. Thus, the build environment accounts for 34% of the total final energy consumption and 37% of the global operational energy and process-related CO2 emissions in 2021 (United Nations Environment Programme, 2022a).

Advanced techniques aimed at reducing the operational impacts of buildings have been widely used. These approaches, particularly focusing on minimizing energy consumption, are well-established and effective. However, the next challenge is to address the embodied impacts of construction materials. To satisfy the Paris Agreement's aims, new low-embodied-carbon materials should be used. Biobased materials are progressively used in the construction industry, providing an efficient and eco-friendly alternative to traditional materials (Yadav & Agarwal, 2021a). Hempcrete has recently attracted more and more interest as a sustainable building material while it has been introduced in multiple countries (Essaghouri et al., 2023a).

Building performance simulations in early design stages, provide insights into expected energy demands and comfort levels associated with alternative architectural decisions occasionally. Despite the broad application of such simulations, there is limited research that combines strategies to minimize both operational energy and embodied carbon.

1.2. Problem statement

Building environment 34% energy consumption, 37% CO2 ➔ Reduce ➔ More sustainable materials ➔ Hempcrete ➔ Optimize early design stages

Climate change is one of the main challenges for the human-kind right now. Greenhouse gases are gathered in the lower atmosphere layers, while the current global concentration of CO_2 has surpassed the normal amount in the atmosphere (Penuelas et al., 2020). As it mentioned in the background, almost 35% of the global energy consumption and 40% of the global carbon dioxide emissions are generated by the construction sector (United Nations Environment Programme, 2022b).

There have been several studies that focus on the buildings' energy consumption. Researches aimed to reduce the energy through the orientation (Kohansal et al., 2022) , the different climate (Schnieders et al., 2015), the future proof design (D'Agostino et al., 2022), by changing the façade (Bui et al., 2020; Despoina Pouniou, 2019) and even more variables (Giouri, 2017; Wang, 2022). In the same way, there are papers that emphasize in innovative construction materials (Schiavoni et al., 2016a; Yadav & Agarwal, 2021b) such as hempcrete. Recently, an interesting number of papers have been written for this material due to its negative carbon footprint (Pandian et al., 2023). However, the existing research is about the limited application of hempcrete in the building environment as the main material (Costantine et al., 2018; Essaghouri et al., 2023a; Florentin et al., 2017a), or the optimization of the material itself (Agliata et al., 2019a; Bas et al., 2022a; Zemam et al., 2019). The lack of computational methods that combines strategies to minimize operational and embodied energy to support preliminary designs with this material, result to uncertainty about its effectiveness comparing with the conventional materials. Meanwhile, it requires a corporation's time and funds to figure out which material is most suitable for a project.

The current graduation project will emphasize on the lack of knowledge and of a systematic method, that support decision made in early design stages by using hempcrete as the main material, of high energy efficiency buildings, worldwide. Performance-driven architectural design is proven that has a significant influence on early decision-making within a design process (Shi & Yang, 2013). By shifting the attention towards the initial stages of a concept, the effect on both performance and cost of the design is more notable compared to delaying it(Trach et al., 2019). The development of a computational approach will aim to supply architects and engineers with possible suggestions regarding the performance of various layout design options using hempcrete, contributing the early design phase.

The lack of computational methods that combines strategies to minimize operational energy and global warming potential to support preliminary designs with hempcrete.

1.3. Objectives

General objective

The general objective of the current thesis is to develop an efficient optimization workflow for energy-efficient and eco-efficient hempcrete structures to be used in the initial phases of design, aiming to propose optimal designs for a variety of buildings and climates. Within this scope, quantitative variables will be applied via a multi-objective optimization process, to determine hempcrete's evaluation and optimization of several layout possibilities in terms of energy and comfort efficiency.

Sub-objectivee

- Define if different hempcrete compositions can have a significant effect on the energy optimization or the layout.
- Determine the most effective combination of design parameters and hempcrete, to accomplish building energy and sustainability rating systems.
- Map the different parameters that mostly influence the design with hempcrete in a variety of climates.
- Map the different parameters that mostly influence the design with hempcrete in different building types.
- Develop a tool to explore different layout options with hempcrete in every circumstance, to reduce time and cost in early design stages and encourage the use of this material.

Final product

The final product of this graduation topic is a computational optimization approach that enables supporting decision made in primary design phases to enhance the energy efficiency of buildings constructed with hempcrete and therefore its global warming potential. This approach can adapt to thermal and visual comfort without restrictions on climate conditions or building types.

1.4. Limitations and boundaries

- Incorporate the BENG (Energy Performance of Buildings) rules from the Netherlands as a benchmark for each location assessment.
- Integrate BREEAM standards into each location's evaluation procedure.
- Recognize the analysis's exclusion of urban environment complexities in order to obtain more universally applicable connections.
- Limit the layout's area and shape to a restricted amount to simplify the study of various layout designs.
- Limit the parameters amount to simplify the study and focus on hempcrete's integration.

These limits highlight the various constraints directing the research, underlining the necessity for customized methods and in-depth assessments to effectively address each challenge.

1.5. Research question

How can a computational workflow optimize hempcrete's integration in various type of buildings across diverse climates, with the objective to support preliminary designs that achieve high energy performance and minimize global warming potential?

Sub-questions

- How can multi-objective optimization identify the ideal hempcrete composition for thermal conductivity in different climates?
- Which ways can a workflow define the impact of hempcrete thickness on thermal and visual comfort in buildings across different regions?
- How may operational energy and global warming potential optimization influence hempcrete thickness in different contexts?
- How can a computational workflow be used to establish a balance between energy efficiency and occupants comfort preferences, in hempcrete buildings?
- In which way can this workflow be evolved into a useful tool for reducing the required time during the first design stages and promote the use of hempcrete?

Background questions

- What are the main design guidelines to be considered when it comes to energy efficient buildings?
- What are the existing simulation and optimization of hempcrete in literature review and what kind of method do they use?

1.6. Approach and methodology

The current graduation project's methodology and approach seek to address the lack of knowledge and of a structured approach that support performance-driven designs, while providing insights on the energy performance within a computational workflow. The process consists of multiple stages.

Research Framework

The preliminary phase includes an extensive review of existing literature in order to determine the problem, identify gaps in existing studies, and determine the thesis' aims and the research question.

Literature Review

The second part consists of a vast analysis of the literature, beginning with hempcrete's data, such as its thermal properties, its sustainable nature, and current applications. Following that, the emphasis is on the energy usage and current comfort requirements, which are essential for later modeling purposes. Climate data are also covered in the review, as well as methods for obtaining and validating future climate data. A significant part of this phase is dedicated to optimization, which includes investigating existing approaches linked to hempcrete as an insulating material, present energy optimization tools, and performance-driven architectural design.

Simulation Implementation and Optimization

The third step focuses on developing the framework of the simulation approach. A method is designed to assist the subsequent optimizing of designs using tools such as Grasshopper, as well as plugins such as Honeybee, Bombyx and Wallacei. To ensure efficiency, the developed approach is validated using existing energy data of similar case scenarios.

Design Proposal Collection and Evaluation

In the fourth phase, the simulation functions on multiple proposed designs, using optimization techniques to determine ideal layouts integrating hempcrete walls. The last phase comprises gathering and visualizing design options regarded as appropriate based on location and usage requirements, followed by an evaluation.

Discussion and Conclusion

The research concludes with a discussion and conclusion. Furthermore, the report states prospective future Improvements focusing on the practical application and evolution of the computational tool produced throughout this research.

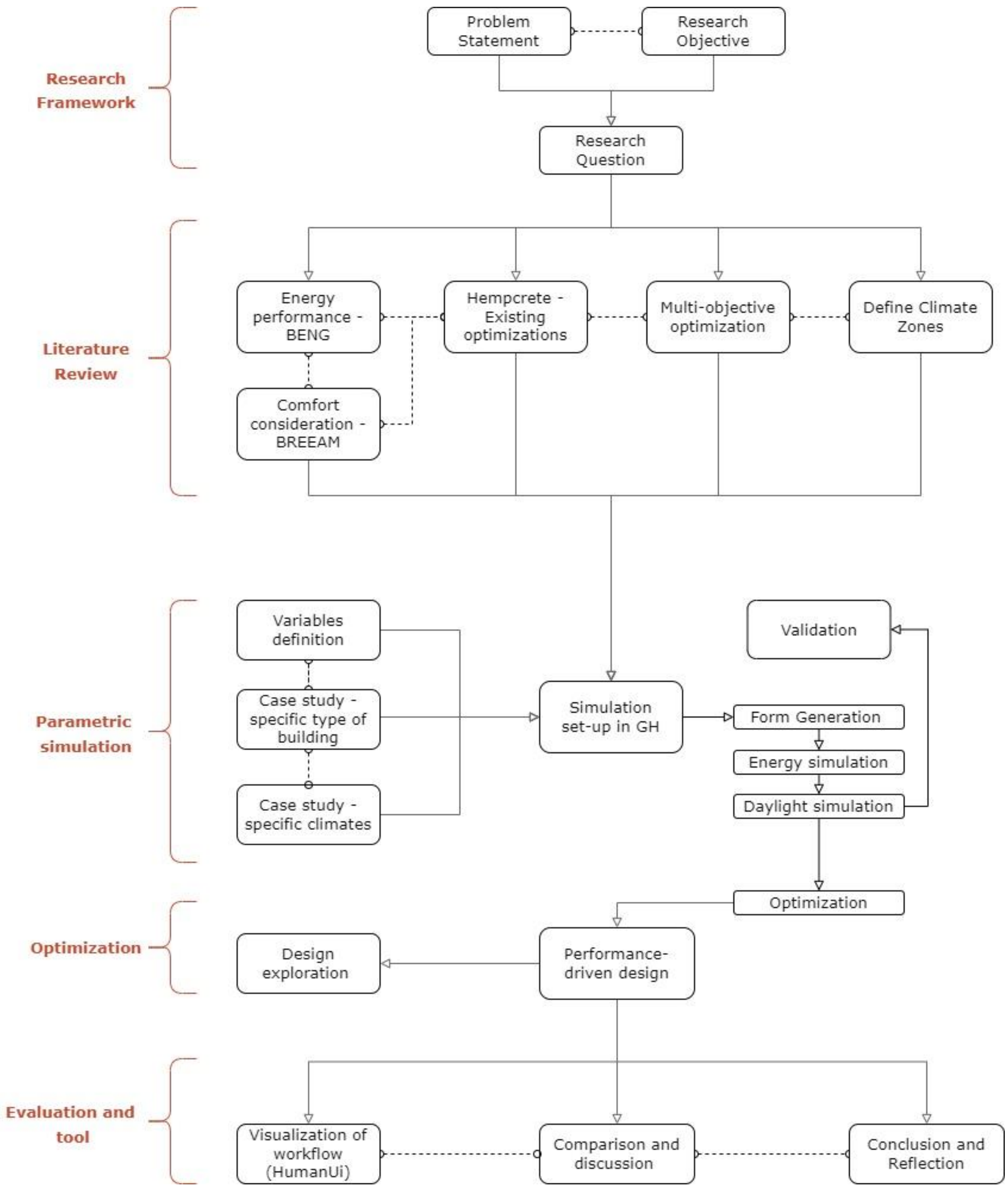


Figure 1. Methodology and approach of the graduation project.

1.7. Timeline

The proposed timeline corresponds to the methodology. The first phase focuses on the literature evaluation, establishing the basis for subsequent stages. Following the P2 evaluation, the focus switches to in-depth research on the modeling and optimization procedures, as well as determining parameters for the testing phase. The transition time from P3 to P4 is devoted to both the optimization phase and an extensive analysis of the outcomes, as well as their visualization. The final stages, which will last from P4 to P5, will involve extensive analysis of the results and conclusion formation.

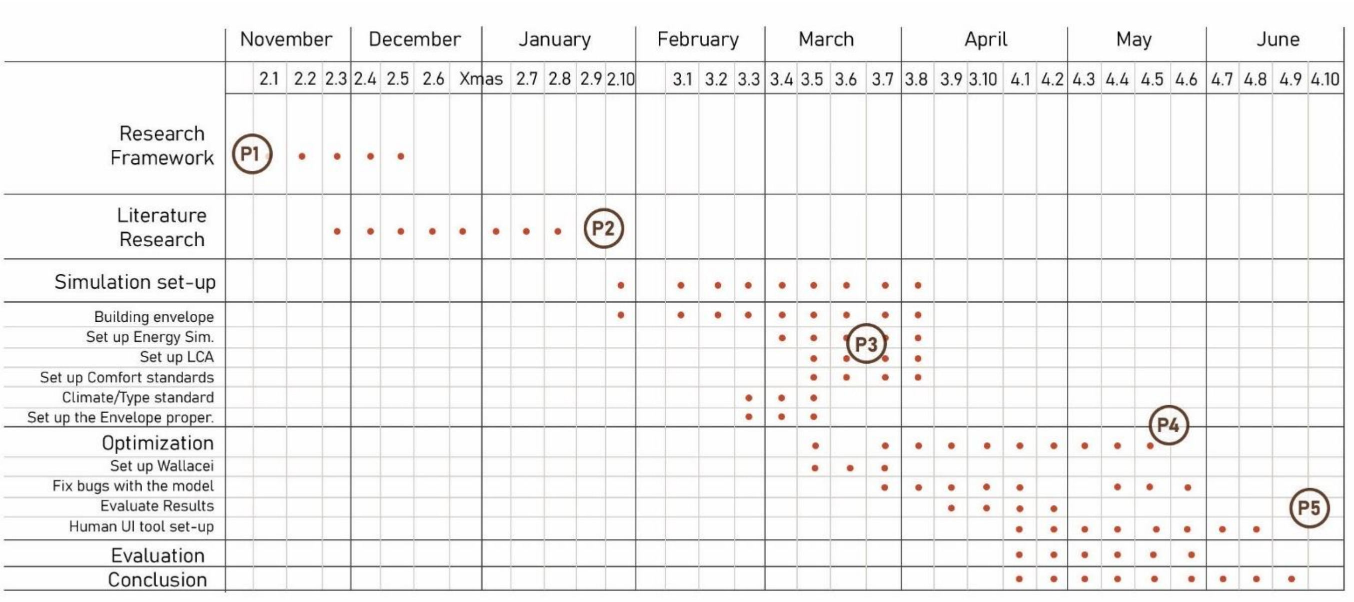


Figure 2. Timeline of the graduation project.

2. Hempcrete

The next section dives into the origins of hempcrete, explains its characteristics, and present the existing literature research.

In the late nineteenth century, the concept of modularity evolved as a technical system based on standard measurements, allowing for parallel production through components made according to accurate technical drawings (Uhlenbrock et al., 2019). Natural and biodegradable materials were widely used in construction before industrialization, since the previous centuries. With the increase of world's population, the fast construction was necessary with more superior structural performance materials, causing a decrease in the use of bio-based. In response to the 21st century environmental crisis, the scientific community has recognized the prospect of biobased materials as an ecologically friendly alternative to traditional manufactured materials (Azhar et al., 2022; Yadav & Agarwal, 2021a).

2.1. Background of hempcrete

Hemp, which originates from cannabis plants, is a fast-growing annual plant that is produced worldwide(Industrial Hemp Market Size, Share & Trends Analysis Report By Application (Animal Care, Textiles, Food &, 2023). Cannabis sativa or hemp has been cultivated by humans since Neolithic times and has a wide range of applications, including oils, resin, food, fuel and more. Hemp cultivation was introduced by the Romans to Britain and continued(Crini et al., 2020). Due to its sustainability and flexibility, hemp is rapidly growing in a variety of industries, including the building sector.

The application of hemp in construction involves the production of hempcrete, a hemp-lime composite building material. The woody part of the plant consists of high concentrated silica, which distinguished hemp from other natural fiber, by allowing everything to be securely bonded to form the so-called Hempcrete. Hempcrete is a non-load-bearing, bio-composite, breathable and insulating material that can be used for walls, floors, ceilings and roof insulation in both renovated and new buildings (T. Editors of Encyclopaedia, 2024). In the earlies 80s, hempcrete was developed in France as an effective substitute for degrading wattle and daub in the timber structure of medieval buildings. This was a successful way to maintain airflow and prevent timber frame destruction, that had been caused by the regular Portland cement (Sparrow & Stanwix, 2014). The experimental researches on hempcrete are relatively new, mainly due to the legal restrictions that existed.

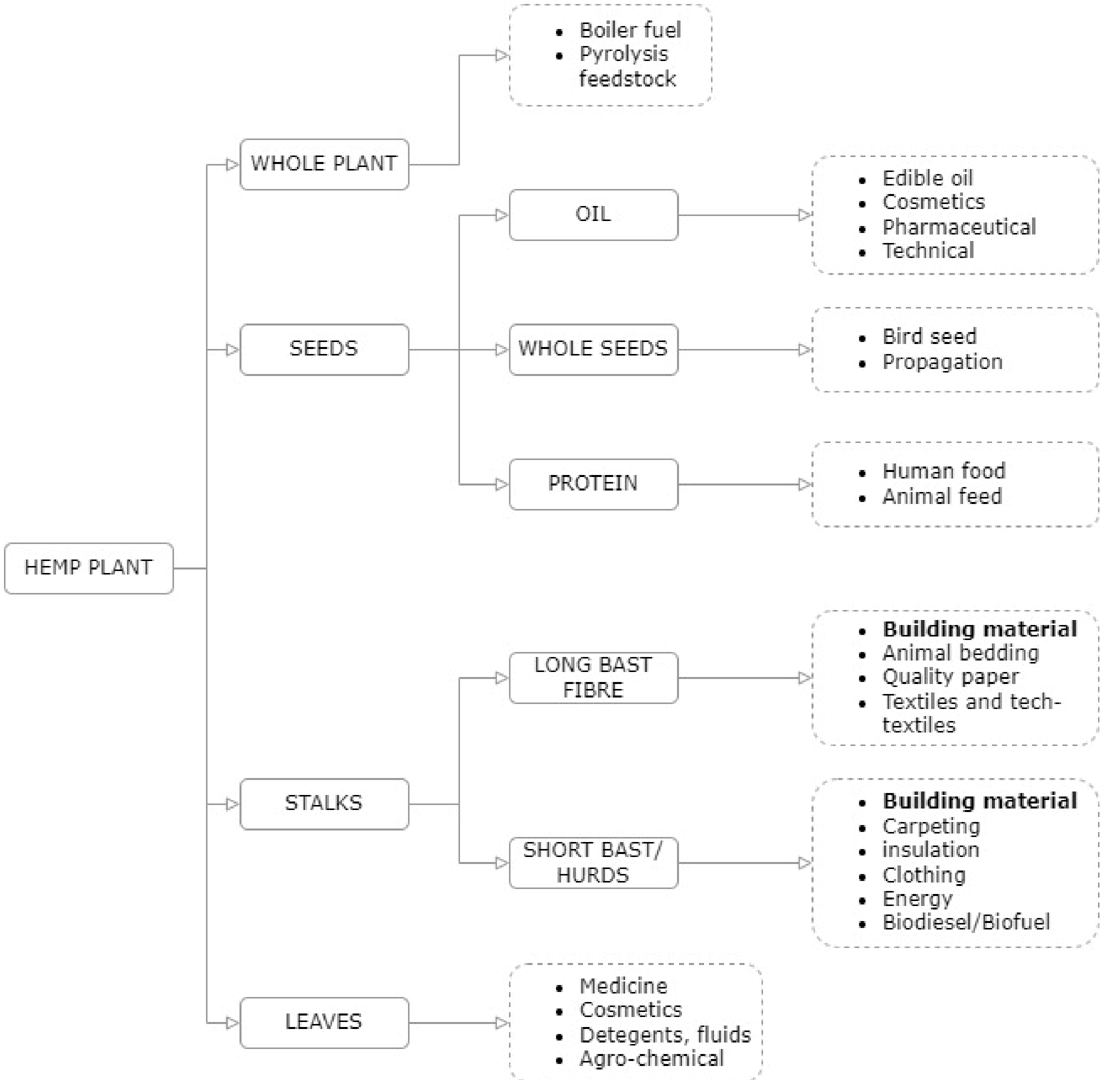


Figure 3. Modern applications of industrial hemp, Image by author, data by: Crini et al., 2020

2.2. Hempcrete production and use

Hempcrete is a bio-aggregate-based material, made by combining hemp shives (the chopped stem core) with a lime-based binder and water (Allin, S., 2012). Lime is made from calcium carbonate (CaCO3) found in quarry limestones, coral rocks, chalk, or shells. Quicklime is mixed with water to generate calcium hydroxide (Ca(OH)2) and then it reacts the carbon dioxide (CO2) in the air, causing carbonation and converting to calcium carbonate (CaCO3). The lime cycle adds to hempcrete's carbon absorption ability (Beningfield, 2003). It has a comparable viscosity and application to concrete, but is more solid. Hempcrete, as it mentioned before, can be used to construct walls, roofs and floors. It can be molded (monolithic), sprayed or precast (like hemp bricks and panels). This leads to a variety of uses, such as insulating walls, sustainable alternatives for concrete masonry units, or fire safety panels (Zuo, n.d.-a).

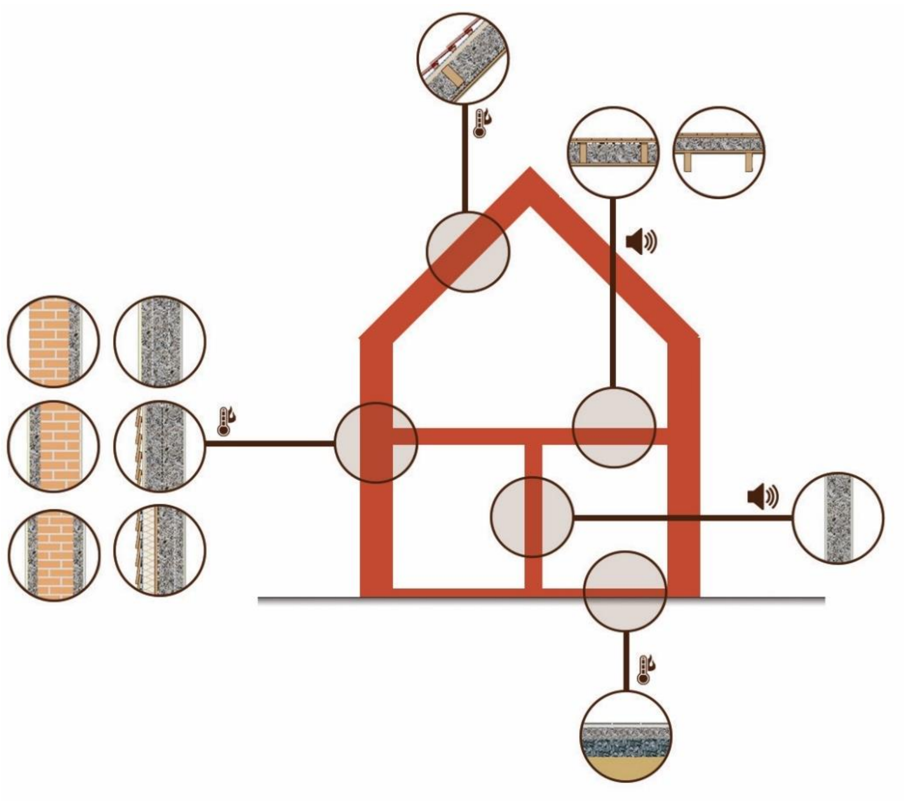


Figure 4. Implementations of hempcrete on buildings and its use, Image by author, Adapted from: *(Evrard & Zurich, 2008)*

Walls

Hempcrete can be implemented in two techniques: cast-in-situ or as prefabricated blocks. The cast-in-situ approach requires constructing a simple stud-work of softwood, and then casting hempcrete between the studs. Concerning hempcrete is permeable, it can be combined with untreated timber. The existing installation options: manual placing or spray application with fully robotic delivery. Even though cast-in-situ hempcrete provides better insulation and is more cost-effective, the final product's characteristics are influenced by on-site conditions during production and application.

Alternatively, prefabricated hempcrete blocks are manufactured in regulated environments using standardized processes, leading to certain properties. The blocks are linked with a thin mortar around a structural timber frame. The process of drying hempcrete blocks takes place off-site, decreasing the on-site construction period. Even though higher-density mixes provide structural integrity, they sacrifice insulating performance and sustainability. Plastering hempcrete block walls is feasible, however, breathable plasters are required to retain the material's breathability, and plastering can begin once the wall construction is complete. Given the alkaline nature of hempcrete, considerations for load-bearing structures, rendering options, moisture regulation, and compatibility with materials must be made when employing it in the structure (Sparrow & Stanwix, 2014).

Floors

Hempcrete, as a flexible construction material, is used in flooring providing insulation and vapor permeability, combined with other materials to have high efficiency. Hence, high-thermal-mass floors are developed reducing thermal bridges when connected to hempcrete walls. Simultaneously, floors use a higher density of mix for additional structural strength, allowing a thinner floor build-up depth than concrete floors, potentially saving money, energy and material during construction. Hempcrete ground floors are usually designed 80-150mm to be structurally stable, or with an overall thickness of 120-180mm for thermal resistance (Sparrow & Stanwix, 2014).

Roofs / Ceilings

Hempcrete is a suitable alternative for ceilings on flat or sloped roofs, as well as between floors, and is frequently used as cast-in-place insulation right above the ceiling. Nevertheless, due to additional expenses, its application for interior ceilings and between floors is limited, unless specific needs for improved acoustic or thermal insulation is required (Stanwix & Sparrow, 2016).

2.3. Technical properties

The demand for hemp-lime implementation is increased since it provides an efficient solution for achieving energy reduction while additionally ensuring indoor comfort and healthy conditions. The following sections describe the most interesting properties. The ideal hempcrete composition varies depending on the application in the construction. A small quantity of binder is needed for interlocking shivs in roof insulation, but an additional quantity of binder is necessary for the wall to accommodate the higher mechanical properties in the wall. In floor integration, the maximum amount of binder is utilized to achieve the greatest mechanical properties (Colinart et al., 2012a). Hempcrete's mostly low density (one-seventh the weight of concrete by volume) makes it easier to transport and deploy on-site. It is adaptable to all climate zones and cures quickly (Essaghouri et al., 2023b).

Physical and mechanical properties

Hempcrete's physical characteristics are significant due to presence of variable-sized pores, with micropores in the shives, mesopores in the mixed matrix and macropores between the shives. Despite its insulating benefits and high porosity ratio of around 80%, it has a substantial water absorption rate, which is a challenge in the modern construction due to the extended time to dry and become stiff (Elfordy et al., 2008a). However, this porosity allows shiv particles to be flexible, combined with the macroscopic porosity has as result many unique properties (Sparrow & Stanwix, 2014). Several studies have been made recently to define the mechanical characteristics of the material, with variables results, leading to the conclusion that it is easily affected by many factors (Colinart et al., 2012b; Demir & Doğan, 2020a; Elfordy et al., 2008b; Pietruszka et al., 2019; Zuo, n.d.-b).

	Density (kg/m^3)	Compressive strength (MPa)	Young modulus (MPa)
Hempcrete	200 - 1140	0.10 – 4.74	3.16 – 44.01
Reference	(Vontetsianou, 2023a)	(Demir & Doğan, 2020a; Elfordy et al., 2008b)	(Niyigena et al., 2016)

Table 1. Mechanical and physical characteristics of hempcrete,

Thermal performance

The thermal performance of a material is mostly related to its density, with an increase displaying a quasi-linear relationship. Furthermore, by using breathable materials, prevents or at least reduces the formation of humidity in the envelope (Agliata et al., 2019b). Since hemp is a highly porous wooden tissue with a substantial air content, it reduces heat conductivity when merged with concrete due to air's poor thermal conductivity (Walker & Pavía, 2014a). There are multiple studies focusing on the thermal conductivity of this material, providing a variety of numbers. Researchers found that 300 mm hemp-lime wall has a thermal transmittance (U) of 0.3 to 0.7 W/m^2K, which increases with higher density (Walker & Pavía, 2014b). Furthermore, hempcrete's uniform composition reduces thermal transfer at nodes, reducing thermal bridge construction (Ronchetti, 2007). Another research showed that, by using hemp-lime bio-composite can reduce linear transmittance (σ) by up to one quarter when compared to different methods of construction for external corner intersections, including a conventional concrete surface, a hemp-lime surface, and a hemp-lime surface with a rigid wooden frame. The report concludes that linear thermal conductivity values of 0.088 W/mK for the concrete block wall, 0.083 W/mK for the hemp-lime block wall, and 0.065 W/mK for the hemp-lime wall with a wooden frame, demonstrating hemp-lime's efficacy in minimizing heat transmission (Daly et al., 2012). However, most of the technical datasheets in private companies have a thermal conductivity of 0.07 W/mK with density of 330 kg/m^3.

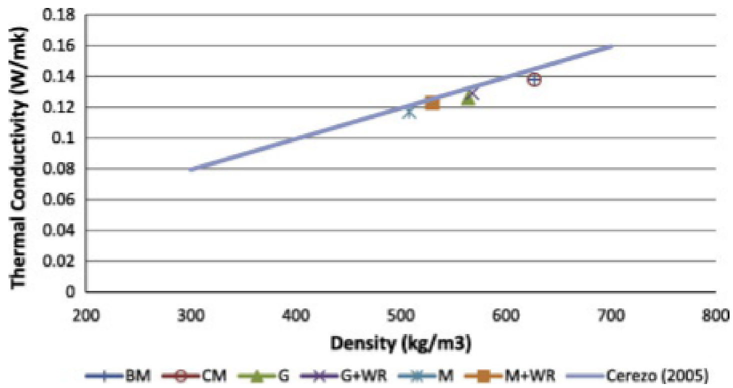


Figure 5. Relation between thermal conductivity and density on hempcrete. Reference: *(Walker & Pavía, 2014c)*

Vapor permeability and hugroscopicity

Hemp-lime, as mentioned above, has fundamental vapor permeability and hygroscopicity thanks to the natural porosity. Hemp shiv's capillary structure influences this hygroscopic tendency, which store and hold moisture from the external environment, and release it back as it adapts to fluctuations in humidity. The lime-based binders in hempcrete, especially those high in calcium lime (such as air limes), increase vapor permeability and hygroscopicity. The macroscopic porosity of hempcrete, formed from interlocking pieces of hemp shiv forming an open matrix, elevates the vapor's permeability substantially. This unique ability to control water vapor condensation, preventing mold formation on wall surfaces, not only benefits indoor air quality but also has consequences for hempcrete's thermal efficiency (Sparrow & Stanwix, 2014).

Fire resistance

Researches focused on the fire resistance of the hemp-lime composite, indicating that the "stony" nature of the compound contributes to its fire resistance without the requirement for flame-retardant chemical treatment. The material is considered "flame resistant" and does not emit harmful or flammable fumes. An evaluation on the fire resilience of a 3m x 3m Tradical® Hempcrete® non-rendered or plastered façade by BS EN 1365-1:1999 showed that after 73 minutes of fire exposure, the structure maintained its stability, insulation, and load-bearing capacity (The building Research Establishment, 2009).

Acoustic performance

To provide the optimal indoor comfort, walls and floors should be soundproofed against external or internal noise sources. The sound reduction index (Rlw) assesses the level to which a structure reduces noise. The soundproofing power of a hemp-lime wall of 300-400mm is around 57 decibels (dB) which fulfill the highest standards of 55dB in eleven European countries (Daly et al., 2012). The high porosity absorbs up to 80% of acoustic energy, providing good sound absorption.

Indoor air quality

Hempcrete promotes health-conscious profile, with the only potential dangers being the non-toxic dust formed during hemp processing. Such problems are mitigated by adequate safety measures during raw material processing and construction. Hempcrete, as a naturally produced material, does not emit hazardous fumes during construction or destruction. Its hygroscopic characteristics regulate internal moisture, preventing condensation and reducing the growth of mold, spores, and germs, resulting in better indoor air quality. The material's high thermal mass helps to preserve air quality by permitting natural ventilation without causing rapid heat loss, and allowing for controlled air exchange through doors and windows (Agliata et al., 2019, Sparrow & Stanwix, 2014).

2.4. Life cycle analysis

Sustainable materials are essential for developing energy-efficient structures that do not jeopardize environmental, societal, or user well-being. To ensure comfortable indoor environments, their sustainability is determined based on several criteria, including emissions, embodied energy, interference in nature, circularity, reusability, durability, resource use, and efficiency in reducing energy consumption. Several studies have been focused to compare the environmental impact of hempcrete walls according to different properties. Non-load-bearing, load-bearing, the well properties, and the construction method were some of the factors that were tested to determine the sustainable nature of hempcrete (Arrigoni et al., 2017; Boutin et al., 2005; di Capua et al., 2021; Ip and Miller, 2012; Pretot et al., 2014; Sinka et al.).

The embodied energy of hempcrete is relatively low, requiring almost 1MJ/kg for its production. Carbon emissions per kg of hemp shives are 0.085-0.19 kg CO_2. It has high CO_2 absorption rate during hemp growth (1.5-2.1 kgCO_2) and the lime process. Overall hempcrete is considered carbon negative since it absorbs more carbon dioxide that it emits during manufacture in use in 100 years. By adding the CO_2 that lime emits during the manufacturing, hempcrete has an embodied carbon of 0.3-1.0 kgCO_2/kg (Bas et al., 2022b; Essaghouri et al., 2023b; Florentin et al., 2017b; Pandian et al., 2023; Vontetsianou, 2023b).

Furthermore, hempcrete had a long-lifespan and is durable, with carbonization increasing its mechanical strength gradually during the operational stage. In commonly used material, modification is extremely rare, while hempcrete can be recycled and reused even in agriculture (Essaghouri et al., 2023b). In addition, casted hempcrete blocks can be reused without additional processing, demonstrating good energy efficiency and delivering outstanding indoor comfort due to their attractive hygrothermal qualities.

2.5. Existing studies with hempcrete

Hempcrete is a relatively new material that has been used in France for nearly 30 years and is now gaining popularity around the world due to its low embodied energy and excellent insulating properties.

Recent studies have examined:

- The mechanical properties and established that increased with higher density (Demir & Doğan, 2020b; Elfordy et al., 2008a; Niyigena et al., 2016),
- Its thermal (Jere, 2018) and moisture transfer properties that can contribute int the stabilization of the indoor temperatures with high mass (Walker & Pavía, 2014b),
- Hygrothermal behavior (Evrard & Zurich, 2008),
- Hempcrete's low load-bearing ability (Zemam et al., 2019)
- Drying process effect on hempcrete's properties (Colinart et al., 2012b)
- Regulatory frameworks (Agliata et al., 2019a).

These are some of the studies carried out to regulate the qualities of hempcrete as a building material. There have been more studies trying to simulate hempcrete behavior on buildings such as:

- Experimental and numerical investigations of the thermal properties in an external building insulation to find the gap between the reality and the simulation (Costantine et al., 2018)
- A comparison of hempcrete with traditional insulation materials (Schiavoni et al., 2016b)
- An attempt to reduce the performance gap between hempcrete in reality and simulations (Bana & Jankovic, 2019)
- Life-cycle analysis found hempcrete to be an equal and superior insulating material in terms of energy and carbon efficiency (Essaghouri et al., 2023a; Florentin et al., 2017a).

Despite numerous studies on hempcrete as a material, there aren't many optimizations of it at the building level:

- Using VIP-energy v2.1.1, (Ahlberg et al., 2014) found that hempcrete has a greater impact on colder climates while simulating varied thicknesses of walls in 5 European locales.
- HAMFitPus analysis of hempcrete wall performance in cold and moderate regions found no significant variation in energy consumption, but CO_2 emissions were 23% lower in mild areas and 9% in cold (Shang & Tariku, 2021).

- Using Matlab on Marocco, researchers evaluated the thermal behavior of a multilayer wall to identify the best insulation thickness for both energy efficiency and cost (Dlimi et al., 2019).
- Building's geometry was optimized to maximize energy efficiency and daylight utilizing a steel frame and hemp-lime material on Galapagos/Ladybug/Grasshopper (Jankovic & Carta, 2021).

However, on the latter the thickness of hempcrete walls was not optimized, and the criteria employed were mainly for energy and LCA. Even if there are steps to begin optimizing hempcrete on structures, there are still many variables that must be considered, and there is a need for an automated simulation that can produce the ideal hempcrete wall by combining all of the key elements.

2.6. Conclusion

In conclusion, hempcrete appears as a sustainable and flexible construction material with numerous ecological and performance advantages. Hempcrete, which is composed out of hemp shivs, lime binders, and water, has excellent thermal insulation capabilities, making it useful for energy-efficient structures and comfortable indoor environments. Its particular composition offers vapor permeability and hygroscopicity, which controls humidity and reduces the risk of mold growth. Additionally, hempcrete has a low embodied energy and functions as a carbon-negative material, absorbing more CO2 than it emits during its lifespan.

Aside from its environmental benefits, hempcrete is long-lasting, requiring only occasional replacements, and can even be recycled. Hempcrete's adaptability in design and building processes extends to diverse construction aspects such as walls, floors, and ceilings. Similarly, its compatibility with other sustainable methods, such as using lime binders, complies with the values of eco-friendly and energy-efficient construction. Applying hempcrete serves develop buildings that value both environmental responsibility and occupant well-being, making it an attractive option for modern, sustainable construction processes.

Last but not least, in terms of basic qualities, hempcrete is a relatively new addition to the building materials scene. Although research and uses are still in their early stages, particularly in nations such as France, existing studies show comparable energy performance to conventional materials. The promoting characteristics include hempcrete's potential to play a key part in minimizing CO2 emissions in the construction industry. The flexibility for installation in both new and existing structures develops opportunities for sustainable retrofitting, highlighting its role in contributing to a more environmentally friendly and low-carbon future in construction. Hempcrete research and widespread acceptance might bring in a new era of sustainable building practices.

3. Energy demand and comfort

The following chapter describes the energy requirements and the indoor comfort standards used in the simulation, while it defines what a zero-carbon structure is.

3.1. Background

Climate change has brought concerns that had previously been neglected by global policies. Particularly, the United Nations Framework Convention on Climate Change (UNFCCC) attempted to address it. According to the Intergovernmental Panel on Climate Change (IPCC), the amount of carbon dioxide emissions and greenhouse gases in general must be decrease by 50% by 2050 to avoid a 2 °C temperature rise, while wealthy nations have to reduce them by 80 to 95% (Masson-Delmotte et al., 2022).

The Kyoto Protocol, signed in 1997, was the first global climate change pact. In summary, the first limits on the rise in greenhouse gas emissions formed for the period 2008-2012, with valid terms for industrialized nations, such as European Union member states (United Nations, 1997). The Copenhagen Accord (2009) obliged developed countries to continuing their efforts to decrease greenhouse gas emissions as stated by the Kyoto Protocol. The Cancun Agreement (2010) established a funding package for technological development from wealthy countries to assist developing nations in following to the updated 2°C maintenance goals (United Nations, 2010).

The Paris Agreement (2015) is a historic turning point in the climate change approach since, for the first time, all nations agreed to take drastic steps to announce these actions by 2020, with the common goal of limiting the temperature increase to 2°C and ideally below 1.5°C above pre-industrial levels (Unfccc, 2015). In 2019, Europe establishes the European Green Deal, which commits to reaching climate-neutral by 2050, strengthening GDP through green technologies, developing environmental friendly industry, and lowering pollution (European commission, 2019). In 2023, COP28 was held to assess the world's progress in terms of climate action. Given the difficulties of fulfilling the Paris Agreement targets, a plan has been developed to increase renewable energy capacity, double energy efficiency, and phase out the use of fossil fuels. This plan intends to reduce greenhouse gas emissions by 43% by 2030 (United Nations, 2023).

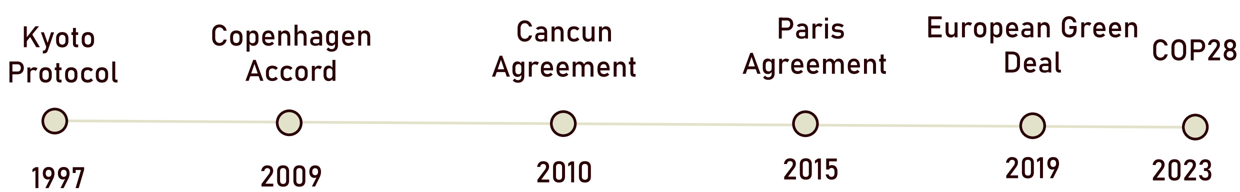


Figure 6. International treaties for climate change. Figure created by the author

The global building sector continues to support green building certification systems, that serve an important role in encouraging sustainable construction practices. With 74 green building certification systems globally, governed by organizations such as the World Green Building Council, and certifications in at least 184 countries, these frameworks offer an in-depth analysis of sustainability in areas such as energy, water, waste, and materials. By 2021, 14 of these systems, including WELL, BREEAM, and LEED, had a total growth rate of 19%, highlighting the growing acceptance of sustainable standards. Beyond supporting environmentally friendly building, green certifications contribute to better regional understanding, awareness, and training possibilities, as well as serve as standards for sustainable investment and financing (United Nations Environment Programme, 2022b).

3.2. Energy demand-BENG

To determine the optimal energy performance for the simulation BENG, the Dutch Energy rules, has been used to understand the values and not to compare, for every climate location. Notably, these numbers are unrealistic for climates other than this found in the Netherlands, which is oceanic temperate. Consequently, these values can be used to assess performance in Milan. The Dutch regulations focus on 3 terms:

BENG 1: New construction requirements for the maximum energy requirements in kWh/m^{2}yr of usable area. The requirement energy is the overall heating and cooling energy demand.

BENG 2: New construction requirements for the maximum primary fossil energy use in kWh/m^{2}yr of usable area. The primary fossil energy use is heating + cooling + domestic hot water (DHW) + fans + (lighting + humidification when it is not residential)

BENG 3: New construction requirements for the minimum share of renewable energy on percentage (%). The share renewable energy is Renewable energy / (renewable energy + fossil energy use) (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2012)

This study will specifically focus on the BENG 1, with an emphasis on the operational energy aspect of the building. Moreover, the types of buildings are restricted into residential function, office function, accommodation function and shopping function.

Function	Limit values		
	Energy requirement [kWh/m 2.yr]	Primary fossil energy use [kWh/m2.yr]	Share of renewable energy [%]
Residential function	65 *	50	40
Office function	90*	40	30
Accommodation function	100*	130	40
Shopping function	70*	60	30

* There is different requirement according to the ratio of the usable area and the loss area.

Table 2. Proposed requirements for BENG indicators for residential, office, accommodation and shopping function. Adapted from: Rijksdienst voor Ondernemend Nederland, 2012)

3.3. Health and comfort standards

To establish a pleasant and functional indoor environment, certain requirements have been established for every climate, based on BREEAM and EN principles. These suggestions prioritize visual comfort, thermal comfort, indoor air quality and acoustic comfort.

Visual comfort

One major part of the study is the building envelope and its impact on both energy consumption and indoor environment, by emphasizing on the importance of conducting early-stage performance-driven analysis.

Window-to-wall ratio

Multiple study results have shown that the facade's window-to-wall ratio (WWR) impacts a building's thermal comfort, visual comfort, and energy consumption (Tzempelikos et al., 2007). The table below summarizes study findings on the ideal WWR for various building types and climates. Nevertheless, there was limited data available for the sub-polar.

Function	Climate	Ratio (%)	Reference
Residential	Tropical	25	(M. Al-Tamimi et al., 2011)
Office	Tropical	20	(*Energy Efficiency Guidelines for Office Buildings in Tropical Climates*, 2013)
Residential	Sub-Tropical	20	(Xia et al., 2023)
Office	Sub-Tropical	50	(Chan & Chow, 1998)
Residential	Temperate	35-40	(Goia et al., 2013)
Office	Temperate	50-60	(Moumdjian, 2020)

Table 3. Existing studies on the optimal WWR for residential and offices in different climates.

Daylight

BREEAM has set standards for recommended daylight factors to achieve a healthy indoor environment for working, studying, and living. BREEAM has been used for daylight evaluation since it assesses total environmental performance, which might potentially enrich the tool with more aspects in future study. Furthermore, it may be implemented to a wide range of buildings, including retail spaces, where WELL may not be the best solution.

The main equation for a room depth is:

$\left(\frac{d}{w}\right)+\left(\frac{d}{HW}\right)<(\frac{2}{1-RB})$, where D is room depth (m), w is room width (m) HW is window head height from floor level (m) and RB is the average reflectance of rear half of the room ("BREEAM_INC-Manual-English," 2016a).

Function	Avg. Daylight factor (%)	Avg. Illuminance (lux)	Min. area to comply
Residential function	>2	>100 lux for 3450 h/year	100%
Office function	>2	>300 lux for 2000 h/year	80%
Accommodation function	>2	>100 lux for 3450 h/year	80%
Shopping function	>3	>300 lux for 2650 h/year	80%

Table 4. Space type, average daylight and illuminance requirements. Adapted by: ("BREEAM_INC-Manual-English," 2016a)

Thermal comfort

The European standards EN-ISO 7730 defines the state of mind that indicates satisfaction with the thermal conditions, taking into account environmental, personal and psychological aspects. Two models, steady-state and adaptive thermal models, have evolved over time to meet occupants' expectations and provide control over indoor environment (*NEN-EN 16798-1*, 2019a).

The steady-state thermal comfort model, which is based on laboratory studies, estimates the ideal atmosphere and is frequently used in mechanical ventilated buildings. To quantify levels of heat sense and dissatisfaction this model uses the Predict Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) indexes. The European standard NEN-EN 16798-1:2019 uses different values for different building types, with a focus on the construction of air-conditioned areas (*NEN-EN 16798-1*, 2019a)

On the contrary, the adaptive thermal model, based on field tests, emphasizes occupants' ability to manage and change their indoor environment. This concept, which applies to free-running buildings without mechanical cooling, results in decreased energy use. The acceptable internal operative temperature in natural ventilated structures is proportional to the mean running outdoor temperature, and the European standard specifies temperature ranges depending on building classifications for such designs (*NEN-EN 16798-1*, 2019a).

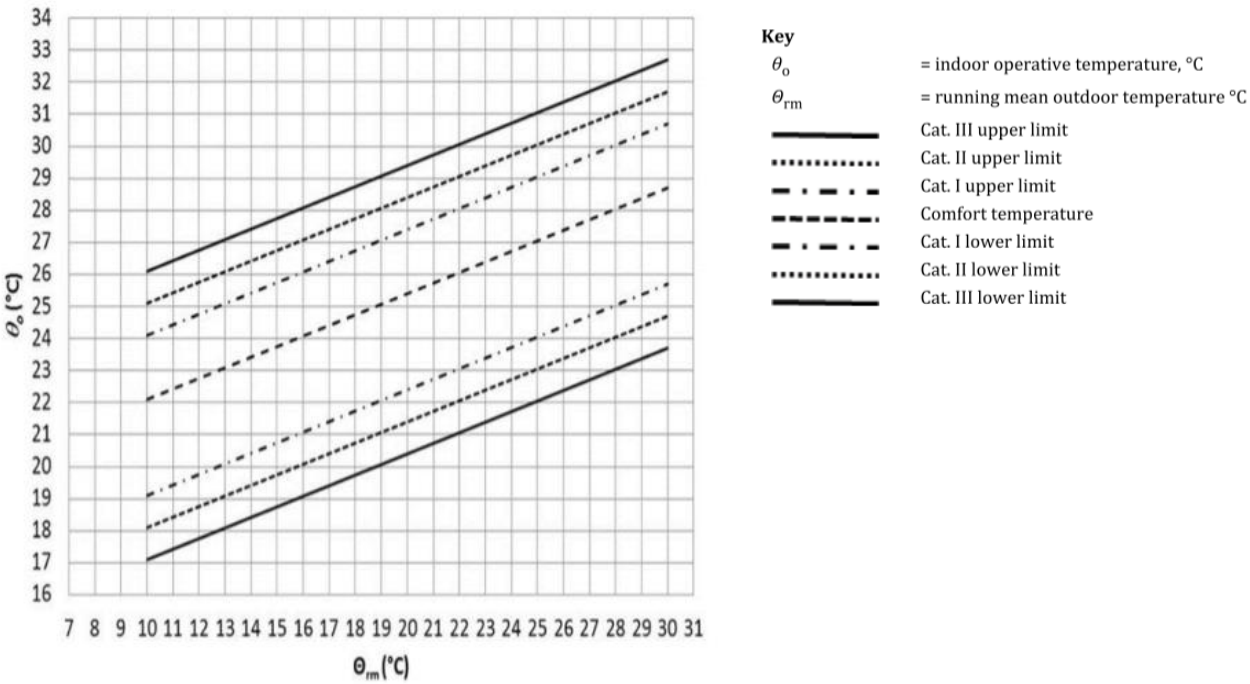


Figure 7. Comfort range for building without mechanical cooling. Reference: NEN-EN 16798-1, *2019a*

Category	Explanation	T (°C) range
I	High level of expectation (people with requirements like, sick, very young children and elderly persons)	±2
II	Normal level of expectation and should be used for new buildings and renovations	±3
III	An acceptable, moderate level of expectation and may be used for existing buildings	±4
IV	Values outside the criteria for the above categories.	±4

Table 5. Acceptable range of temperature in natural ventilated buildings. Adapted from: NEN-EN 16798-1, 2019a

Indoor air quality

Indoor air quality refers to the health and comfort of the air within a building. Ventilation is essential for maintaining internal temperature, adjusting humidity levels, and eliminating undesirable odors and pollutants. As the building envelope's energy-saving efficiency improves, so does its airtightness, making the ventilation strategy for fresh air even more critical when developing energy efficient structures.

BREEAM recommends limiting total volatile organic compounds (TVOC) to 300 µg/m³ and formaldehyde concentrations to less than 100 µg/m³ within a 30-minute timeframe ("BREEAM_INC-Manual-English," 2016b). To ensure indoor air quality, the European standard EN 16798-1 (2019) specifies that various ventilation rates are required to serve different building purposes (*NEN-EN 16798-1*, 2019a).

Residential: 7 l/s Category II, 10 l/s Category I (Cooking: 20* l/s and Bathroom 10* l/s)

Office: 14 l/s for Category II, 20 l/s for Category I

Accommodation: 7 l/s Category II, 10 l/s Category

Shop: 14 l/s for Category II, 20 l/s for Category I

Acoustic comfort

Acoustic comfort refers to the perceived level of noise in an indoor place, which is measured in decibels (dB). Noise can annoy residents and disrupt the proper functioning of operations inside the building (Athienitis & O'Brien, 2015). BREEAM has standards for indoor ambient noise level ("BREEAM_INC-Manual-English," 2016b):

Residential: 35-40 dBL_{AeqT}

Office: 40-50 dBL_{AeqT}

Accommodation: 35 dBL_{AeqT}

Shop: 50-55 dBL_{AeqT}

3.4. Zero carbon buildings

Carbon dioxide (CO_2) emissions from buildings and construction are described in a variety of terms. The Global Status Report gathered and provided definitions from several international reports. The definitions are based on the Net Zero by 2050 report (IEA 2021b), Zero Energy Building Definitions and Policy Activity, an International Review (Organisation for Economic Co-operation and Development [OECD] and International Partnership for Energy Efficiency Cooperation [IPEEC] 2018) (United Nations Environment Programme, 2022b).

- Energy-efficient: a building with a high degree of energy efficiency in its fabric and building services that consume energy, e.g. heating, cooling, cooking, lighting, ventilation, hot water and appliances.

* These varies according to the number of dwelling and rooms.

- Low-carbon: a building that is energy efficient (low energy) and is supplied by low-carbon energy. Some building services equipment may not be capable of decarbonizing without being replaced (e.g. fossil gas boilers).
- Nearly zero-carbon: a building that is energy-efficient and may have some available zero-emission energy supply (onsite or offsite), but that does not offset 100 per cent of the building's energy demand.
- Net zero-carbon: a building that is energy efficient and relies on zero-emission energy sources that meet the energy demand over the course of a year (or another established timeline, e.g. a month).
- Zero-carbon: a building that is energy efficient and has its energy demand completely met through zero-emission energy generated either onsite or offsite.
- Carbon-negative: an energy-efficient building that generates renewable energy onsite that not only fully covers the building's own energy demand, but also produces excess renewable energy which is fed back into a grid and can be used for other offsite purposes.
- Whole life cycle, net zero-carbon: A zero-carbon building with the additional requirement that the embodied emissions associated with the materials used for construction are themselves net zero, either through decarbonization or offsetting (IEA 2022e).

Hempcrete, being a carbon-negative material, complies with the goal of reaching whole-life cycle, net zero-carbon structures. Its distinct properties contribute to a building component that not only ensures energy savings during the operational stage, but also absorbs CO2 onsite, allowing for the reduction of embodied emissions linked to materials, thereby contributing to a sustainable and environmentally friendly construction industry.

4. Climate data

The selection of climate data and the future climate data predictions are analyzed in this chapter.

4.1. Climate types

Climate is the regular pattern of weather conditions of a particular place (Oxford dictionary). In particular, it refers to the average and variations of weather elements throughout periods ranging from months to millions of years. Temperature, humidity, air pressure, wind, and precipitation are some of the most commonly measured meteorological variables. In a wider context, climate refers to the situation of the climate system's components, which include the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere, as well as the interactions between these elements (Mathews et al., 2023). Thus, climate can offer significant information about a region's past weather patterns, allowing for better understanding and preparation for specific climate circumstances.

The Köppen climate classification is the most used in the recent bibliography, even though it based mostly on vegetation and rainfall. The world is divided into five main climate zones, A the tropical, B the arid or (sub-tropical), C the temperate, D the continental (or sub-polar) and E the polar. However, there are not so many researches on the polar zone, since it is mostly uninhabited (Köppen, 2011). However, there are other climate classification systems that are appropriate for building design such as ASHRAE Standard 169-2020 (ASHRAE Standard 169-2020, 2020). The world is divided into 9 zones, and these are subdivided. In the current study, the 4 first climates zones from Köppen classification will be used for the simulation. Research has been made to define the most represented locations on each climate (Mansy, 2006a). Therefore, the regions that are going to be used are Singapore, Asia (Tropical), Cairo, Africa (Sub-tropical), Milan, Europe (Temperate) and Oslo, Europe (Sub-polar) (Mansy, 2006b).

Figure 8. World map with the most represented locations per climate category.

4.2. Climate data sets

EnergyPlus Weather File (EPW) is common hourly climate data file that is used in the current computational tools as a design parameter. It contains 13 different types of hourly climate information, such as dry bulb temperature, dew point temperature, relative humidity, atmospheric pressure, horizontal infrared radiation intensity from the sky, direct normal radiation, diffuse horizontal radiation, wind direction, wind speed, current weather observation, current weather codes, snow depth, and liquid precipitation depth(*EnergyPlus Weather File (EPW) Data Dictionary*, 1996). These data sets are accumulated over decades, therefore are not so practical or even relevant some times to be used in a computational model.

EPW is considered the Typical Meteorological year (TMY) model to reduce the simulation time. This is because the TMY is composed of the month that is closest to the average month, generating one typical year of climate conditions. For example, it calculates the average climate conditions for January and then retrieves the data for the January that has the closest match to this average. This process is applied for the rest of the year, excluding extreme conditions, which are becoming more prevalent with recent climate changes and are anticipated to increase further (*EnergyPlus Weather File (EPW) Data Dictionary*, 1996). Consequently, climate change is not represented on this weather files since they provide insights only on the historical meteorological conditions.

4.3. Future climate - morphed

The scientific community is generally in agreement about the impact of climate change, especially how global CO2 emissions modify weather patterns in response to rising temperatures (Akpan et al., 2012; Wadanambi et al., 2020b). Building simulations are essential for evaluating a building's performance and implementing energy-saving techniques. Simulations use weather data to capture the local climate, taking into account aspects such as sunlight, wind, and temperature in order to provide optimal building design and performance evaluations.

Historical weather files are frequently utilized to develop and execute energy models. However, this method makes present climate-response designs insufficient before they are completed, underlying the importance of structures that can face future climate change. To solve this, two primary methodologies are used to generate future climate scenarios: analogue and global circulation models. The analogue scenario uses meteorological data from a region with a comparable climate, but it may not be optimal due to the latitude. Global circulation models simulate atmospheric processes, demanding downscaling, for individual regions, which results in changes and morphing of current weather files to project future scenarios based on climate models (Belcher et al., 2005).

Introduction to morphing

Morphing is a mathematical method that matches current meteorological data with future variables from climate change scenarios, by using mathematical representations of atmospheric, marine, cryospheric, and land surface processes (Belcher et al., 2005). With this method, accuracy is maintained by aligning the periods of present-day records with baseline changes, maintaining local climate and assuming continuity in current weather patterns for future conditions (Herrera et al., 2017). Despite some downsides, such as increasing the frequency of extreme weather and overestimating it, morphing is efficient. It requires limited computing resources and thus is a popular weather production technique in building performance research (Rodrigues, Fernandes, et al., 2023). Nowadays, there are four available tools: the WeatherShift, Weather Morph, Future Weather Generator and the CCWorldWeatherGen, with the last one being the most popular for energy performance simulations (P.Tootkaboni et al., 2021).

Morphing tool

The tool to morph climate data for this thesis is Future Weather Generator, since it is free to use, it is user-friendly, it is up to dated and can change weather data from any location in the world. It is developed in collaboration between ADAI-UC and CESAM-UA. The weather file generator uses data from GCMs models such as UKESM1.0-LL, BCC-CSM2-MR and more, which contributed to the 6th IPCC Assessment Report (2022) (Rodrigues, Carvalho, et al., 2023).

The data obtained for the current climate and for two future periods. For the current weather, the reference year is 2000 which is the mean between 1985 and 2014, and the same has been made for the period 2036-2065 and 2066-2095. The tool converts existing EPW data into a predicted climate file for years 2050 and 2080 with four Shared Socioeconomic Pathways from the CMIP6:

- SSP1-2.6: Temperature will remail at roughly 1.8 °C higher by the end of the century. Net-zero emissions after 2050
- SSP2-4.5: Temperature is expected to be 2.7 °C higher. Net-zero emissions cannot be achieved by 2100.
- SSP3-7.0: By the end of 2100, the average temperature will be 3.6°C and double global emissions from current levels.
- SSP5-8.5: Temperature will rise to 4.4°C and almost quadruple CO2 emissions.

In the current study, the SSP2 scenario has been used, which entails a temperature increase of 2.7°C. It records weather time series that represent typical circumstances in future climate scenarios while maintaining realistic weather sequences. Essentially, the technology offers a way to include climate change factors (Rodrigues, Carvalho, et al., 2023).

4.4. Morphed climate data

EPW files with current climate data for the four locations were used to generate the morphing data. The Future Weather Generator uses a variety of climate data derived from global circulation models. Table 6 illustrates the different data used by EnergyPlus, which are also included in the generator.

EPW data field	Future Weather Generator	Energy Plus
Dry Bulb Temperature (°C)	■ (Morphed)	✓
Dew point Temperature (°C)	■ (Morphed)	✓
Relative Humidity (%)	■ (Morphed)	✓
Wind Atmospheric Pressure (Pa)	■ (Morphed)	✓
Horizontal Infrared Radiation from the Sky (Wh/m2)	■ (Calculated)	✓
Direct Normal Radiation (Wh/m2)	■ (Calculated)	✓
Diffuse Horizontal Radiation (Wh/m2)	■ (Calculated)	✓
Wind Direction (°)	■ (Kept)	✓
Wind Speed (m/s)	■ (Morphed)	✓
Total Sky Cover (deca)	■ (Morphed)	✓
Opaque Sky Cover (deca)	■ (Calculated)	✓
Present Weather Observation	■ (Kept)	✓
Snow Depth (cm)	■ (Morphed)	✓
Ground Temperatures	■ (Calculated)	✓
Typical / Extreme Periods	■ (Calculated)	✓
Liquid Precipitation Depth	■ (Morphed)	✓

■ - Morphed value

■ - Calculated value

■ - Kept the original value

✓ - Used variable

Table 6. EPW field's that are morphed, calculated, kept the same and required for EnergyPlus. Adapted by: (Rodrigues, Carvalho, et al., 2023)

Combining GCMs models of the generator with the SSP2-4.5 scenario for 2080, follows a relatively realistic goal on which world doesn't shift considerably from the current situation. Global population growth decreases in the second part of the century, although financial inequality is slightly improved. Table 7 displays the current weather data and the results obtained from the generator. Morphed and current data were used for the energy simulation. Temperatures will probably rise by at least 3°C across all scenarios, with Milan and Cairo experiencing significant increases in both direct and diffuse radiation. Given these climate differences, buildings must be designed to be future-proof, and able to adapt to expected changes in environmental circumstances. In Appendix there are diagrams with dry bulb temperature for morphed and current weather data for visual comparison.

Location	**Singapore**	**Singapore (morphed)**	**Oslo**	**Oslo (morphed)**	**Milan**	**Milan (morphed)**	**Cairo**	**Cairo (morphed)**
Latitude	1.36	1.36	59.9	59.9	45.4494	45.4494	30.5	30.5
Longitude	103.91	103.91	10.62	10.62	9.2783	9.2783	31.217	31.217
Elevation (m)	19.8	19.8	17	17	103	103	18	18
Dry bulb temperature **avg**.(°C)	28.4	30.1	6.7	9.8	14.7	17.8	22.4	25.1
Dry bulb temperature **max**.(°C)	35	37.2	28.2	31.7	36	42.2	40.5	43.6
Dry bulb temperature **min**.(°C)	23	24.5	-17	-9.4	-5	-3.6	4.7	6.8
Relative humidity **Avg**. (%)	80.2	79.4	74.2	72.4	72.6	67.3	54.7	52.6
Wind speed **Avg**. (m/s)	2.3	2.6	2.3	2.3	1.8	1.7	3.1	3.2
Direct normal rad. **Avg.** (Wh/m2)	177	158.2	79.7	84.2	187.9	257	285.1	358.9
Diffuse horizontal rad. **Avg**. (Wh/m2)	79.7	119.6	58.8	57.7	53.2	65.9	56.1	67.6
Direct normal ill. **Avg.** (lux)	13797.8	12795.3	7330.4	7731.6	18673.2	20648.1	28272.1	30458.7
Diffuse horizontal ill. **Avg.** (lux)	11364.9	15891	7092.2	7002	7199.7	8371.3	7547.3	8963.7
Ground temperature **Avg.** (°C)	28.4	30.1	6.5	9.7	14.5	17.7	22.3	25.1

Table 7. Location data with current weather data and morphed weather data.

5. Simulation and optimization

In this chapter, the simulation methods will be described, simultaneously with existing researches.

5.1. Background

Building simulation tools dates back to the 1960s, when United States government conducted studies to investigate the thermal condition in fallout shelters' area. Since then, it has evolved into a dynamic discipline, providing a wide range of scientifically and internationally recognized Building Performance Simulation (BPS). In the 80s, BPS tools were massively generated to support architects in the early design phases and design more efficient buildings (Van Leeuwen & Timmermans, 2004). However, building simulations were not highly used until 90s, when computer-aided architectural design (CAAD) and virtual environment (VE) tools were integrated (Attia et al., 2009).

Building Performance Simulation (BPS)

Building Performance Simulation (BPS) is the process of reproducing building performance components using computer-generated mathematical models that are based on fundamental physical principles. BPS aims to quantify aspects of building performance that are essential to building design, construction, operation, and control. This tool can focus on different disciplines, such as temperature simulation, lighting simulation, acoustic simulation, and air flow simulation (Wilde, P. de., 2018).

Architects and engineers use the BPS tools to assess a proposed design's energy efficiency and indoor comfort. Although it analyzes design's performance, it does not provide any support on decision making. Thus, the designers should manually consider the design area and compare the simulations' results to select the optimal fit. In a multi-context project, this is time-consuming and not advisable due to the trial-and-error strategy. The Building Performance Optimization (BPO) solved the limitations of this approach. A review of ten different tools indicates that the application of BPO may decrease potential building energy demand by two-fifths in the early phases (Attia & Herde, 2011).

Building Performance Optimization (BPO)

Building Performance Optimization (BPO) is an automated method that selects the best approach from a set of possibilities for a specific design or control challenge using specified performance criteria. The criteria are expressed as mathematical functions, frequently referred to as objective functions. The optimization process employs a variety of algorithms, each designed to optimize one or more design parameters. The objectives of optimization are to quantify the effects on cost, energy, and the environment. An objective function subject to optimization is an equation that the process attempts to maximize or minimize, sometimes within the limitations of the dependent factors. A single objective optimization problem exists when the goal is to minimize a single objective parameter. If there are numerous target elements, the problem is classified as multi-objective optimization (Attia et al., 2013). In the construction context, multi-objective optimizations are applied more, since building design includes numerous factors that affect performance.

Multi-objective tools such as Hypervolume Estimation (HypE) or Non-dominated Sortic generic Algorithm II (NSGA-II) algorithms in performance analysis. More algorithms are used to solve design problems such as Multi-Objective Particle Swarm Optimization (MOPSO), Pseudo Random Generation Algorithm (PRGA+), ev-MOGA and more (Hamdy et al., 2016). NSGA-II, that employs Fast Non-dominate Sorting and Crowding Distance Assignment on the entire population, is noted for its speed and broad coverage of objectives (Skolpadungket et al., 2007). However, it is better suited to optimization problems with two goals. For projects with up to four objectives, the accuracy of NSGA-II drops and targets might have to be defined as constraints or limitations. In contrast, HypE performs best when there are more than two objectives, but it takes additional time to complete the same number of generations (Bader & Zitzler, 2011).

With the growth of computer science, a plethora of computer programs have become accessible for optimization studies, including those for architectural designs. These tools, including Galapagos, Octopus, Opossum, Wallacei, Goat and more are integrated into Grasshopper. Other individual optimization software that can be connected with the model are ModeFrontier, Matlab, GenOpt, ParaGen etc (Huang & Niu, 2016).

5.2. Performance-driven architecture

The concept of performance-based architectural design began in the 1970s. The "Architectural machine" was the first reference that proposed the idea of performance-based design (Negroponte, 1970). Unfortunately, due to a lack of computational and technological expertise, it remained only a vision in that era. Performance-based architectural design acquired popularity around the end of the twentieth century, owing to the increased emphasis on sustainable practices. This move was helped by the developing of simulation tools, which were essential in enabling the feasibility of performance-based design. In response to environmental obstacles, environmentally friendly building codes such as LEED and BREEAM ("BREEAM_INC-Manual-English," 2016a) emphasize several performance criteria, requiring architects and engineers to prioritize issues such as natural lighting, energy consumption, and visibility. The demand for rapid and reliable performance analysis has contributed in the gradual integration of simulation programs into architectural design workflows, allowing professionals to rapidly and precisely assess building performance, which is an important part of modern design decisions (Shi, 2010).

The transition from performance-based to performance-driven architecture design implies an effort toward an automated successful sequential method supported by effective optimization approaches. Originally, the design process includes performance simulations after the conceptual design, which causes manual adjustments depending on assessments.

Nevertheless, project timelines and resource restrictions frequently limit the iteration cycle. The use of optimization algorithms accelerates the entire procedure, making it easier and cost-effective, while shifts architecture from performance-based to performance-driven (Shi, 2010).

The MacLeamy curve (Figure 9) shows that design modifications are less expensive and have a greater impact on the project when implemented at the start of the process rather than later stages. Generally speaking, the earlier the project requirements are specified, the more expected the facility will meet them (Nguyen, n.d.). Therefore, the performance-driven design integration in computational approaches, for optimal early design proposals, assist architects in the overall design process.

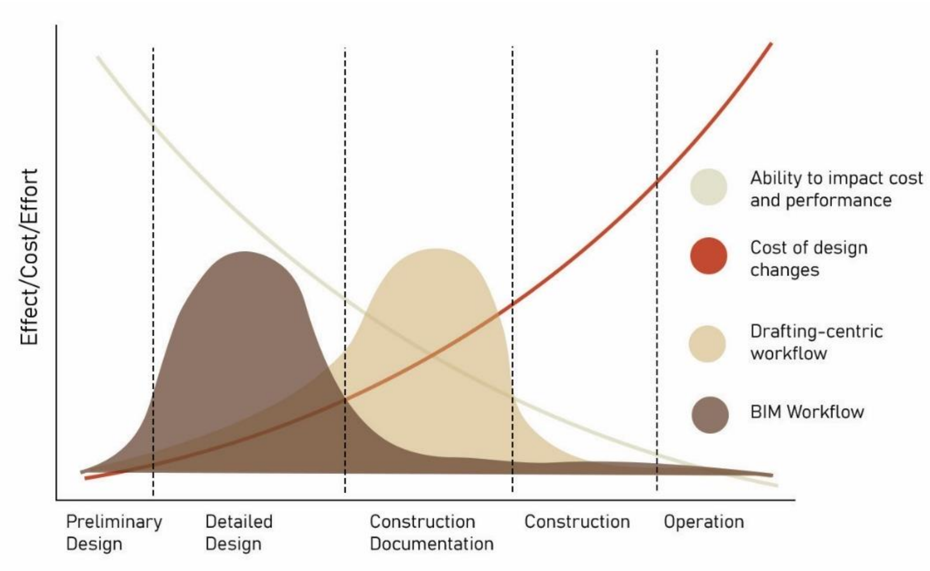


Figure 9. The MacLeamy curve. Image by author. Adapted by Macleamy P.

Performance-driven design employs two distinct digital tools: the formation model and the generative model. The formation model includes parametrizing geometric objects and how they relate, which requires designers to develop a preliminary geometric link between the parameters. The optimization program then takes over to identify the ideal combination, while the designers retain control over the process. The generative model, on the other hand, is based on rules and defines relationships between the project's properties without the use of geometry. Designers are responsible with establishing the generative rules, which enable the model to discover new design directions (Oxman, 2006).

5.3. Performance simulation

Parametric modeling and algorithms have considerably improved building design, where actual environment conditions and energy use are primarily measurable. Building performance simulation, especially centered on energy consumption, is critical for understanding the relationship between design decisions and building performance. As it mentioned before, optimization based on performance simulations might result in a significant 40% reduction in power consumption (Attia et al., 2013). Building performance modeling and optimization consists of three major components: the environment (built and physical), building geometry parameters, and building performance and demand (Bamdad et al., 2021).

- *Environment:* The building environment includes the surround and terrain, both of which influence the local variables. The physical environment includes climatic data, light and acoustics, all of which are constant.
- *Building geometry parameters:* It consists of four major components: the building shape and orientation, the building envelope, the structure's height, and the layout.
- *Building performance and demand*: The building performance includes both energy consumption and energy generation. Occupants' comfort concerns temperature, lighting, air quality, and acoustics (Bluyssen, 2009; "BREEAM_INC-Manual-English," 2016a).

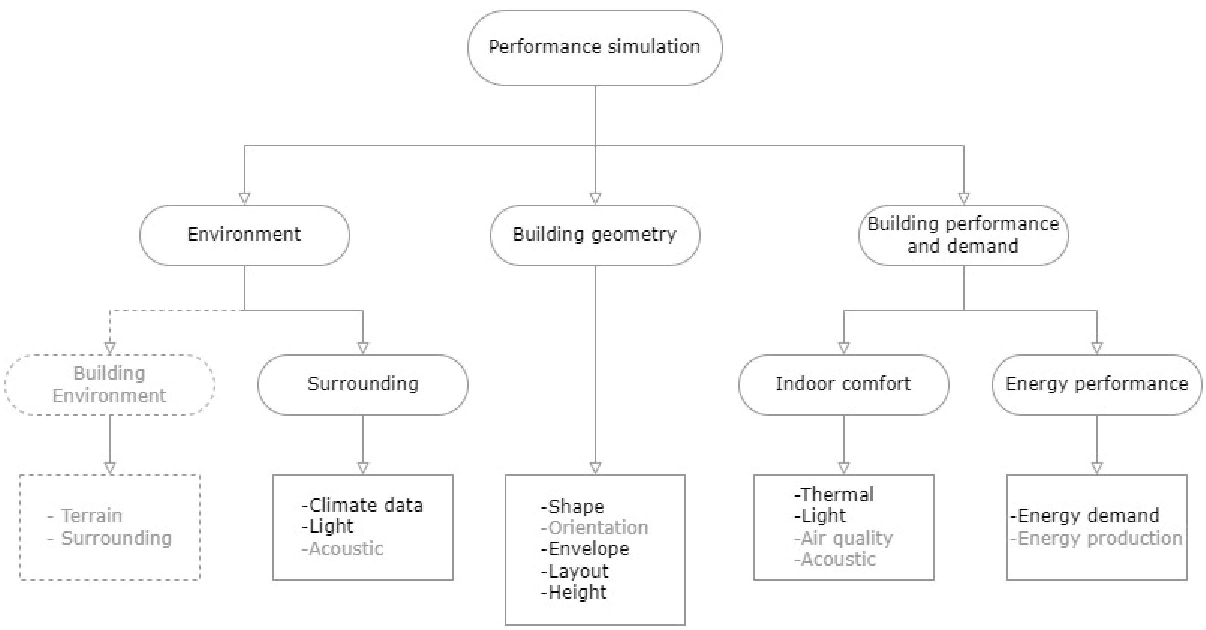


Figure 10. Performance simulation components used in this graduation project.

The energy-efficiency study for this graduation project focuses on specific components, such as the envelope and building performance. The energy simulation is based on the Honeybee engine, which is a Grasshopper/Rhino plugin. Honeybee enables extensive daylighting and thermodynamic modeling with Radiance and energy models with EnergyPlus (Roudasri, n.d.).

5.4. Global Warming potential simulation

A building's life cycle is divided into several parts. Each cycle uses energy, raw materials and other natural resources to variable degrees.

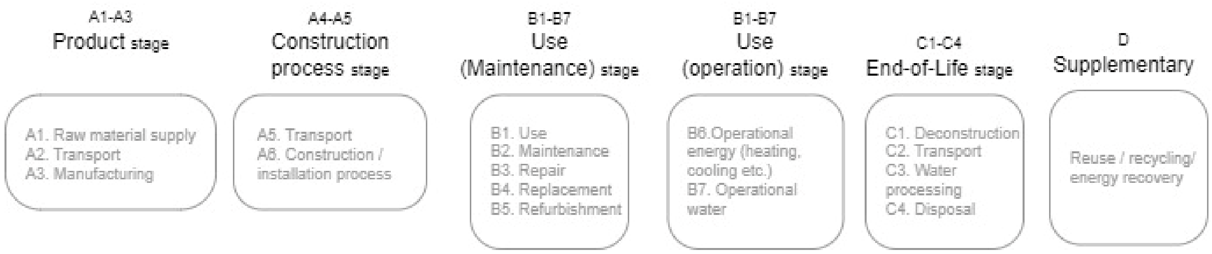


Figure 11. Building life-cycle scheme. Image by the author. Adapted by EN15604 standards

The overall energy consumption of a construction has six stages:

- Embodied energy (linked to the product stage of construction)
- Grey and induced energy (associated with the construction process)
- Operating energy (related to the building's use stage)
- Demolition and recycling energy (comes with the life-end)

Operating energy accounts for the majority of a building's life-cycle energy consumption, creating large opportunity for energy reductions within the building (Koonath Surendran et al., 2015). Computational techniques allow for optimizing many objectives to achieve energy-efficient solutions.

Greenhouse gases (GHGs) contribute to global warming by collecting energy and slowing its space release, essentially serving as an insulator. Variable greenhouse gases have varied warming effects depending on their "radiative efficiency" (capacity to absorb energy) and "lifetime" (how long they stay in the atmosphere). The Global Warming Potential (GWP) meter was developed to help evaluate the warming effects of various gases. It calculates the amount of energy absorbed by 1 ton of gas emissions over a particular time period, usually 100 years, in comparison to 1 ton of carbon dioxide (CO_2). A higher GWP indicates a larger warming effect than CO_2 over that time. GWPs allow for the aggregation of pollution from diverse gases into a single measure, helping to organize national GHG inventories and policymakers in evaluating emissions reduction efforts across sectors and gases (Environmental Protection Agency, 2024).

A Genetic Algorithm is one technique to structure the design process around the global warming potential computation. In short, the design variables give identifying code, which acts as a gene and generates a population with all possible combinations (chromosomes) of these gens. The optimizer chooses random choices to generate the preliminary list. This data is fed into the energy calculator, which returns fitness value (high or low energy usage).

The optimizer then selects the best-matching chromosomes and recreates new from the discarded ones. The revised list includes a new energy computation that results in fitness values. The process continues until only the fittest combination remains (Koonath Surendran et al., 2015). Different parametric life cycle assessment (LCA) tools are Bombyx, Cardinal LCA, Tortuga, One Click LCA and Epic that are mostly open access plug-ins of Grasshopper / Rhino. Each tool focuses on different steps of the LCA analysis and has varying capabilities. Epic was found to be the most promising tool for free form geometries after conducting research on the differences between them. (Stephan et al., 2024). However, Bombyx is the most suitable for this project due to the wide range of materials availability, such as two types of Hempcrete (Basic et al., 2019). Bombyx uses a Swiss material database for the simulation(KBOB, 2009).

5.5. Simulation and optimization workflow

The workflow is separated into three stages: the initial stage is parametric modelling of the building, which includes geometry, glazing ratio, shading systems, envelope, and building structure by using grasshopper. The second step is to set up the energy analysis on Honeybee and life cycle analysis on Bombyx, which involves the building's function, material properties, and weather data. The final stage is to optimize the building on Wallacei and visualize the outcomes with Human UI.

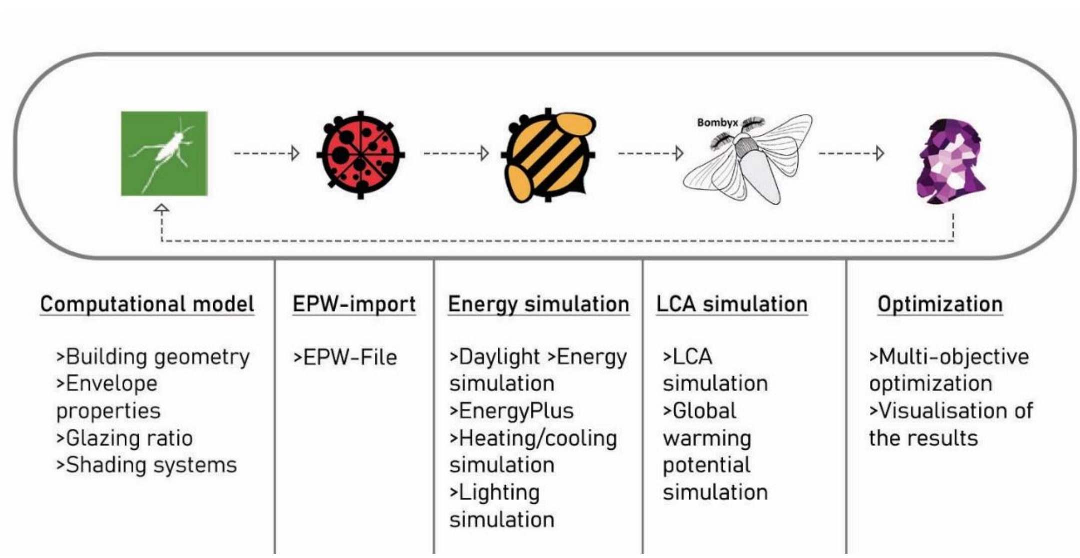


Figure 12. Workflow between all the plugin and Grasshopper.

- Several aspects are addressed during the parameter-building stage. First, the geometry is thoroughly designed, taking into account the form, dimensions, height, area and structural framework. The building's function is then defined, including the program, loads and schedules. The geometry is integrated into Honeybee with the proper window features, envelope properties and blind, which can be adjusted later on for the optimization.

- In the simulation set up stage, the parameters that control the simulation are assigned. The simulation uses the defined by the user building with the specific function and location. The prepared geometry run through the simulation engines.

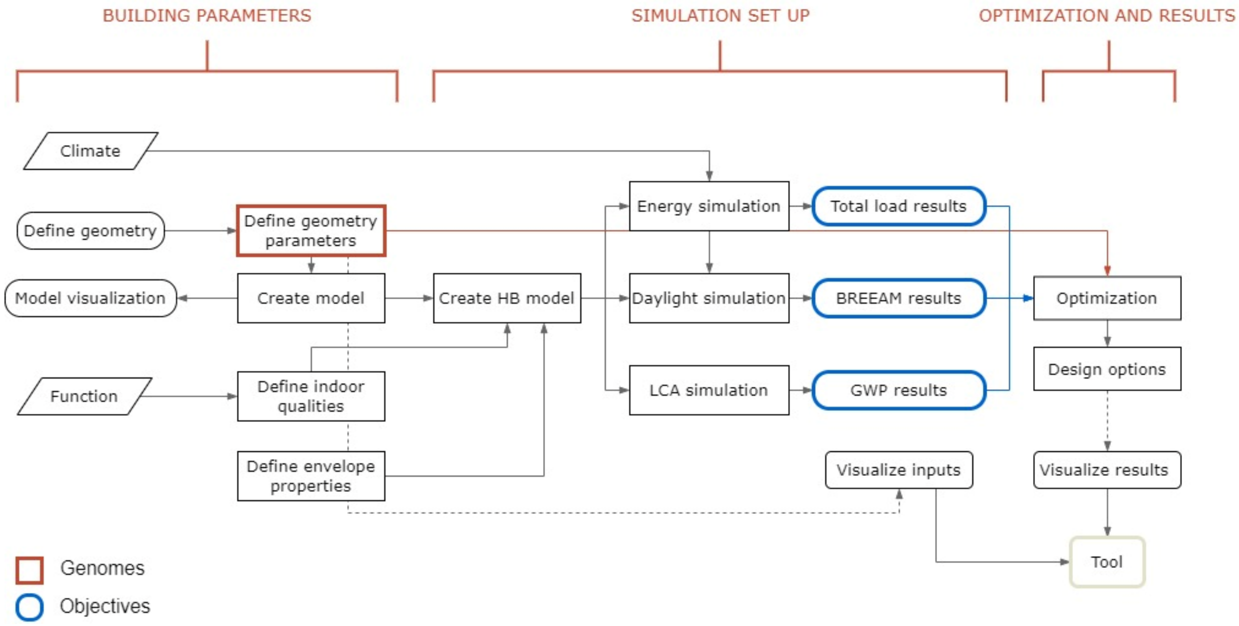


Figure 13. Overall workflow.

- Finally, the objectives for the optimization are defined, total load, daylight and global warming potential (GWP) results, while the geometry properties constitute genes. The results are visualized in the tool by using Human UI, BREEAM pass or failed are displayed for daylight, BENG pass or fail for Energy simulation, while the total GWP and the total primary energy results are given, followed by different model options. In the tool the user can first decide on the site properties and then optimize the design. The proposal ends with the ability to compare between the designs and their objectives.

6. Building Overview

In this chapter, the geometry building up process will be described in detailed

6.1. Optimization Objective

The thesis examines various building functions based on user preference across several locations, with the goal of improving energy efficiency, daylight usage and eco-efficiency, regardless of the building systems. The model evaluates heating, cooling, lighting, and equipment demands throughout the year, as well as the percentage of the surface area that receives sufficient daylight each year. Furthermore, eco-efficiency is measured by decreases in global warming potential and overall primary energy usage. Consequently, decreasing energy demand conforms with BREEAM requirements.

Subsequently, a multi-objective optimization approach is used to reduce targets while also increasing daylight utilization. The final goal is to construct a workflow dedicated to designing high-performance buildings following the Paris goals, which will be accomplished by identifying the most appropriate hempcrete components during the early design stages.

6.2. Design parameters

The design parameters are limited to aspects that significantly affect space layout, building energy demand, and eco-efficiency. The process includes two types of design parameters: user-selected variables predetermined for the construction (as shown in Table 8), and optimization variables focused on reaching the ideal design (as shown in Table 9).

Parameter	Unit	Range	Application
Area	m^2	20-1000	All building
X/Y dimension	m	2-20	2/2 directions
Floor height	m	2.7-4.5	1 direction
Column span	m	3-15	All building
Factor	-	10-20	All building
Reference Study Period	years	1-100	All building
Location	-	Oslo, Milan, Cairo, Singapore	All building
Function	-	Residential, Accommodation, Office, Retail	All building
Efficiency category	-	High, Good	All building

Table 8. Overview of the user design parameters.

Parameter	Unit	Range	Application
Type of building element	-	Various	All building
Type of Hempcrete	-	4	All building
Thickness of building element	m	0.1 – 1.0	1 direction
Size of blinds	m	0.5, 1.0, 1.5, 2.0	1 direction each blind
WWR	(%)	0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.55, 0.60, 0.65	4 directions

Table 9. Overview of optimization's variables.

6.3. Envelope

The study aims to improve building efficiency by modifying envelope characteristics, with a particular focus on the implementation of hempcrete. As a consequence, the envelope has a significant impact on the overall performance of the building. Several types of hempcrete composites and building components were examined to determine the optimal choice for every particular region. Additionally, window-to-wall ratio and blind's size have been part of the optimization, due to their significant impact on daylight availability and, by extension, building performance.

Hempcrete

The model includes four distinct types of hempcrete, which have been derived from existing bibliography.

Name	Density (kg/m^3)	Porosity (-)	Thermal capacity (J/kgK)	Thermal conductivity (W/mK)	Reference
Hempcrete 1	440	0.73	1560	0.115	(Evrard & Zurich, 2008)
Hempcrete 2	480	0.71	1550	0.110	(Evrard & Zurich, 2006)
Hempcrete 3	405	0.83	1500	0.073	(Pierre et al., 2014)
Hempcrete 4	398	0.78	1500	0.094	(Pierre et al., 2014)

Table 10. Hempcrete types and their properties.

Building elements

The model provides a wide range of building element possibilities for each component, making it easier to optimize and find the best solution for each location.

External wall

The external wall has four different construction types:

- Wall 1: Lime plaster d=0.002m, Hempcrete, Clay d=0.01m (Vontetsianou, 2023b)
- Wall 2: Lime plaster d=0.002m, Magnesium bonded board d=0.025m, Hempcrete, Clay d=0.01m (Anderson, 2023)
- Wall 3: Hempcrete, Fiber panel d=0.01m, Sand-lime d=0.002m (Bureaux En Béton de Chanvre-Sur-Vilaine, 2018)
- Wall 4: Lime plaster d=0.002m, Hempcrete, Double lime plaster d=0.004m (Tradical, n.d.)

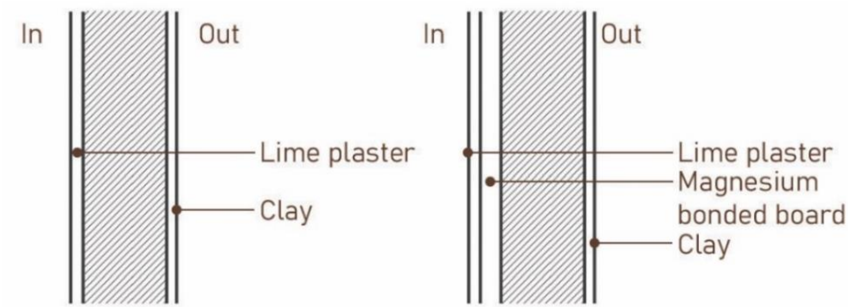


Figure 14. Wall 1 (left), Wall 2 (right).

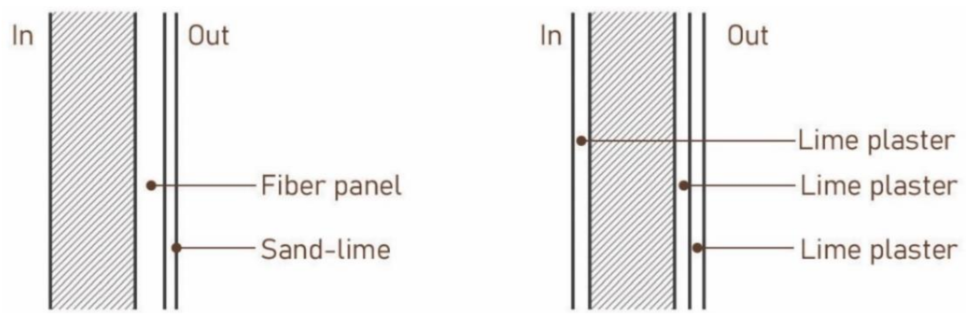


Figure 15. Wall 3 (left), Wall 4 (right).

Internal wall

The internal wall has two different construction types:

- Wall 1: Lime plaster d=0.002m, Hempcrete, Lime plaster d=0.002m (Vontetsianou, 2023)
- Wall 2: Clay d=0.01m, Hempcrete, Clay d=0.01m (Vontetsianou, 2023)

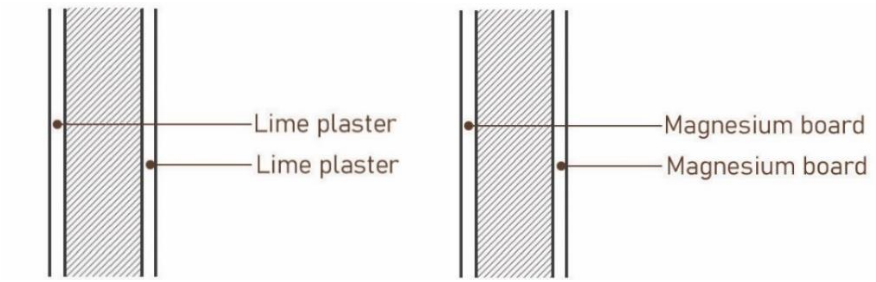


Figure 16. Wall 1 (left), Wall 2 (right).

Ground floor

The ground floor has, as well, two different construction types:

- Ground floor 1: Ceramic tiles d=0.008m, Lime screed d=0.02m, Hempcrete, Geotextile (Saint-Astier, n.d.)
- Ground floor 2: Parquet d=0.0065, Joist, Hempcrete, Geotextile (Saint-Astier, n.d.)

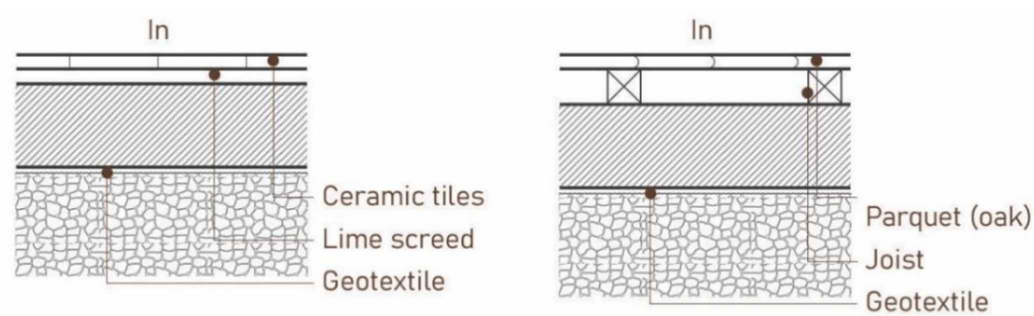


Figure 17. Ground floor 1 (left), Ground floor 2 (right).

Internal floor

Similar, the internal floor has two construction types:

- Internal floor 1: Parquet d=0.0065, underlay (plywood) d=0.018m, Hempcrete, Particles board d=0.01m, Joist (Tradical, n.d.)
- Internal floor 2: Parquet d=0.0065, Joist, Hempcrete, Magnesium board d=0.025m (Tradical, n.d.)

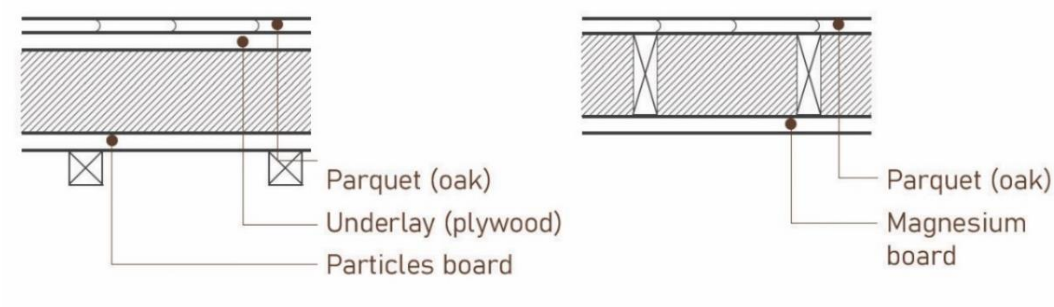


Figure 18. Internal floor 1 (left), Internal floor 2 (right).

<u>Flat roof</u>

The flat roof has two construction types:

- Flat roof 1: Screed d=0.02m, Vapor barrier, Hempcrete, Timber deck d=0.018m, Joist, Plasterboard d=0.0125m (NHBC, 2024)
- Flat roof 2: Plywood d=0.018m, Joist, Hempcrete, vapor barrier, Plywood d=0.018m (NHBC, 2024)

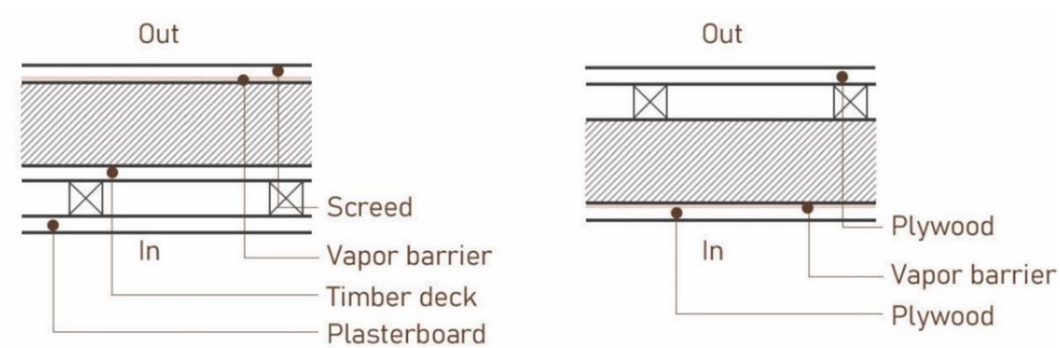


Figure 19. Flat roof 1 (left), Flat roof 2 (right).

<u>Glazing</u>

Glazing has also two types:

- Window 1: U-factor 2.2 W/m^{2}K, Solar heat gain coefficient (shgc) 0.48, Visible transmittance (t_vis) 0.55 (Cort & Widder, 2015)
- Window 2: U-factor 1.5W/m^{2}K, shgc 0.59, t_vis 0.62 (Cort & Widder, 2015)

Spatial parameters

This thesis seeks to optimize spatial attributes within these ranges due to the significant influence on the daylight:

- Window-to-wall ratios range from 20% to 65%, with 5% increments.
- Shading overhangs range in size from 0.5m to 2.0m, with increments of 0.5m.

Function parameters

The model has four distinct kinds of building functions that users can choose from. To ensure the generalization of the findings, these functions comprise basic dwellings, multi-offices, accommodation, and retail spaces. Table 11 summarizes the functions evaluated for this study, along with their associated design standards, as established in the European standards. (*NEN-EN 16798-1*, 2019b). Table 12 provides the corresponding set point values for the building's efficiency category (Good or High) as required by the user. (*NEN-EN 16798-1*, 2019b)

Function	Occupancy (m^2/pp)	Lighting (Watt/m^2)	Equipment (Watt/m^2)	Infiltration (m^3/s)
Residential	28.3	3	3	0.001
Accommoda-tion	15	3	5	0.001
Office	12	10	8	0.001
Retail	17	25	1	0.001

Table 11. List of functions along with their respective input values. Adapted from: NEN-EN 16798-1, 2019

Function	Category	Cool Set Point (°C)	Heat Set Point (°C)	Humidifying Set point (%)	Dehumidifying Set point (%)
Residential	Good	26	20	25	60
Accommoda-tion	Good	26	20	25	60
Residential	High	25	21	30	50
Accommoda-tion	High	25	21	30	50
Office	-	26	20	25	60
Retail	-	25	16	25	60

Table 12. List of functions along with their respective values for Set Point. Adapted from: NEN-EN 16798-1, 2019

7. Simulation Set-up

Chapter 7 explains the simulation and optimization setup, along with an extensive overview of the model

7.1. Overview of the model

The study developed a process using Grasshopper and a variety of plug-ins. This procedure allows repeated interaction based on user preferences. The model utilizes a rectangular form, with users specifying desired dimensions, location, and function to achieve optimal design solutions. At the end of this procedure, the user will receive feedback on whether they have met BREEAM daylight criteria and whether their energy usage meets BENG guidelines. BENG standards have been used to improve understanding of the values, even though they are not suitable for inter-location comparisons due to their variability among regions. When standards are not reached or the global warming potential exceeds acceptable levels, the user can alter parameters to achieve the objectives.

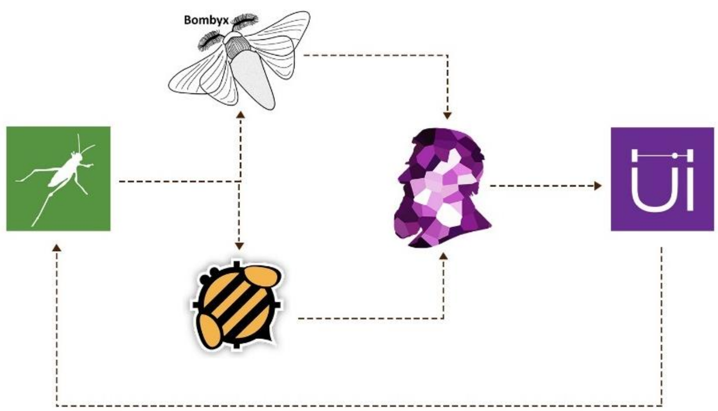


Figure 20. Software workflow.

7.2. Form generation

The workflow commences with the definition of geometric parameters and the generation of the form within a parametric software, Grasshopper. Parametric modelling allows for rapid efficient design development and modifications, while also facilitating a preliminary analysis of many possible designs. This process is characterized by parametrization, which interconnects design variables inside the following hierarchical chain:

- Core
- Structure
- Wall structure

This workflow allows users to quickly produce a variety of energy-efficient and environmentally friendly building designs by specifying material kinds and construction methods for each building element.

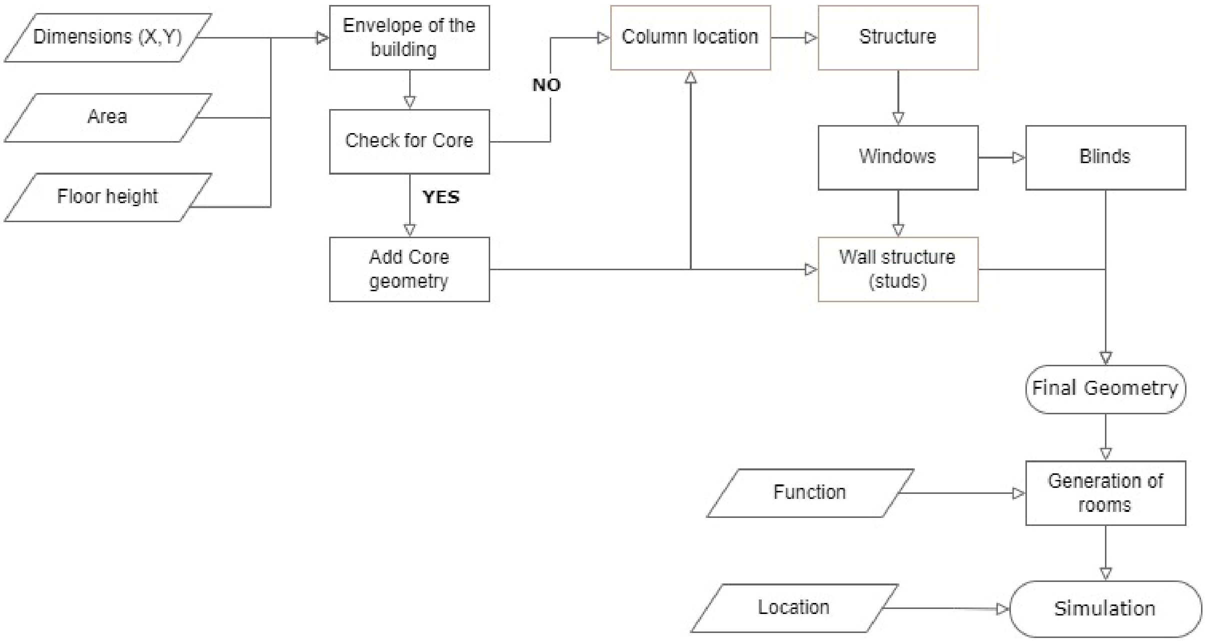


Figure 21. Final Geometry Generation Workflow.

Core generation

The building dimensions vary from 2 by 2 to 20 by 20 meters, requiring the establishment of a core in the middle when the depth surpasses a particular threshold. As a result, the appropriate shape is generated. Within this design, Grasshopper expression determines whether a core is required for each geometry.

Users can set the room's depth (represented by 'a' for the y-axis and 'b' for the x-axis) to 6, 7, or 8 meters. The Grasshopper script then determines the proportions of the core, if necessary. The obtained dimensions are then passed to a Python script for validation. When one of the two dimensions is zero, both are set to zero, indicating that a core is not required.

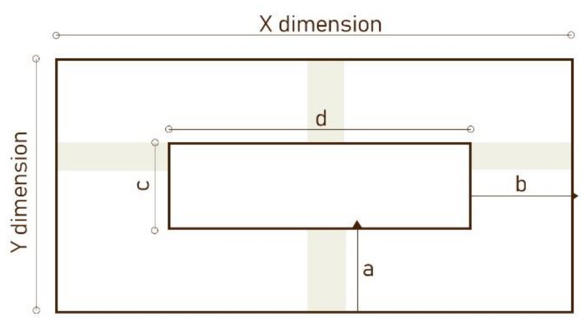


Figure 22. Geometry relation between core and building envelope.

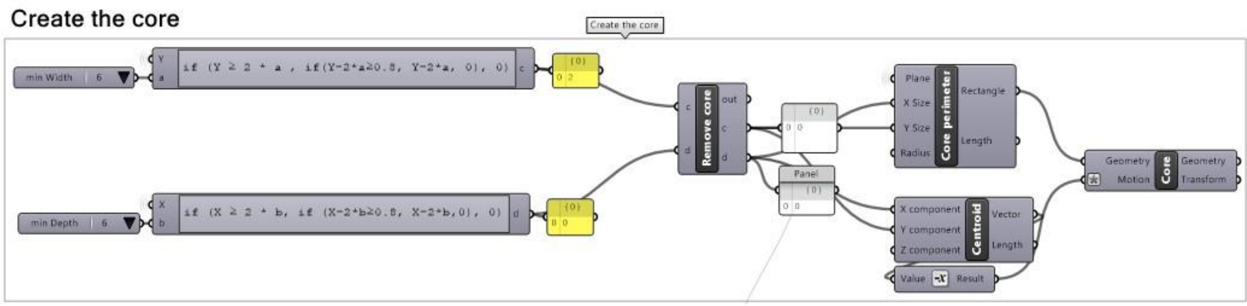


Figure 23. Grasshopper script to determine core's proportions.

Structure

To perform a complete Life Cycle Assessment (LCA) at a later phase in the model, the building's structure had to be established. As a consequence, post and beam timber construction was used, with calculations based on existing rules of thumb, intending to deliver emissions data that closely corresponded to the actual conditions.

Users can define the span between columns in addition to the factors that influence their size. This approach is a significant tool for architects and civil engineers during conversations, allowing for a quick assessment of alternative solutions and their impact on the total global warming potential. Equations 1 and 2 calculate the number of columns on each side by dividing the lengths (X, Y) by the required column span (col_{span}). The column size is then calculated by dividing the column span by the factor (f).

$$\frac{X}{col_{span}} = n \quad (1),$$

$$\frac{Y}{col_{span}} = n \quad (2),$$

$$\frac{col_{span}}{f} = col_{size} \quad (3)$$

After identifying the column locations, the next step is to remove any possible column points that might be present within the core's perimeter. This method is carried out using a Python script in Grasshopper, which generates a set of points for both the x and y axes. If the coordinates of the columns fall within this set of points, they are deleted. As Figure 24 shows, the set of points that are in the yellow area are deleted, like point B. Finally, the script keeps only those elements that exist outside the core. The process ends by generating the columns and their placement on façade. Beams' height is computed using identical equations, and their width is set to half the column's diameter.

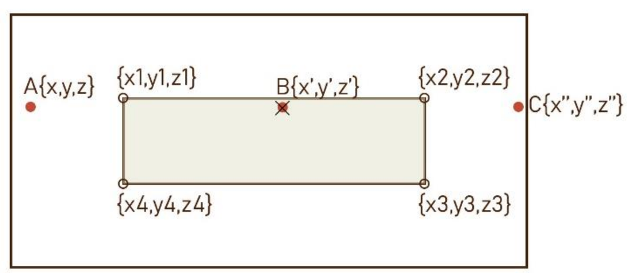


Figure 24. Geometry relation between core and column location.

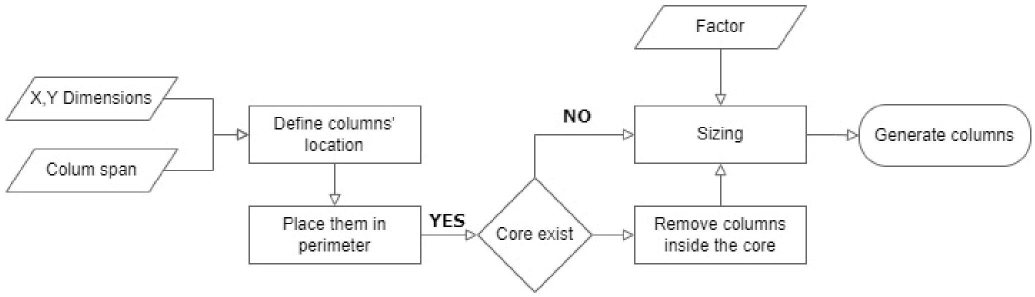


Figure 25. Column Generation Workflow.

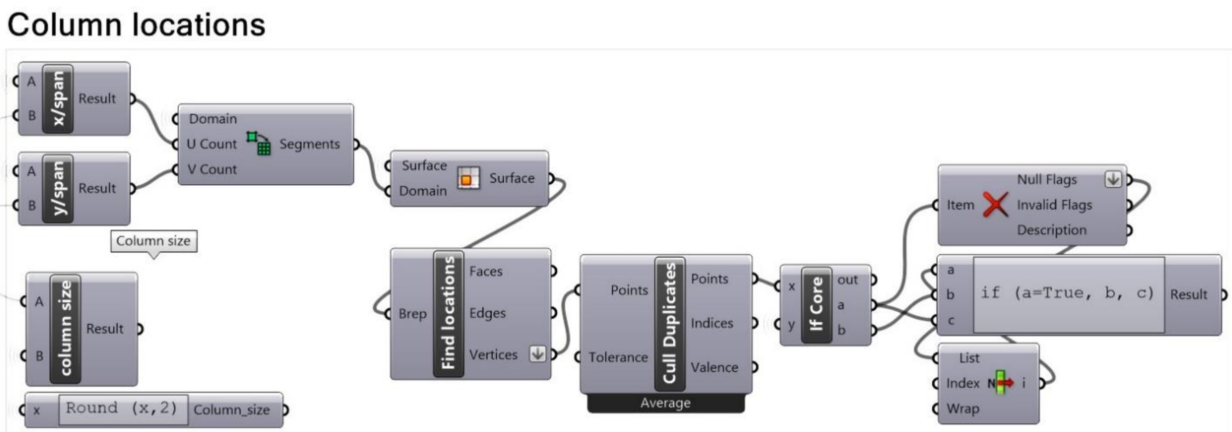
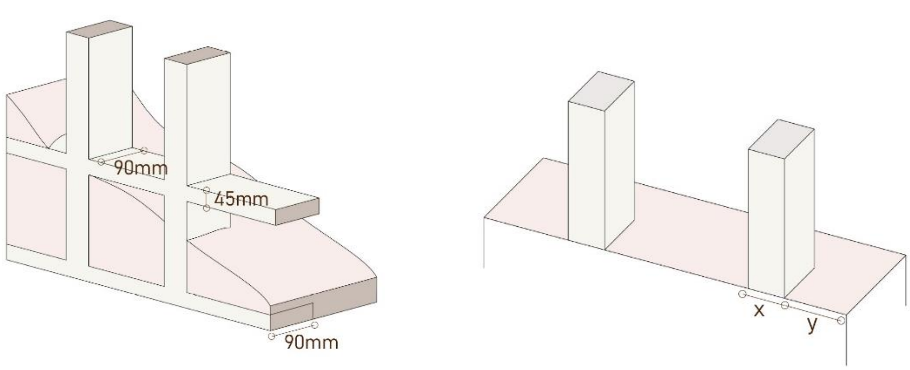


Figure 26. Grasshopper script to determine columns' location.

Wall structure

To ensure a full Life Cycle Assessment (LCA), the construction of the hempcrete wall was required. This addition adds the structural component and incorporates it into the carbon emissions calculation. The wall's construction, complete with all studs, was included in the form generation process. To guarantee a strong framework, the proportions followed conventional building methods (Tradical, n.d.). According to the literature, studs have in between distance 0.6m, width varies according to the thickness of hempcrete, and thickness is 0.09m.



x	y
40	70
50	75
60	80
70	85
80	90

Figure 27. Hempcrete wall construction details. Adapted by: (Tradical, n.d.)

To design the exterior walls, each side's length was divided by 0.6m to determine the number of studs required, and points were then set at each side. These points are then filtered by utilizing a Python script to generate two lists: those placed beneath the windows and those not. This procedure included getting the coordinates of each window edge and generating sets of X coordinates for the x-axis, as seen in Figure 28. The process entailed acquiring the coordinates of each window corner and constructing sets of X coordinates for the x-axis, as shown in Figure 28. The coordinates on either side are compared to these values, providing two unique lists: one having studs beyond the window frame (marked as A and B in Figure 28), and another containing studs beneath the window (identified as C). Finally, studs that are created outside the window perimeter, reach the height of the beam, in contrast with those under the window that only reach the windowsill height.

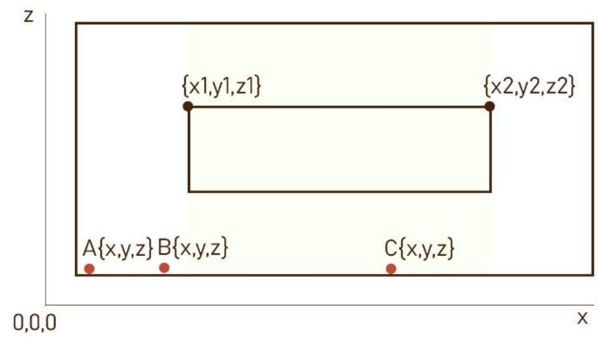


Figure 28. Geometry relation between window and studs' location.

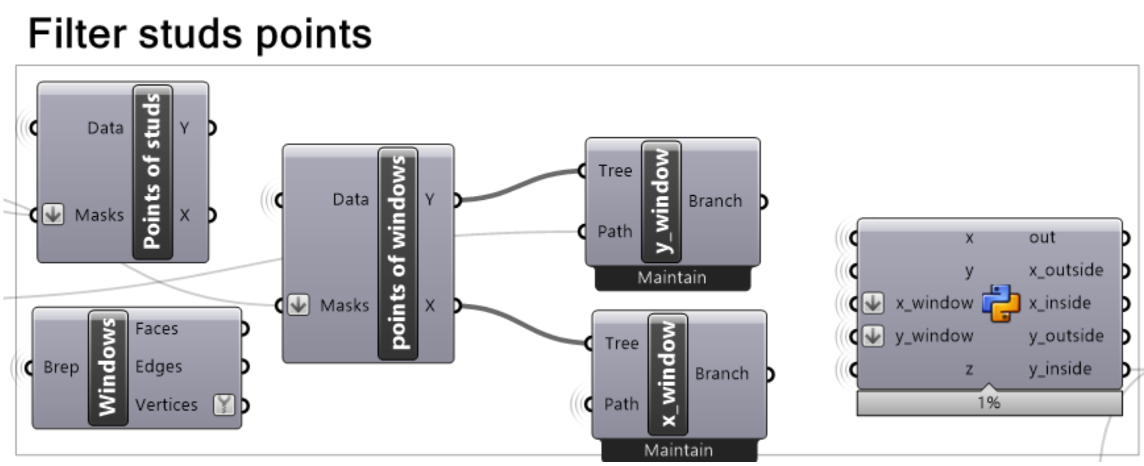


*Figure 29. G*rasshopper script to determine stud's height.

7.3. Energy simulation setup

The second part of the workflow involves energy and daylight simulation, as shown below. Honeybee was implemented to define the program and create the room for EnergyPlus simulations. Honeybee also made it easier to simulate daylight conditions. Following geometry generation, users can launch the simulation by selecting a location and function. This process includes the detailed definition of:

- Program variety
- Construction variety

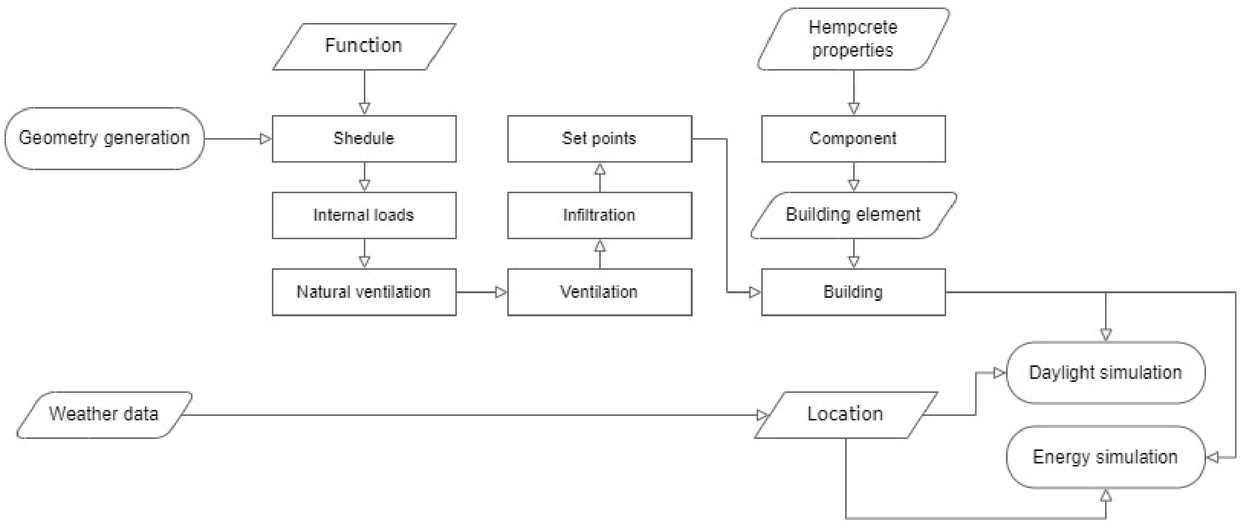


Figure 30. Energy and daylight simulation Workflow.

Overall program variety

The approach allows for program adjustments based on user preferences. It has four functions: residential, accommodation, office, and retail. The first two functions enable simulation runs to achieve either good (Category II) or high (Category I) targets under NEN-EN 16798-1 design standards. This technique involves integrating a Python component within the Grasshopper software to build unique datasets for each function, which are modified dynamically based on user input. As shown in Figure 32, the Python component receives a value representing the user's preferred function (Residential = 0, Accommodation = 1, Office = 2, Retail = 3), and then generates results based on this numerical identification. Similarly, each component within the program section comprises a set of design standards derived from NEN-EN 16798-1 that operate in an identical way. The outputs of these components are then connected to the corresponding Honeybee components. This segment's Python script (Figure 32) works as a filter, allowing simulation parameters to be adjusted based on user preferences.

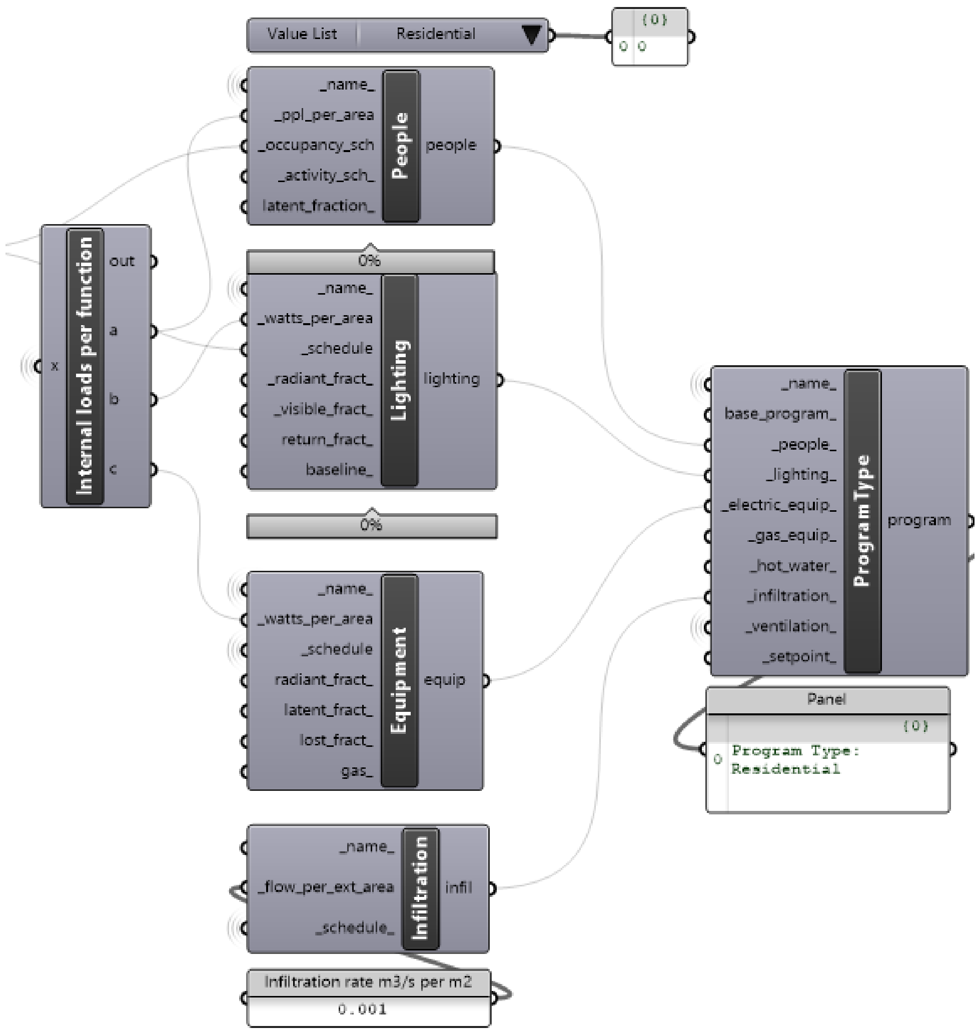


Figure 31. Grasshopper script to determine internal loads per function.

```
if x == 0:
    a = 1/ 28.3         #28.3m2/pp - Residential
    b = 3               #LED
    c = 3               #EN 16798-1:2019
elif x == 1:
    a = 1 / 15          #15m2/pp - Hotel
    b = 3               #LED
    c = 5               #EN 16798-1:2019
elif x == 2:
    a = 1/ 12           #12m2/pp - Office
    b = 10              #LED
    c = 8               #EN 16798-1:2019
else:
    a = 1 / 17          #17m2/pp - Retail
    b = 25              #LED
    c = 1               #EN 16798-1:2019


#Reference: https://www.engineeringtoolbox.com/number-persons-buildings-d_118.html
```

Figure 32. Python script to determine the different variables for every function.

Schedule variety

Consecutively, schedules for internal loads such as lighting, occupancy, and equipment, ventilation, infiltration, and set points are established. Table 11 and Table 12 provide an overview of the building program organized by function. A weekly schedule has been developed for each function, with principles based on Dutch standards (*NEN-EN 16798-1*, 2019b).

Residential		Accommodation		Office		Retail	
weekly	weekend	weekly	weekend	weekly	weekend	weekly	weekend
1	0.8	1	1	0	0	0	0
1	0.8	1	1	0	0	0	0
1	0.8	1	1	0	0	0	0
1	1	1	1	0	0	0	0
1	1	1	1	0	0	0	0
1	1	1	1	0	0	0	0
1	0.8	1	1	0	0	0	0
0.5	0.6	0.8	0.8	0	0	0	0
0.5	0.6	0.8	0.8	0	0	0	0
0.5	0.6	0.8	0.8	0.6	0	0.1	0.1
0.1	0.3	0.8	0.8	0.7	0	0.3	0.5
0.1	0.3	0.8	0.8	0.6	0	0.3	0.4
0.1	0.3	0.8	0.8	0.4	0	0.7	0.8
0.1	0.3	0.8	0.8	0.3	0	0.6	0.7
0.2	0.3	0.8	0.8	0.7	0	0.5	0.6
0.2	0.3	0.8	0.8	0.6	0	0.6	0.7
0.2	0.3	0.8	0.8	0.4	0	0.6	0.7
0.5	0.3	0.8	0.8	0.2	0	0.9	1
0.5	0.3	0.8	0.8	0	0	0.9	1
0.5	0.3	0.8	0.8	0	0	1	1
0.8	0.8	0.8	0.8	0	0	0.9	0.9
0.8	0.8	0.8	0.8	0	0	0.7	0.8
0.8	1	1	1	0	0	0	0
1	0.8	1	1	0	0	0	0

Table 13. Overall schedules for Residential, Accommodation, Office and Retail. Adapted by: *(*NEN-EN 16798-1*, 2019b)*

This approach aligns with the methodology used throughout the program, that employs a Python component as a database. This component receives various schedules and the assigned function as inputs and returns corresponding weekday, weekend, and holiday schedules as output. In particular, holidays are allocated using factors 0.4, 0.9, 0.1, and 0.9, respectively to the functions on Table 13.

Construction variety

Envelope composition

The implementation of an extensive selection of building components and materials is the primary objective of this procedure. Specifically, the Honeybee material database missed Hempcrete, which is critical for our research. As a result, the development of Hempcrete as a material was essential. As shown in Table 10, several varieties of hempcrete have been implemented. This procedure is supported by a Python component that incorporates the unique properties of each material.

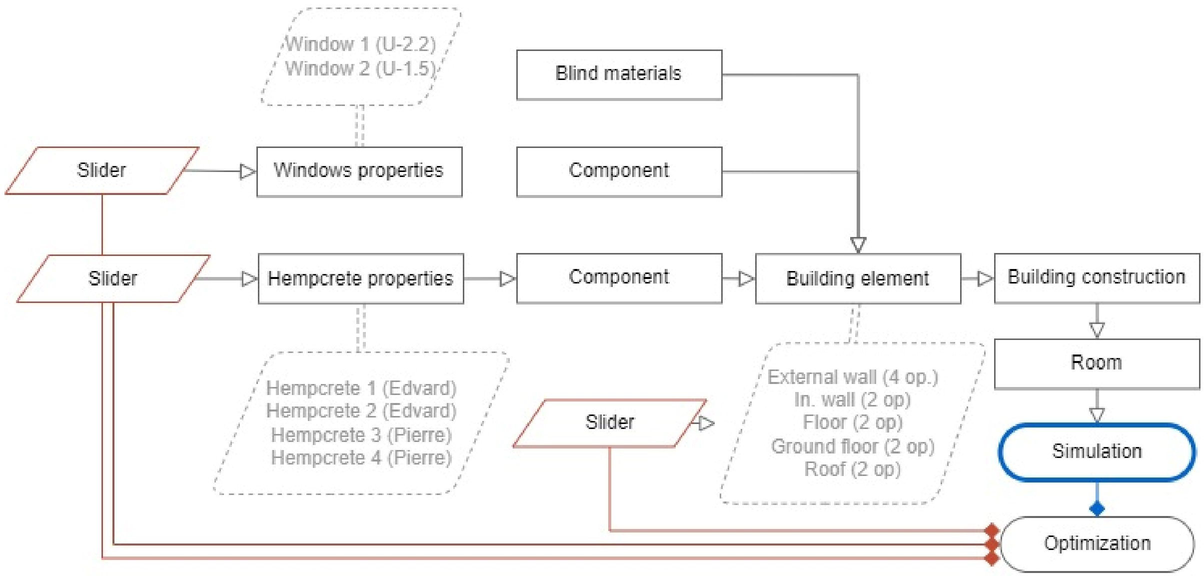


Figure 33. Construction workflow.

A slider input in Python, used subsequently in optimization, determines the selection of the corresponding hempcrete attributes based on their numerical value. These are then linked to the appropriate component within Honeybee (Figure 34). This process is carried out separately for each construction element, ensuring that external walls, floors, ground floors, roofs, and interior walls are built with the best possible material composition. Figure 33 displays the process that model follows for a variety of building elements and materials, and its connection with the optimization. Figure 35 demonstrates the Grasshopper script for developing multiple material for the exterior wall. These are fed into a Python component, which returns a list of materials organized from outside to inside. The thermal resistance of the envelope varies according to the thickness and the element composition.

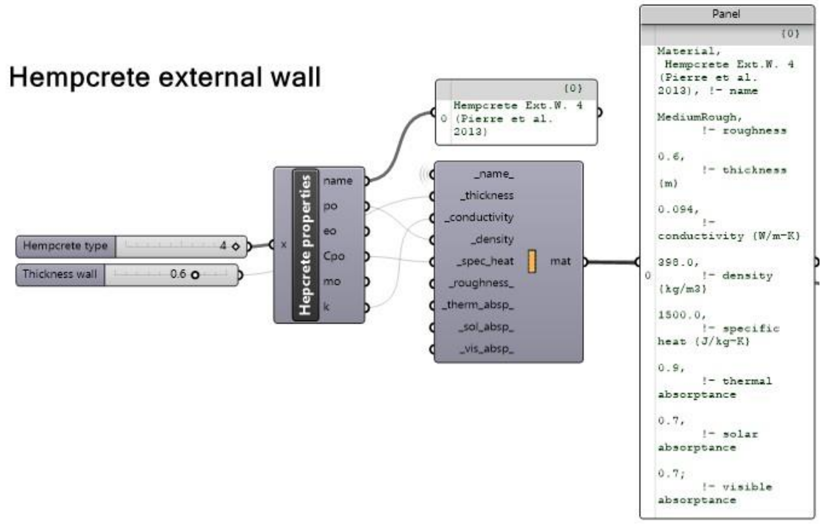


Figure 34. Grasshopper script to determine hempcrete properties.

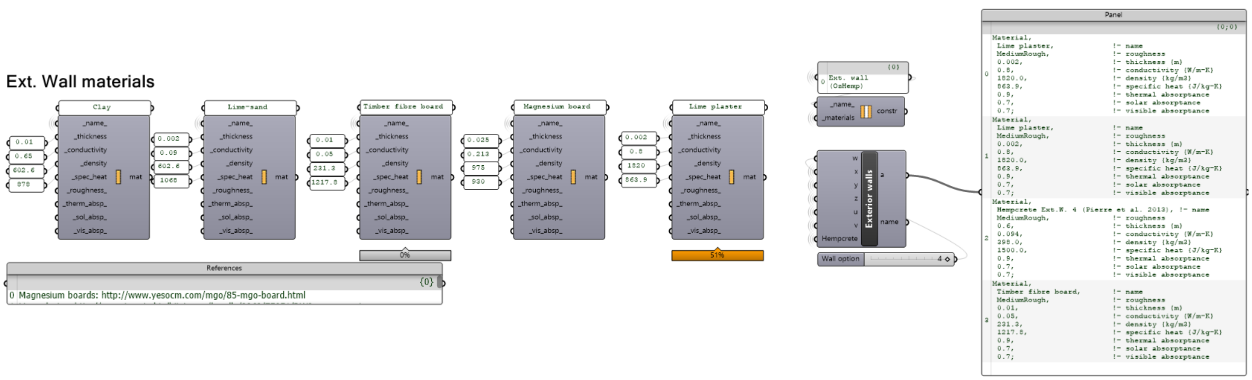


Figure 35. Grasshopper script to determine external wall component.

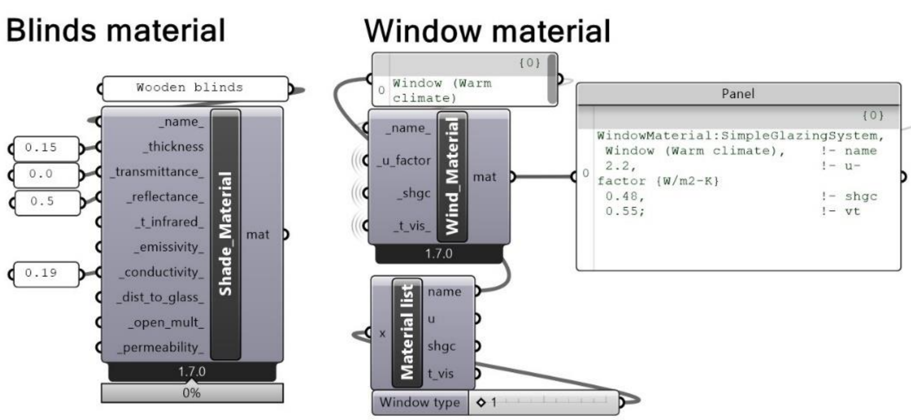


Figure 36. Grasshopper script to determine window and blind materials.

Energy simulation

The energy simulation is carried out using Honeybee's EnergyPlus engine. The input includes all building components, and the user can choose the location for ingesting climate data. This data can reflect either current weather conditions or future climate projections, depending on the user's preference. Future weather data is used to develop permanent structures that will resist climate conditions for at least 60 years, assuring future climate resilience. However, if the facility is only temporary and does not require climate change adaptation, simulations can be run using current climate data. The simulation results indicate the overall energy demand, which includes cooling, heating, lighting, and equipment. The primary goal is to reduce overall energy consumption, with a focus on cooling and heating loads, indicating the building's compliance with BENG 1 criteria.

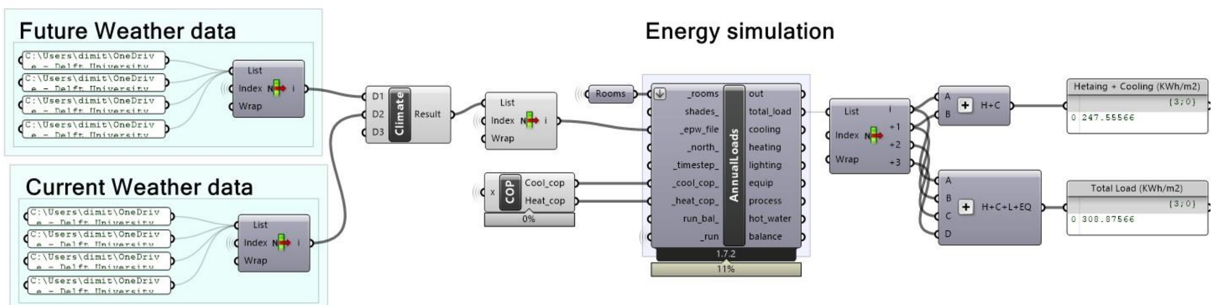


Figure 37. Grasshopper script to location and get results of energy simulation.

Relevant coefficient of performance has been used for heating and cooling according to the climate to achieve more realistic results.

- Oslo: cool_cop=2.5, heat_cop=1
- Milan: cool_cop=2.5, heat_cop=2.5 (Marini, 2013)
- Cairo: cool_cop = 2.9, heat_cop = 1 (Mohamed et al., 2022)
- Singapore: cool_cop = 4.04, heat_cop=1 (National Environmental Agency, n.d.)

Daylight simulation

The daylight simulation makes use of Honeybee's Radiance engine. The input is restricted to one story of the entire building, as the surrounding region, in the model, does not affect the daylighting results per floor. The calculation is conducted for the user-selected location and function. Each function is required to comply with specified standards established by BREEAM criteria ("BREEAM_INC-Manual-English," 2016a). The average daylight autonomy findings are filtered using values from Table 4, which include average illuminance and minimum area requirements for compliance. This allows for an evaluation of whether the model accomplishes the defined aims. The optimization objective is to achieve total daylight autonomy to the greatest extent possible.

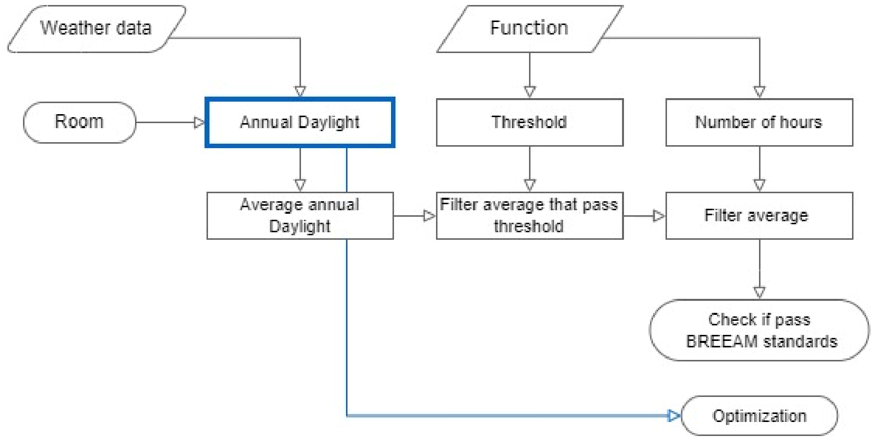


Figure 38. Daylight workflow.

Figure 39 displays the Grasshopper script, which calculates the total number of occupied annual hours based on the specified schedule. This amount is then split to determine the required hours by BREEAM standards, resulting in the percentage of hours required to accomplish each function. This data is then used to filter the average daylight results, leaving just those that satisfy the required requirements (Figure 40).

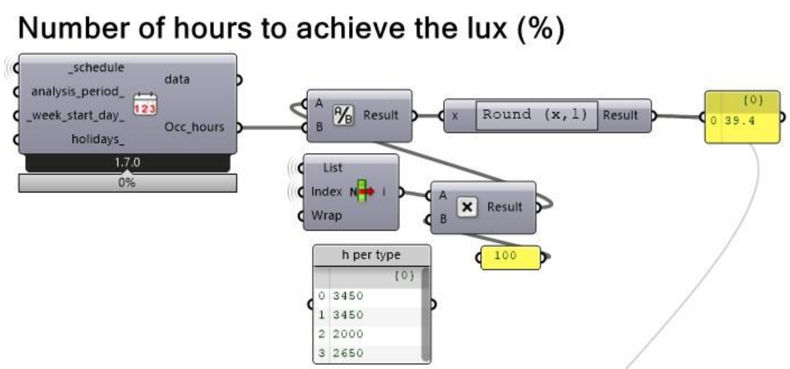


Figure 39. Grasshopper script to get the percentage (%) of required time.

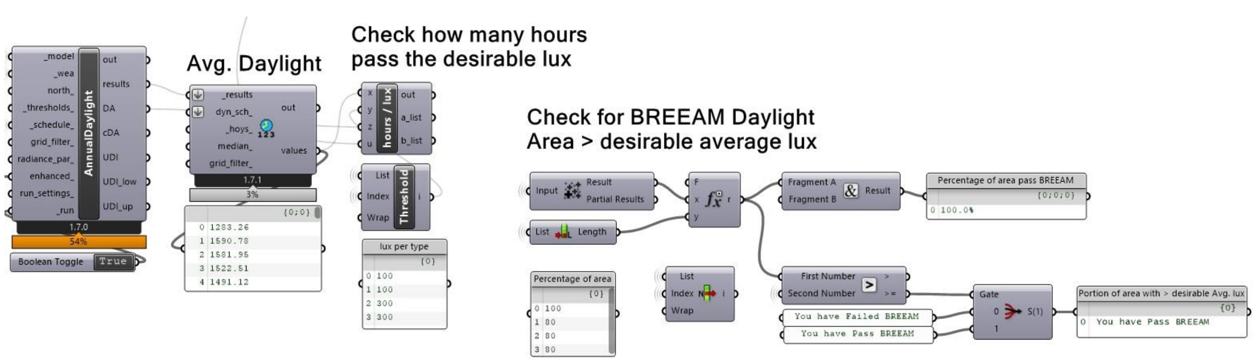


Figure 40. Grasshopper script to evaluate if the model achieves BREEAM standards.

7.4. LCA simulation setup

Bombyx is used to completely evaluate and optimize the building design's environmental performance. Bombyx is a plug-in that simplifies environmental calculations involving the building's shape, materials, and systems (Basic et al., 2019).

- Geometry impacts are determined by evaluating the surfaces of the 3D model, similar to a thermal model.
- The impact of construction materials is evaluated for each element. While there are two ways for detailing, this study focuses on a precise description of layers and material selection to enable more accurate assessments.
- Electrical, heating, ventilation, and sanitary systems are examples of technical equipment that is regarded an input at the component level.

The model operates over a 40-year research period, which can be changed according to user preferences. However, it does not calculate the technical equipment due to restricted information availability and the fact that the thesis focuses mostly on basic design exploration.

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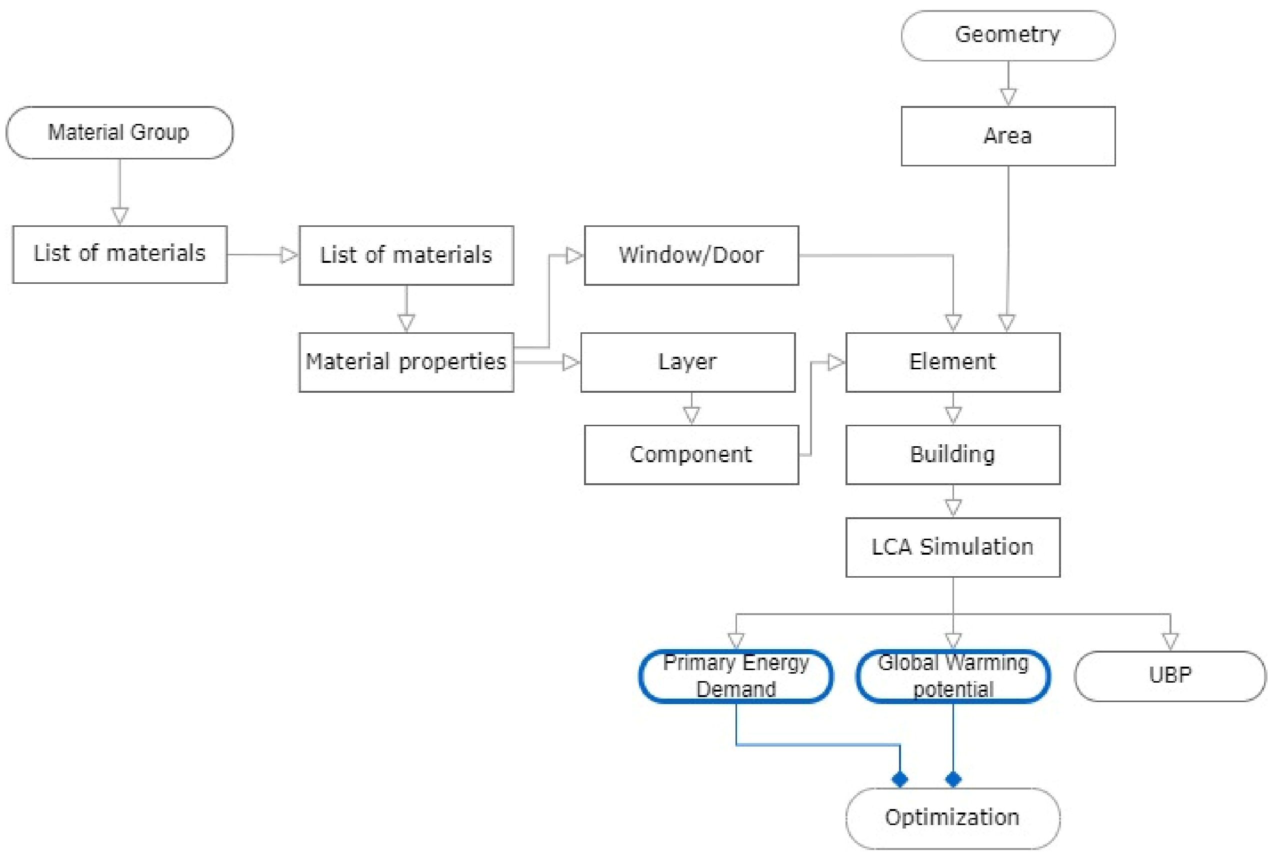


Figure 41. LCA workflow.

As shown in Figure 41, the area of each surface is first calculated to determine the impact of individual surfaces on environmental performance. Following that, each material is selected with the appropriate thickness for the surface and reference lifespan. The material components are arranged by using a Python component, and the building element is generated. These components have identical layers to the material components used in the energy simulation.

Following that, all LCA elements are combined to determine the global warming potential (kg CO2-eq/m^{2}a), non-renewable primary energy (kg CO2-eq/m^{2}a), renewable primary energy (kg CO2-eq/m^{2}a), and UBP impact (P/m^{2}a). The global warming potential and total primary energy are used as objectives to be minimized during optimization.

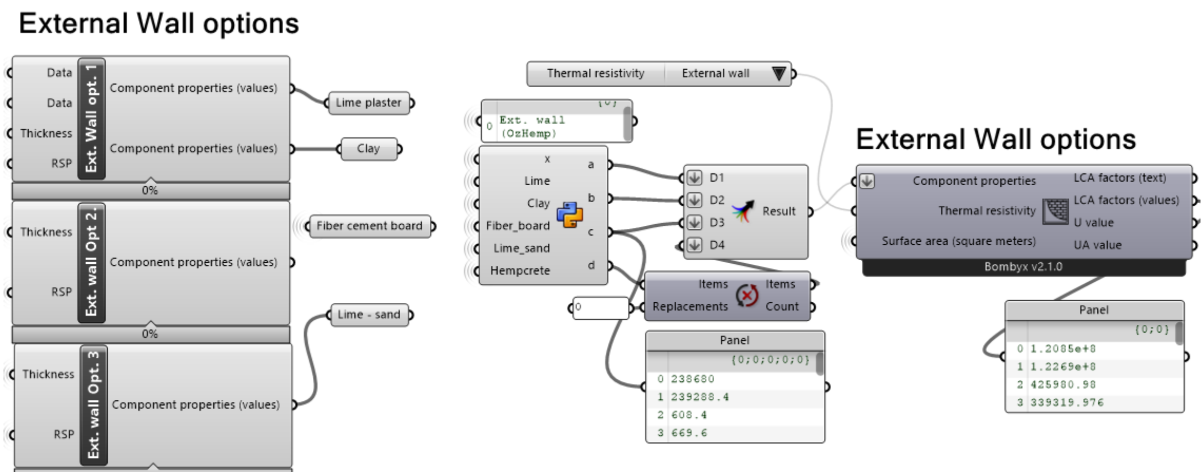


Figure 42. Grasshopper script for the external wall set-up in Bombyx.

7.5. Optimization

The final phase involves optimizing the building design. Design decisions have a substantial impact on a building's energy usage, visual comfort, and environmental impact during its entire life cycle. Architects and engineers carefully evaluate elements such as the location and function of the building when making these selections. These factors are included in the model to help offer appropriate design methods. The following design variables are then used as input in the optimization process. Table 9. Overview of optimization's variables. summarizes the optimization inputs.

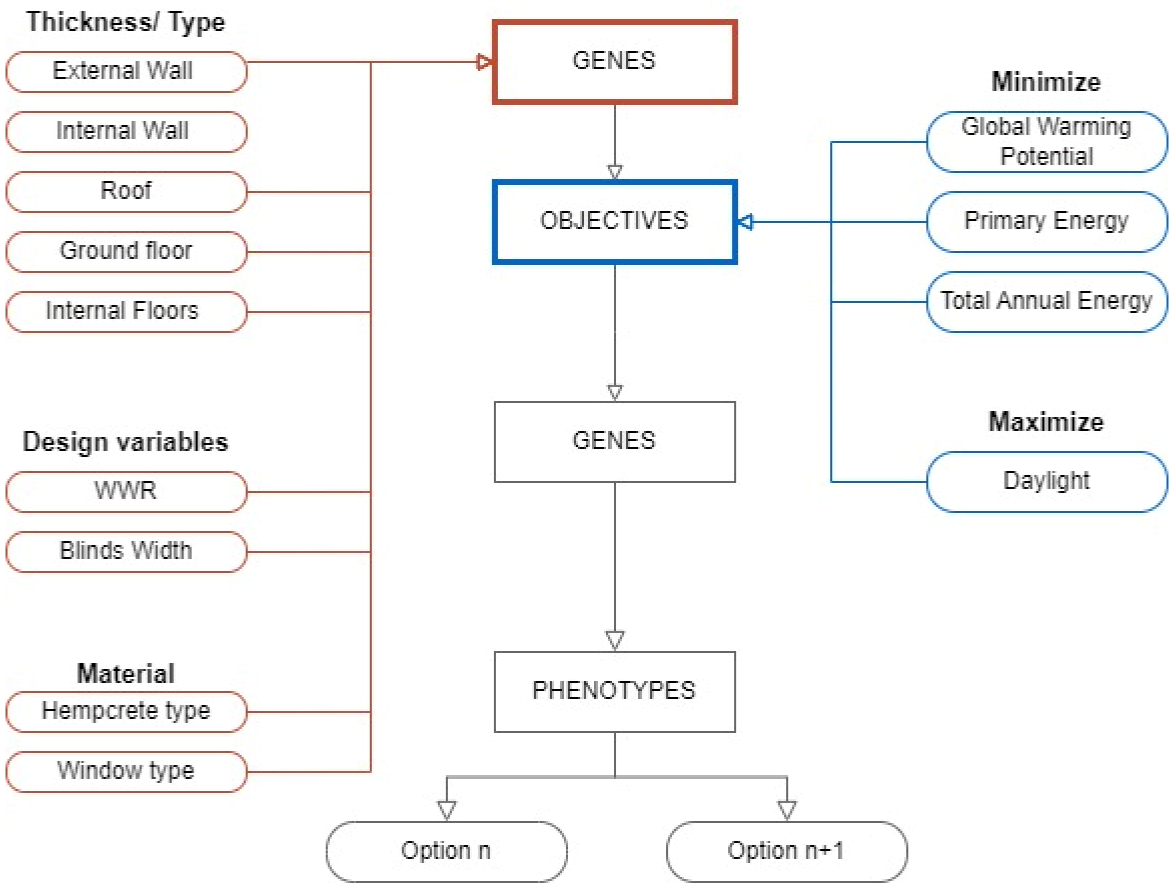


Figure 43. Optimization workflow.

Comparison of energy demand and GWP in an example

The optimization has in total 21 genes and 4 objectives, which takes 90 min to run to achieve 200 different designs. The optimization has been used for every climate and every function to see the results. Then the genomes and fitness values, as well as data are saved in an excel file to be used later on the visualization. In particular, Figure 44 shows the relation between the GWP, total hours of Daylight Autonomy and Total Energy load, which include cooling, heating, lighting and equipment, of a residential building 14m by 8m by 3.6m in Milan. It is interesting to analyze the design solutions that lead to reduce energy demand, still tend to have one of the highest GWP.

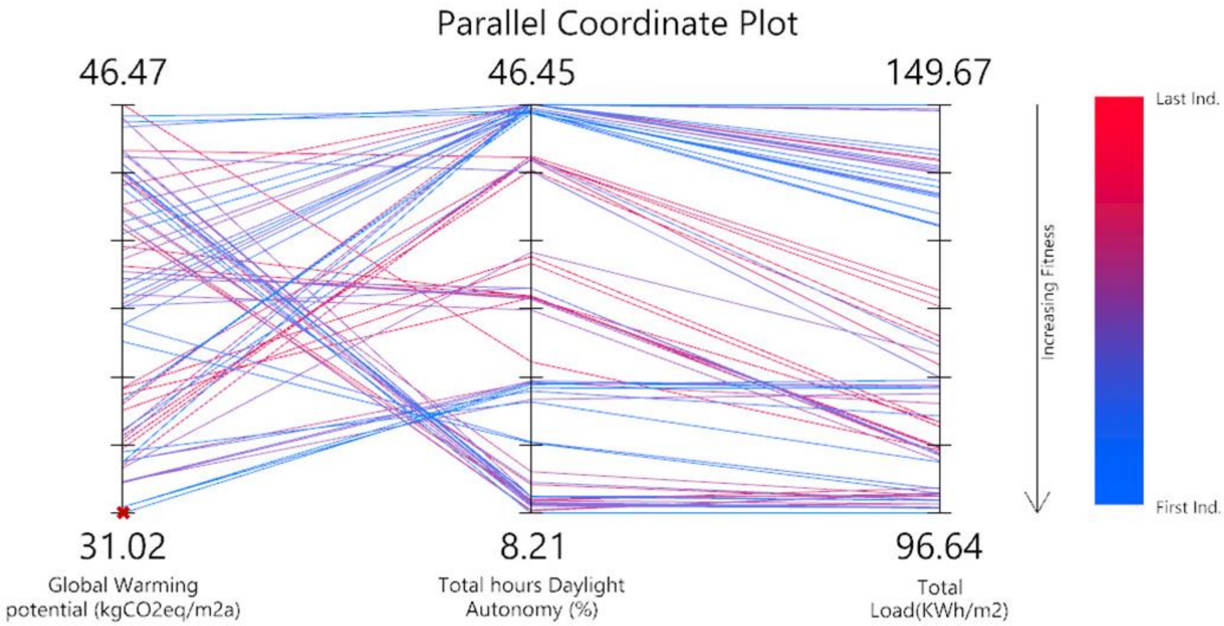


Figure 44. Milan Residential Parallel Coordinate Plot.

	Objectives		Genes							
Opt.	Total load.	GWP	WWR	Hem.w.t	w.t	d. w.	Hem.r.t	r. t.	d. r.
152	96.63	43.61	0.20	2	4	0.2	1	2	0.5
74	97.26	43.89	0.20	3	2	0.4	1	2	0.5
65	97.83	43.82	0.20	1	4	0.2	4	1	0.5
111	98.34	42.49	0.20	2	2	0.4	1	1	0.5

Table 14. Table summarizing designs 49,38,2,3 with their results for Milan Residential. Hem: Hempcrete, w: wall, t: type, d: thickness, r: roof

Four designs were chosen and studied in Table 14 due to their low overall energy load. The values for the wall, the roof and the WWR were compared to identify differences. It is clear that as energy demand decreases, Daylight autonomy decreases as well, influencing Global Warming Potential (GWP). The window-to-wall ratio remains constant, although the other variables vary. Notably, the hempcrete category has a significant impact on both elements (see Chapter 6.3). Additionally, the thickness and kind of wall construction have a minor impact on the outcomes. It is vital to note that reduced hempcrete thickness when paired with wall construction type 4, results in a lower GWP. However, the results differ slightly for a northern site with the same building characteristics. Figure 45, displays the results of optimizing the same building in Oslo. Although a higher Global Warming Potential (GWP) corresponds with lower energy demand, it is worth noting that the lowest energy demand does not always correspond with the highest GWP. Using almost the same elements and changing the hempcrete type on the wall or roof, or altering the construction type, has a minor impact on the total load but a significant impact on the global warming potential (GWP).

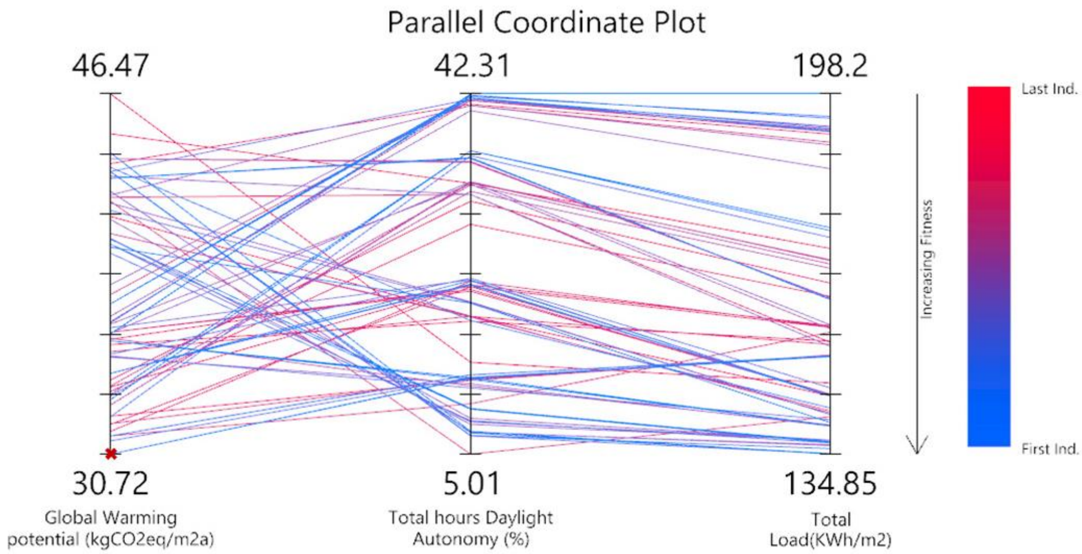


Figure 45. Oslo Residential Parallel Coordinate Plot.

	Objectives		Genes							
Opt.	Total load.	GWP	WWR	Hem.w.t	w.t	d. w.	Hem.r.t	r. t.	d. r.
195	134.85	43.89	0.20	3	4	0.4	1	2	0.3
135	135.82	43.07	0.20	4	4	0.4	1	1	0.3
116	135.36	42.20	0.20	4	4	0.4	1	2	0.3
63	137.29	41.51	0.25	4	2	0.4	2	2	0.3

Table 15. Table summarizing designs 196,174,116,67 with their results for Oslo residential. Hem: Hempcrete, w: wall, t: type, d: thickness, r: roof

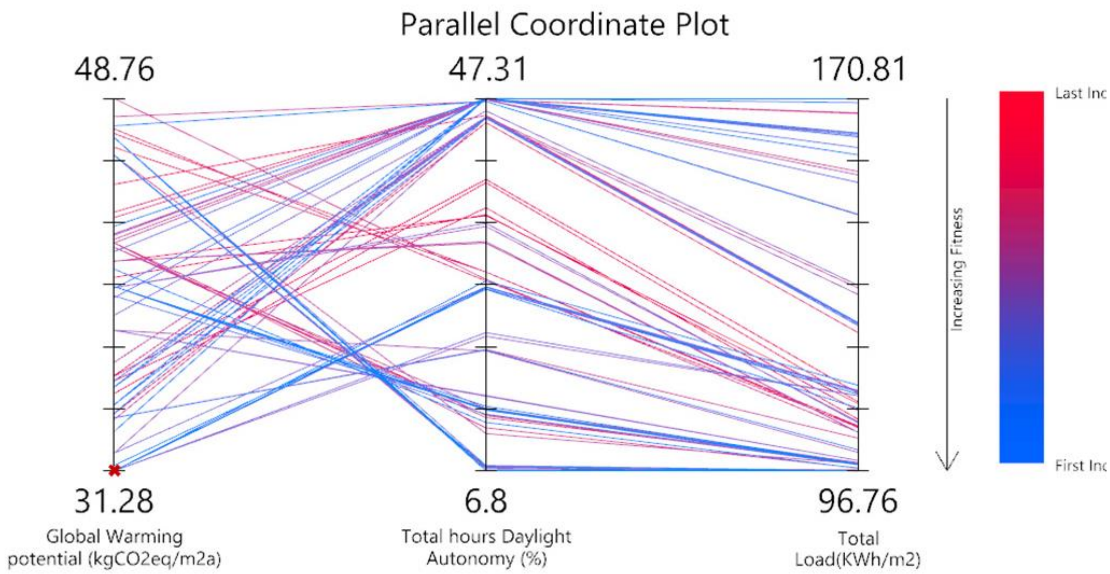


Figure 46. Cairo Residential Parallel Coordinate Plot.

	Objectives		Genes							
Opt.	Total load.	GWP	WWR	Hem.w.t	w.t	d. w.	Hem.r.t	r. t.	d. r.
123	96.76	46.92	0.20	2	1	0.2	4	2	0.4
23	96.93	46.08	0.20	2	4	0.2	4	1	0.5
161	98.06	39.49	0.20	4	4	0.1	1	1	0.4
89	100.45	30.50	0.20	4	1	0.4	4	1	0.5

Table 16. Table summarizing designs 123,23,161 and 89 with their results for Cairo residential. Hem: Hempcrete, w: wall, t: type, d: thickness, r: roof

The data for the same building in Cairo show a lower energy demand than Oslo, with the majority of it now allocated to cooling. Contrary to prior optimization results, the majority of the parameters differ. Examples 23 and 123, which are nearly identical, demonstrate that changing the element type can result in a higher GWP and a lower energy demand without a substantial overall increase. However, despite the low energy demand in prior cases, Singapore (see Table 17) has significant higher energy consumption. In particular, all the designs are nearly identical, with the only difference being the thickness of the building parts. It is also worth noting that the size of the blinds has a considerable impact on the amount of radiation entering the dwelling and the level of overheating.

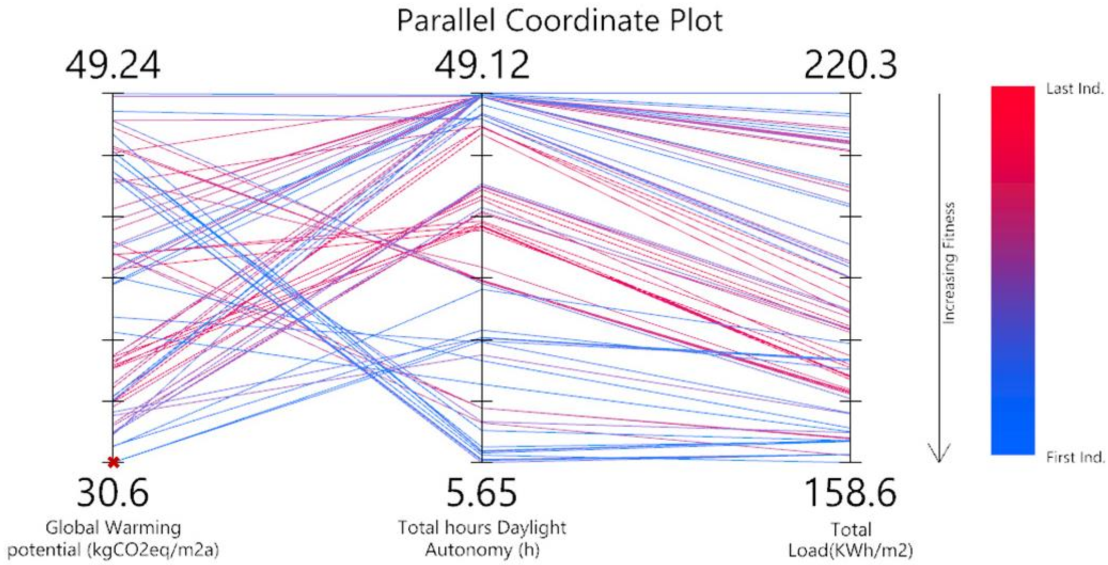


Figure 47. Singapore Residential Parallel Coordinate Plot

	Objectives		Genes						
Opt.	Total load.	GWP	WWR	Hem.w.t	w.t	d. w.	Hem.r.t	r. t.	d. r.
73	158.60	45.30	0.20	2	4	0.2	4	2	0.4
144	159.95	44.98	0.20	2	4	0.2	4	2	0.3
180	162.13	45.14	0.20	2	4	0.4	2	2	0.4
118	163.63	45.30	0.20	2	4	0.4	1	2	0.6

Table 17. Table summarizing designs 73, 144, 180, 118 with their results for Singapore residential. Hem: Hempcrete, w: wall, t: type, d: thickness, r: roof

In conclusion, the type of hempcrete, building element, and thickness all have a major impact on energy demand. The majority of the outcomes exhibit constant window-blind values, allowing for a more emphasized analysis of hempcrete's influence. In all climates, thickness was the most important element influencing energy demand and, as a result, GWP, followed by hempcrete type and building type. However, it is necessary to note that all of the examples have a low WWR, failing to meet BREEAM criteria, despite previous data (Figure 12) indicating that a 20% WWR is one of the most efficient for most regions in a residential structure. Examples with a high WWR generate more energy demand due to greater radiation. As a result, while making final decisions, designers should consider daylight alongside energy demand and carbon emissions to create a comfortable and sustainable building. Finally, it is crucial to notice that the building has roughly the same primary energy consumption in all locations because the shape, geometry, and materials are consistent.

Comparison of building elements' thickness in an example

It is important to conduct a detailed analysis of the results to fully comprehend the relationship between element thickness, daylight supply, energy consumption, and the contextual parameter of location and function. The following results apply to a building of 14 meters by 8 meters by 3.6 meters, and only design solutions that meet BREEAM daylighting requirements are evaluated. Figure 48 depicts the frequency of successful optimized designs meeting BREEAM requirements.

Figure 48 shows that Cairo and Oslo have similar numbers of successful design possibilities, with the exception of the office function, where Oslo has no effective designs. This gap is most likely due to Oslo's reduced solar hours during the winter months. Milan emerges as the most promising climate for meeting BREEAM criteria, as indicated by the abundance of effective solutions. Similarly, Singapore shows promise in terms of BREEAM compliance, with practically every function having more than 30% of its designs satisfying the standards.

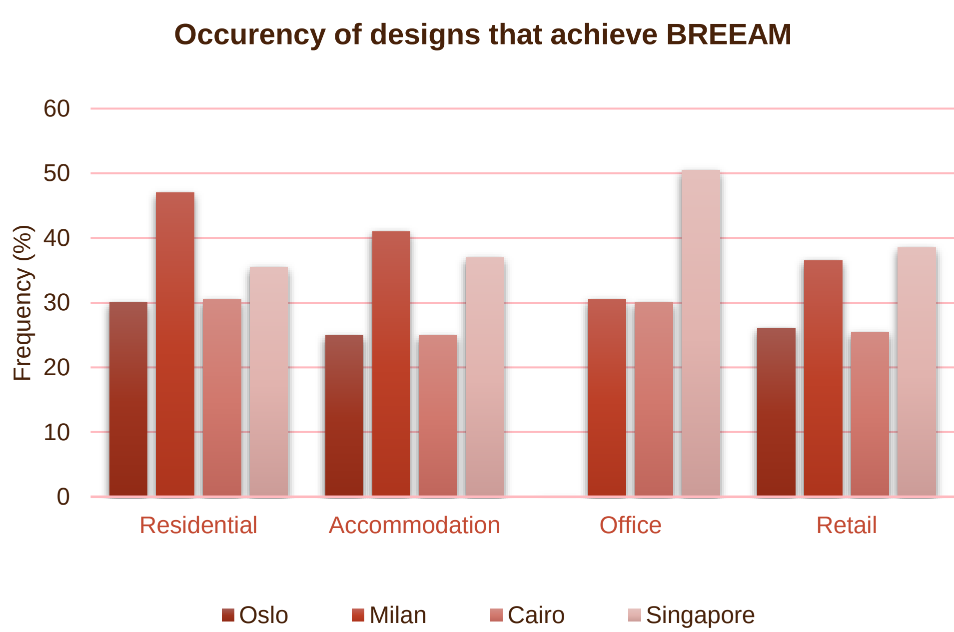


Figure 48. Frequency of Design Options Meeting BREEAM Standards for Daylighting in Various Functions and Climatic Regions

Despite the possibility for more design alternatives to achieve BREEAM requirements by improving daylighting, it is critical to recognize the concurrent increase in cooling demand within buildings, which is optimized for decrease. As a result, this purpose limits the possible possibilities. In Milan, the thicknesses of building parts vary. Figure 49 depicts how the external wall thicknesses of successful Milan designs vary. The most successful models employ a wall thickness of 0.4 meters, with 0.2 meters being used most frequently in residential and retail applications. The second most frequent thickness for lodging and office areas is 0.1 meters. This thickness profile is rather popular for exterior walls in the Milan area.

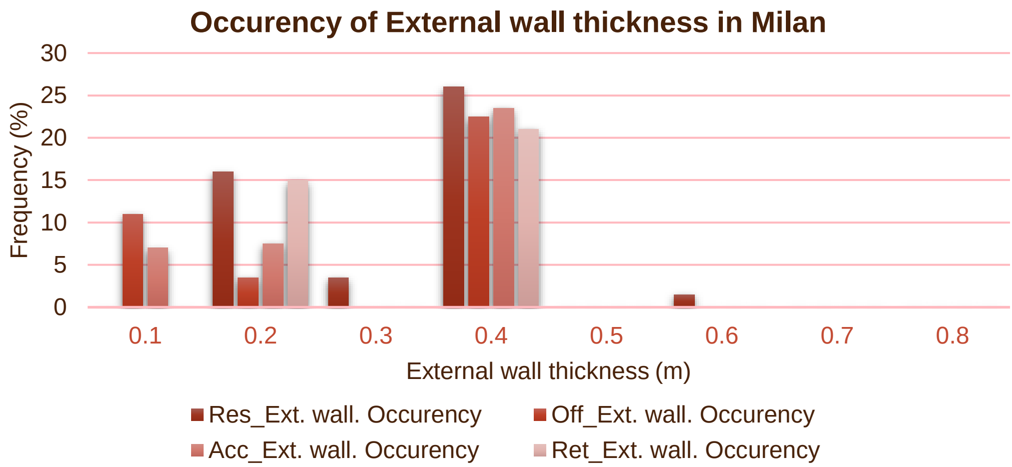


Figure 49. Frequency of external wall thickness in Milan

Figure 50 demonstrates the correlation between building elements' thickness and successful designs' overall energy load. A noticeable tendency is using 0.4 m for wall thickness, which leads to a decreased energy load. Designs with thicker roof and ground floor parts, such as 0.7 and 1 meter, tend to have higher energy requirements. It helps to evaluate the impact of global warming potential on the thickness of building elements, which also affects the overall energy load. Furthermore, observations show that designs with 0.2-meter wall thickness frequently have significant energy loads, which are most likely due to a high window-to-wall percentage that causes overheating.

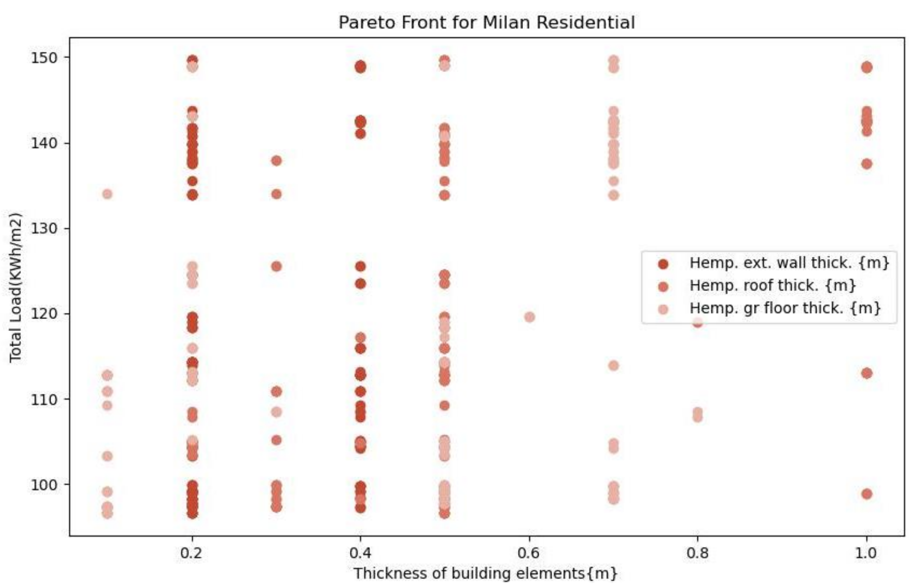


Figure 50. Pareto Front for Milan Residential. Relationship between Total Energy Load and thickness of building elements

Similar to Milan, Oslo's BREEAM-compliant wall thicknesses are predominantly 0.4 meters across all functions, with 0.2 meters being particularly common in lodging. However, as previously said, the office function lacks viable solutions.

Figure 52 shows that all designs fulfilling daylight criteria have the highest energy usage. Optimized designs often lie between 130 and 200 kWh/m^2, while nearly all daytime successful outcomes exceed 190 kWh/m^2. This issue is most likely due to a high wall-to-window ratio, which causes significant heat loss during the cold months.

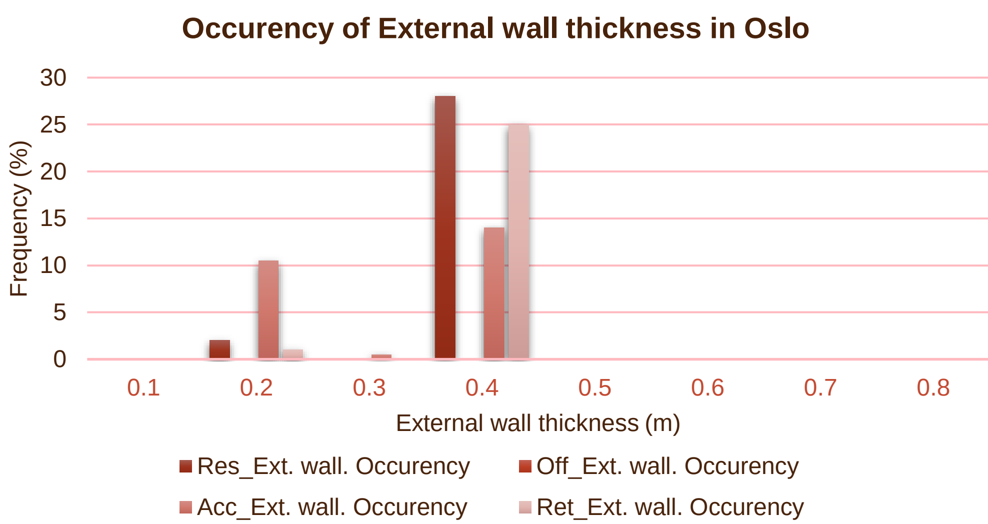


Figure 51. Frequency of external wall thickness in Oslo

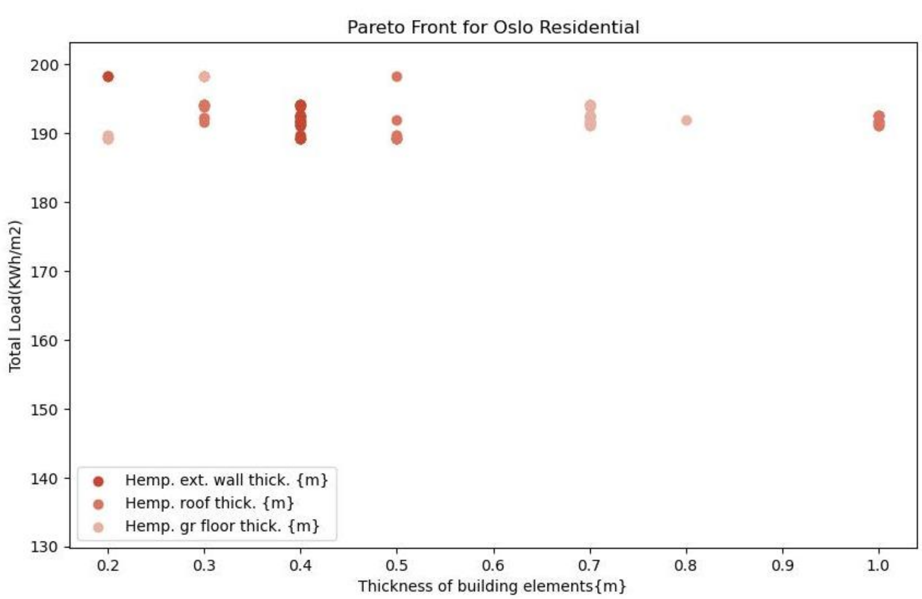


*Figure 52.*Pareto Front for Oslo Residential. Relationship between Total Energy Load and thickness of building elements

In Cairo, wall thicknesses vary, with 0.1 meters preferable for residential purposes and 0.4 meters for other purposes. The office function has a variety of thicknesses for external walls, with 0.4 meters being the ideal and 0.2 and 0.1 meters being the next best alternatives. Figure 54 depicts the various thicknesses of building elements and their association with energy demand. Once again, effective daylight models have greater energy demands, most likely due to overheating difficulties. Nevertheless, thinner elements are preferred for external walls over those for the ground floor and roof.

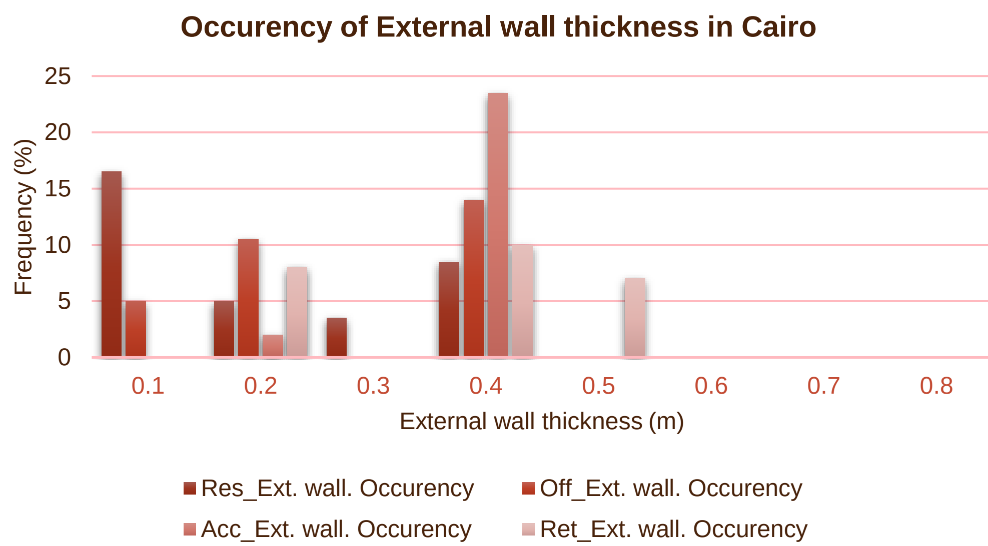


Figure 53. Frequency of external wall thickness in Cairo

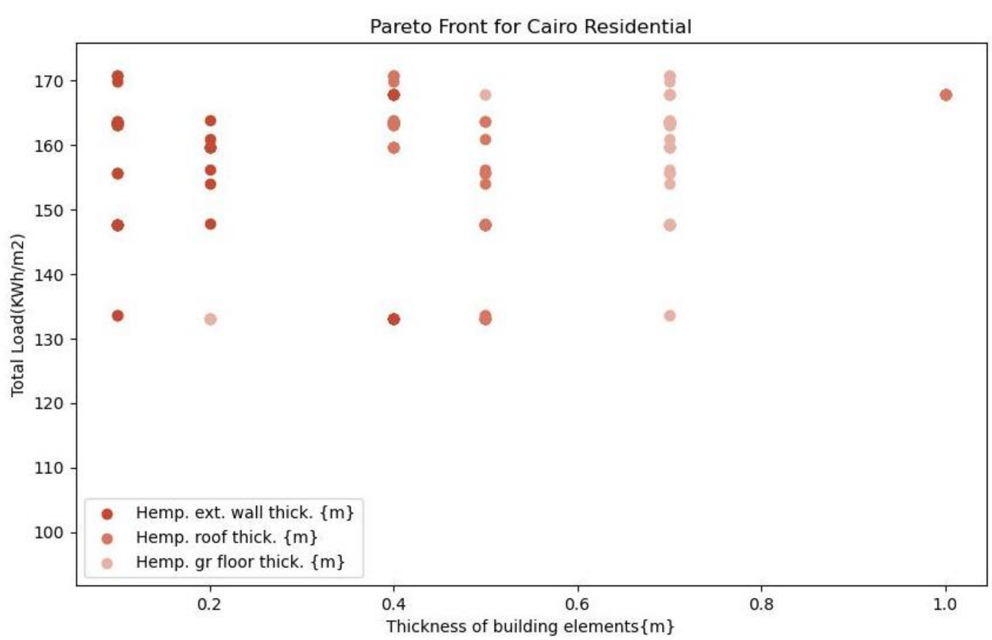


Figure 54. Pareto Front for Cairo Residential. Relationship between Total Energy Load and thickness of building elements

In Singapore, the most promising wall thickness is 0.2 meters, followed closely by 0.4 meters. As previously observed, successful designs tend to demand larger energy loads than unsuccessful designs, with successful designs often starting at 190 kWh/m^2 despite a minimal demand of 160 kWh/m^2. Compared to other places, Singapore prefers thinner roof and ground floor features, with 0.4 and 0.5 meters being the most optimum. However, Figure 56 shows that changing the thickness has no substantial effect on the energy demand.

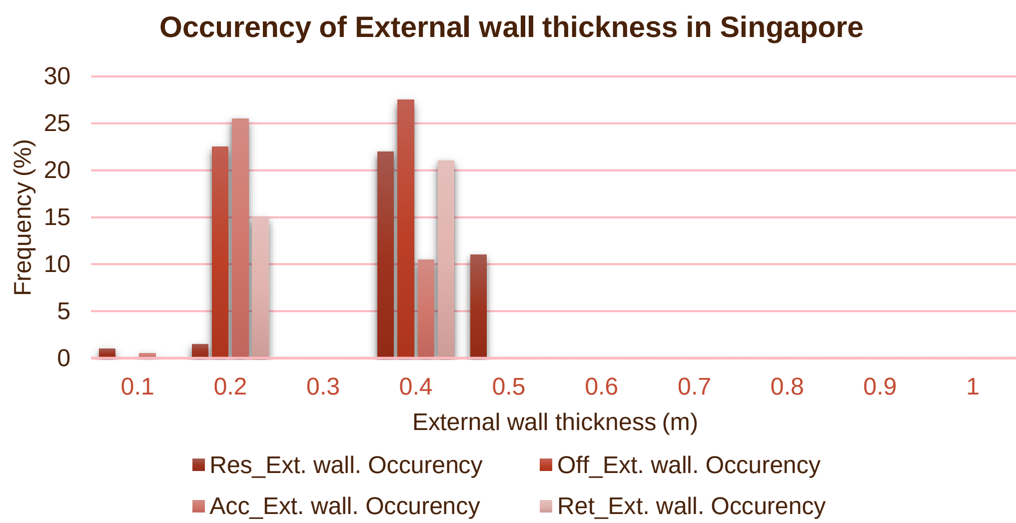


Figure 55. Frequency of external wall thickness in Oslo

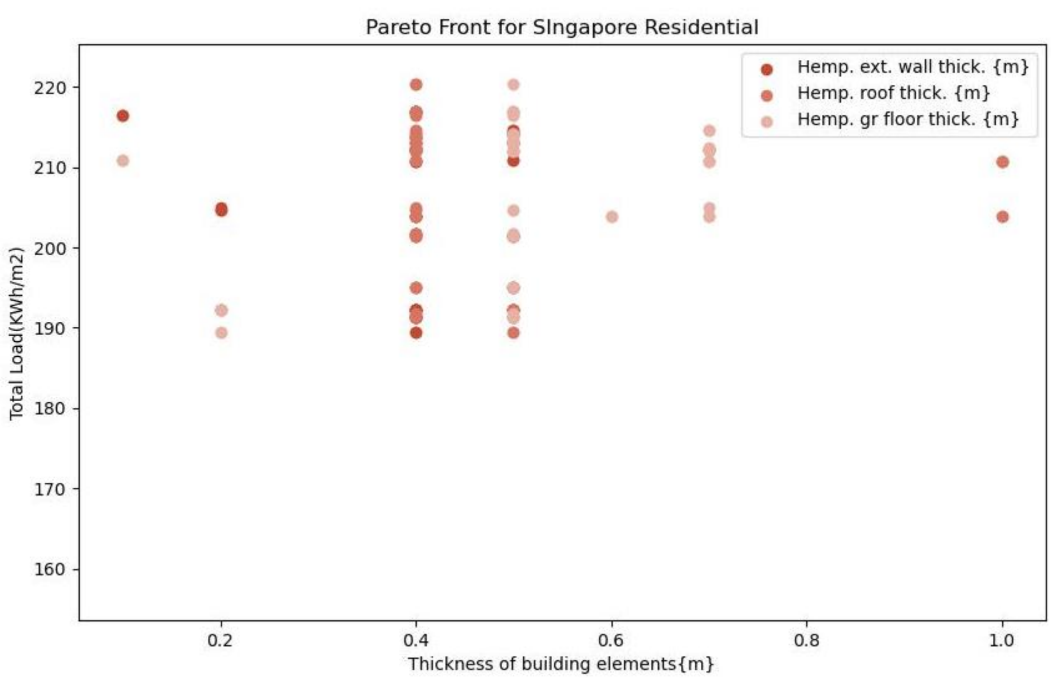


Figure 56. Pareto Front for Singapore Residential. Relationship between Total Energy Load and thickness of building elements

Benchmarks

To validate the outcomes, benchmarks, and typical average energy demand statistics were gathered for each region. Most of the standards apply to residential structures in various climates.

- Oslo: According to the Norwegian National Building Code, the Norwegian building stock ranges in age, which has an impact on energy usage. The code indicates that newer buildings' calculated specific energy demand (kWh/m2) decreases. Small residential buildings can reach yearly energy demands ranging from 389 to 107 kWh/m2, whereas apartments can achieve 313 to 92 kWh/m2. Newer builds follow the regulations described in TEK17 and TEK10. Most buildings belong to energy classes E, F, and G, which need higher energy usage (Møre, 2022) Based on Norwegian statistics, the average energy consumption of residential buildings in Oslo in 2012 was 166 kWh/m2, complying with the criteria of the National Building Code (Energy Consumption in Households, 2014).
- Milan: According to European static analysis, residential buildings in Italy consume an average of 134 kWh/m². This amount changes with the age of the building (Eurostat, 2021). The energy consumption of residential buildings in Milan ranges from 28 kWh/m² to 277 kWh/m², depending on their energy class and age. Almost 90% of these structures are classified as E, F, or G, with annual energy demands ranging from 139 to 277 kWh/m². These findings are consistent with the data published by Eurostat (Mutani et al., 2023).
- Cairo: Unfortunately, existing data on the energy demand of Cairo's building stock is unavailable. The only known information is from a study outlining the results of an Egyptian effort aimed at attaining zero-energy buildings. This scenario assumes that residential buildings have an energy requirement of 54 kWh/m2. However, this is not a reliable source of comparison and may only be used as an estimate (Schimschar et al., 2020).
- Singapore: According to the Energy Market Authority, Singapore's average monthly household power use is 413 kWh, or around 62 kWh/m2 for an 80 m2 dwelling (Energy Market Authority, 2023). In comparison, the National Building Energy Benchmarks for commercial buildings are far higher. The average energy usage for medium-sized office buildings is 185 kWh/m2, hotels average 217 kWh/m2, and retail buildings average 326 kWh/m2 (BCA, 2021).

Location	Function	Benchmark 1 (kWh/m²)	Benchmark 2 (kWh/m²)	Model	
Oslo	Residential	389-107	166	134.85-198.2	✓
Milan	Residential	134	139-277	96.64-149.67	✓
Cairo	Residential	54*	-	96.76-170.81	X*
Singapore	Residential	62	-	158.6-220.3	X
Singapore	Hotel	185	-	272.1-326.7	X
Singapore	Office	217	-	66.88-110.98	✓
Singapore	Retail	326	-	163.0-112.2	✓

Table 18. Comparison between benchmarks and results of the optimization. * The benchmark for Cairo is to achieve zero energy building and not the regular energy load of a residential building.

Table 18 validates the model results by comparing them to the current benchmarks. The majority of the outcomes meet the set requirements, except for Cairo, where no benchmark exists. In Singapore, only office and retail functions produce valid results. For residential applications, the overall energy demand is much lower than the model results, indicating that more research and alternative processes are needed to evaluate whether hempcrete can be efficiently used in this environment.

For Milan and Oslo, the results are significantly lower than the typical energy demand of residential buildings in these regions, implying that hempcrete is viable for new buildings with low energy demand that adhere to European zero-energy building standards. However, hempcrete and passive design alone are insufficient; additional research and mechanisms are required.

7.6. Tool

An optimization process is a critical component in achieving optimal results for a certain purpose. However, the most crucial aspect of optimization is the comparison and analysis of outcomes, which allows for informed decisions about the optimal option, particularly during the early design stages. This method considerably decreases the time necessary to explore and simulate design changes when compared to standard approaches used by architects and engineers. Nonetheless, designing an optimization script might be difficult because it is strongly dependent on the user's skills and expertise. As a result, a user-friendly interface emerges as a valuable tool for speeding up results comprehension and supporting faster design iterations by offering architects and engineers solutions.

Human UI was created in 2016 by NBBJ Design Computation. It provides as a framework for developing user-friendly interfaces for Grasshopper scripts. The major goal is to create tools for designers or clients that hide the complexity of the Grasshopper interface. The interface integrates all aspects of the workflow, such as site information, general simulations, optimization outcomes, and comparisons. The design process is identical across both the interface and Grasshopper, with Human UI serving as the interface's front end and Grasshopper as the back-end control panel. This solution provides users with accessibility and ease of use while using Grasshopper's power and capability for computational design tasks.

Figure 57. Hemp Design user interface tab selection to guide through the workflow. Selection of time, location, function and efficiency achievement.

Users can adjust geometry based on their preferences using the interface's sliders and drop-down options. Users can easily pick site requirements including period, area, dimensions, floor height, and orientation. Future climate data can be applied for permanent projects that are required to be climate change-resistant, whereas present climate data can be used for more temporary projects or based on user preferences. In addition, the early design structure can be set by selecting the column span and factor, giving users more control and flexibility when designing their ideas. Subsequently The general geometry of the building is shown to the designer, allowing them to determine whether it meets their requirements. This illustration contains standard window-to-wall ratios and building element thicknesses. This approach allows the designer to visually analyse the design's compliance with their vision and specifications.

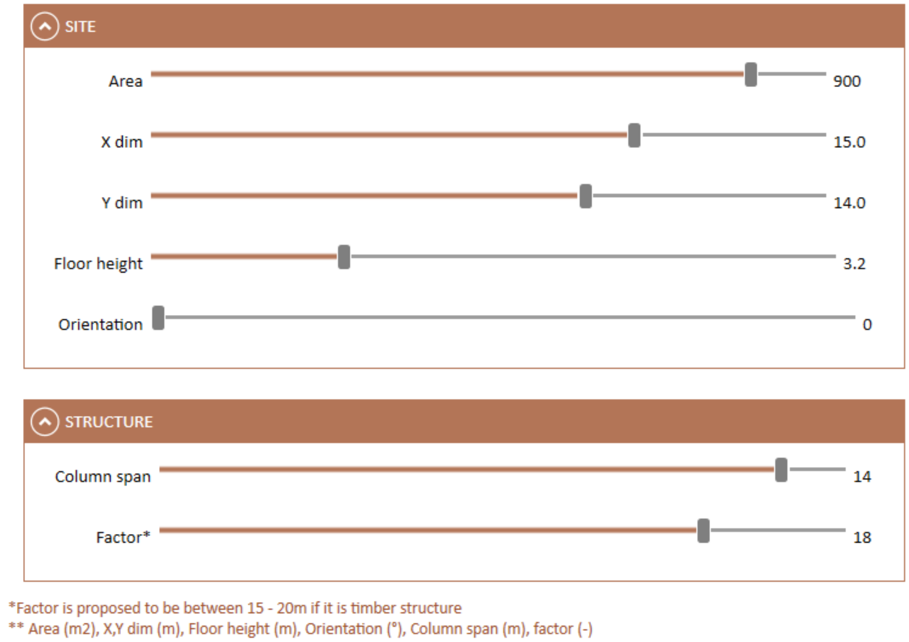
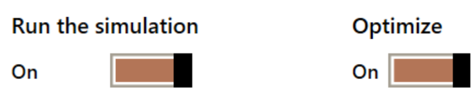


Figure 58. Hemp Design user interface site information selection.

The desired values are going to be proceed and optimized when the toggle button is on. The simulation button allows the EnergyPlus and Radiance to run the simulations, while the optimize allows the saved results to be processed and analysed.



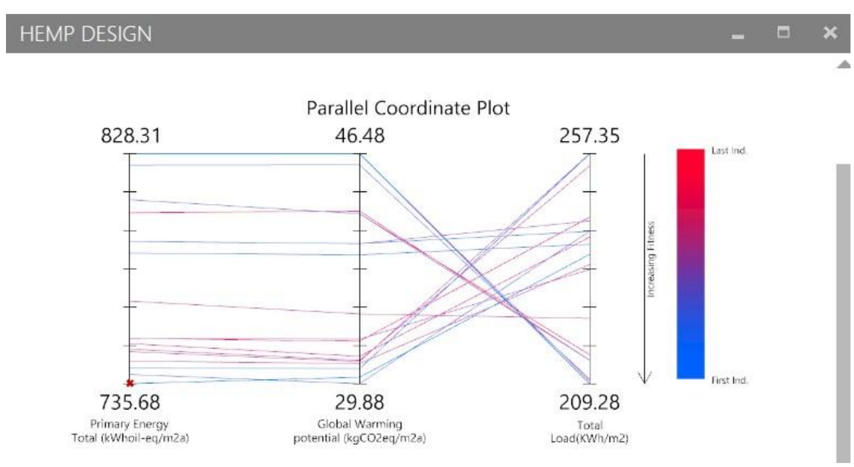


Figure 59. Hemp Design user interface Parallel Coordinate Plot results after the optimization.

The findings are taken from the appropriate Excel file, and a parallel coordinate map is created to show the link between the three objectives: primary energy, global warming potential (GWP), and total load. Users can then use a slider to select among the available possibilities (200), with the results displayed on the expander component. These statistics include the building's energy demand, Life Cycle Assessment (LCA) results, and BREEAM daylighting successes. The next tab includes a detailed presentation of the values that are used for the selected optimized design to achieve these results. This includes the envelope thickness, type, Hempcrete composition and the windows-blinds properties.

Figure 60. Hemp Design user interface Optimization results selection to analyze the different design efficiency.

Figure 61. Hemp Design user interface characteristics of optimized solutions tab

The most important part of the interface is the comparison tab, on which the user can select 4 different designs and compare their visualized results by checking diagrams. The diagrams include total energy comparison, GWP comparison and primary energy comparison. This is the part of the workflow where the user can actually see the difference between the designs and the relation between the energy and eco efficiency and choose the most suitable design.

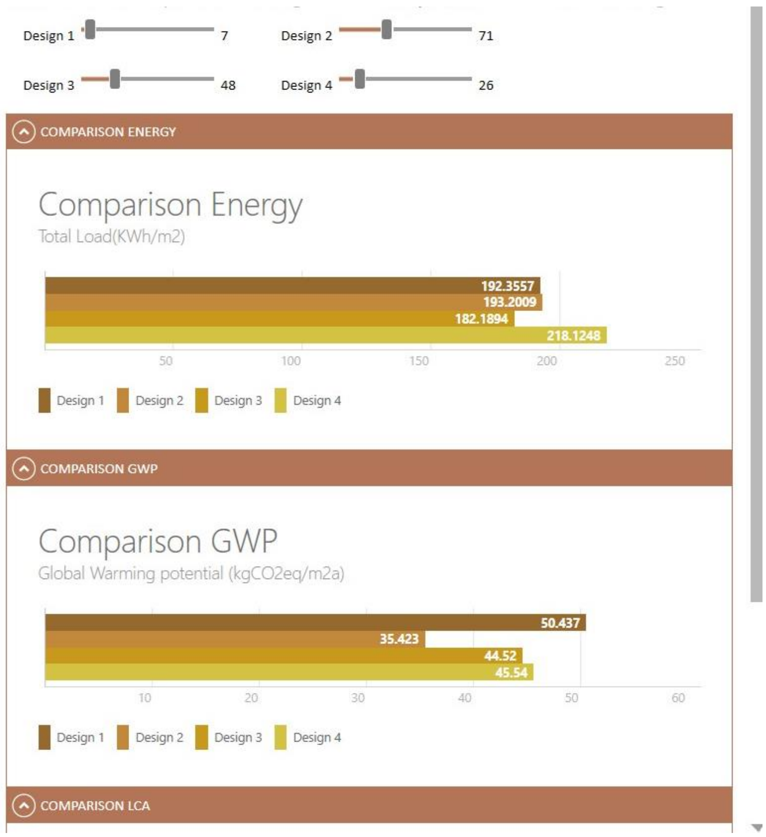


Figure 62. Hemp Design user interface Comparison tab on which the user can compare different designs and their outcomes.

Figure 63. Hemp Design user interface Final building visualization of envelope and structure

Finally, the chosen design is displayed, allowing the user to inspect either the building's envelope or structure. A pull-down list allows the user to pick various building parts (walls, floors, roof, ground floor, windows, and blinds) and examine their specific attributes. This page is intended to simplify the data, but the "Characteristics of Optimized Design" tab has complete construction specifics for the building.

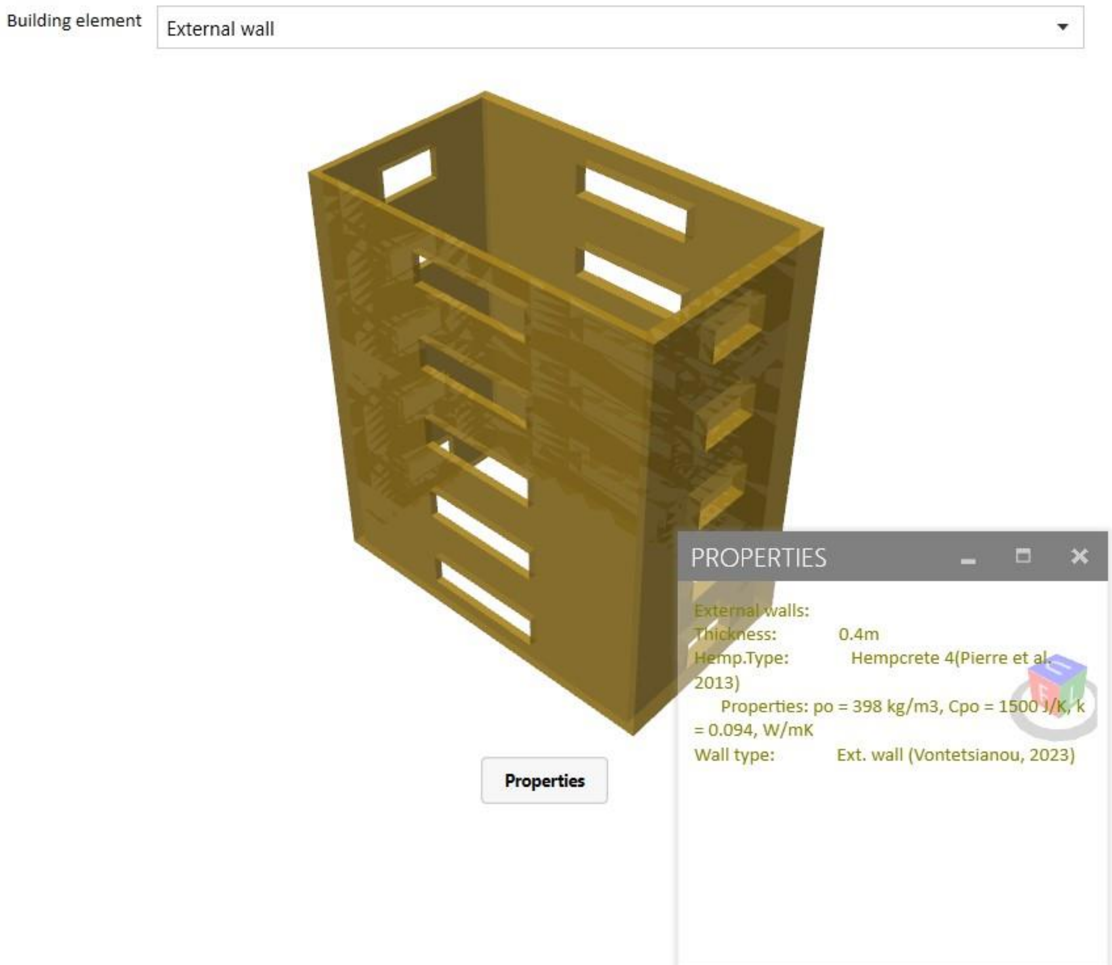


Figure 64. Hemp Design user interface Final building elements visualization and their properties

7.7. Conclusion

The workflow highlights providing users with data regarding building performance and sustainability at the early design stages, with a special emphasis on the usage of hempcrete. It generates a variety of designs capable of meeting low energy requirements and getting closer to Paris-proof buildings. To meet BREEAM criteria, several hempcrete compositions, construction types, and thicknesses are proposed, as well as window-to-wall ratios (WWR) and blinds.

Traditionally, architects have had to consult several programs to examine building energy performance, Life Cycle Assessment (LCA), and daylighting, which can complicate optimization and result comparison, resulting in longer time consumption. However, using this process, architects and engineers can acquire results by entering fundamental building dimensions at the early design phase, allowing for the identification of ideal solutions through contemporaneous result comparison and analysis.

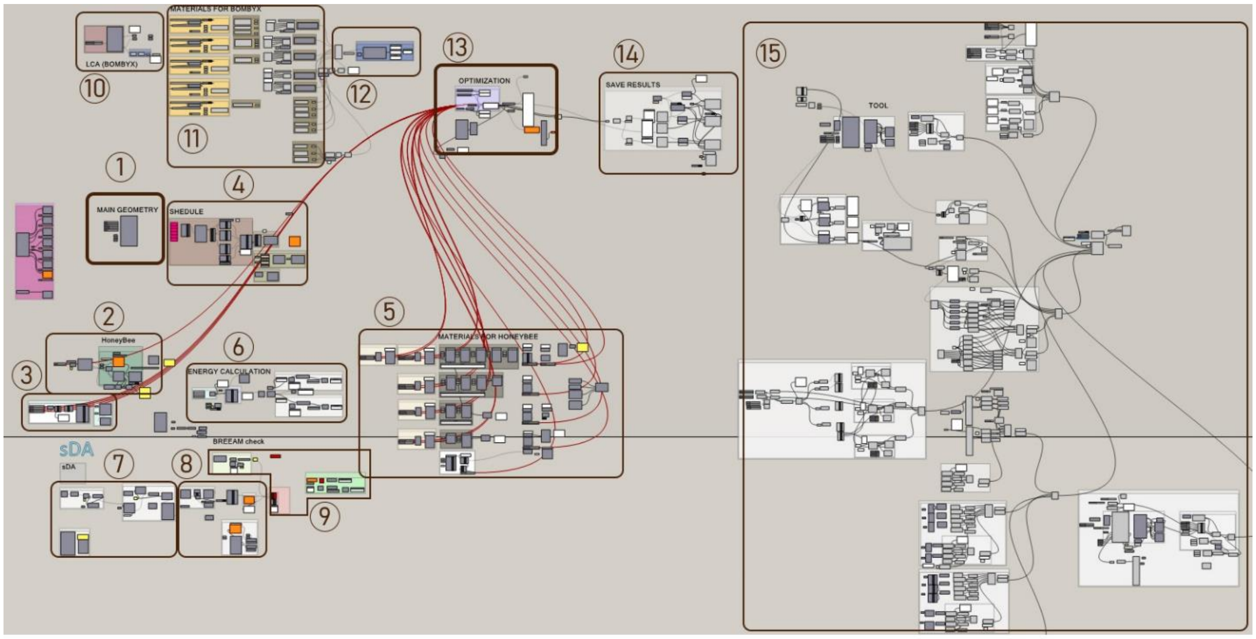
In a following phase, the findings can be saved and integrated into the interface, making it easier to display the designs to clients and discuss potential solutions. Allowing users to create and evaluate performance during the early phases greatly shortens the time required to attain optimal solutions. This allows for a greater emphasis on other design components of the building, such as the client's experience within it, its integration with the surrounding area, and its overall conceptual consistency. Streamlining the design process and delivering fast feedback on performance allows designers to devote more time and attention to these key aspects of architectural development.

Chapter 7.5 and the actual energy consumption of each location show that the workflow works well, producing values comparable to the current situation. Nevertheless, the data for residential structures and hotels in Singapore are substantially higher than average. This mismatch emphasizes determining whether this material is suited for usage in tropical environments. Furthermore, it is critical to investigate whether architectural design changes or the implementation of various energy systems can influence energy demand, bringing figures closer to the current scenario.

Figure 65 illustrates the full Grasshopper script. Following the sequence of numbers reveals how the script was created, which mirrors the procedure stated in the workflow. The majority of the script is divided into clusters to keep it organized and clear. Simulation outcomes are used as objectives in the optimization process, while all values (represented by red wires) serve as genes. This simplifies the operation, storage, and eventual visualization of results.

This method certainly has applications for architectural design. The general model is an effective tool for understanding how energy consumption and daylighting affect the Global Warming Potential (GWP) and, as a result, a building's carbon emissions. However, it is important to note that it does not exactly correlate with real-world settings because it does not include all areas of architectural design. In practice, site-specific optimization should take into account internal partitions as well as surrounding buildings influence. While incorporating these additional criteria into the workflow is possible, it may need more time for optimization. Nonetheless, the primary goal is to equip architects with a workflow that prioritizes early-stage design for sustainable structures.

Finally, the synthesis of the final envelope design, including windows and shades, is an essential part of architectural practice. Additionally, material selection must take into account issues such as availability and geographical compatibility. Importantly, these variables should be supplemented with financial optimization considerations to ensure the profitability and practicality of proposed design solutions. Recognizing these concerns allows architects to navigate towards comprehensive and sustainable design solutions.



1. Geometry definition
2.Create room
3. Windows and blinds
4.Shedule and program
5.Material and construction type
6. Energy simulation
7.Geometry for daylight
8.Daylight simulation
9.BREEAM check
10.Prepare geometry for LCA
11.Materiality for LCA
12.LCA simulation
13.Optimization
14.Save results
15.Interface

Figure 65. Overall Grasshopper script for the workflow.

8. Conclusion and Reflection

The last section focuses on the results of the study and the reflection, while also provides future improvements proposals.

This study focuses on developing a workflow to assist architects and engineers during the early design phases in exploring multiple design options and comparing their performance in terms of daylight, energy usage, and carbon emissions, with the ultimate goal of achieving modern sustainable design. This research digs into designs that integrate hempcrete in every building element, with optimization based on hempcrete composition, construction type, and thickness. The parametric model considers numerous functions and locations based on user preferences in addition to efficiency concerns. The findings provide both computational information and performance measures, which are useful for implementing performance-driven designs.

8.1. Research question

How can a computational workflow optimize hempcrete's integration in various types of buildings across diverse climates, with the objective to support preliminary designs that achieve high energy performance and minimize global warming potential?

The proposed multi-objective optimization approach has the advantage of examining numerous design objectives to find the optimal approach by evaluating different fitness values. It incorporates hempcrete into a variety of architectural features, including walls, floors, and roofs, while taking into account varied hempcrete compositions to determine their impact on the results. Taking into account variables like overall Global Warming Potential (GWP) results and thermal insulation properties, the algorithm defines the most effective hempcrete construction types for each element. The process also optimizes the thickness of hempcrete in each building part to obtain maximum performance and daylight while reducing CO_2 emissions.

Furthermore, the model incorporates climate-specific data to account for a wide range of environmental factors, such as temperature, humidity, and solar exposure. Additionally, the algorithm includes multiple function criteria for various building applications, such as schedules, ventilation, set points, and internal gains. User preferences and design limitations are easily integrated into the workflow to ensure they are consistent with architectural aesthetics and functional needs. Architects and engineers receive visualization tools and performance feedback to help them make informed decisions throughout the preliminary design stages.

Sub-questions

How can multi-objective optimization identify the ideal hempcrete composition for thermal conductivity in different climates?

A multi-objective optimization can be used for several fitness values to find the best solution depending on design requirements. By providing a location, the optimization method determines the most optimal solution for the building's energy needs. The simulation considers the thermal conductivity of the hempcrete type as a crucial aspect in energy simulation, in addition to thermal capacity and density. Given that the optimization attempts to reduce energy usage, it can determine the optimal hempcrete mix with the best thermal conductivity.

As proven in Chapter 7.5, climate data has a substantial impact on the choice of hempcrete solution, even for the same building and function. Lower thermal conductivity is sought in colder locations, resulting in the widespread use of hempcrete with these qualities. In contrast, warmer climates require lower thermal resistance, necessitating the use of appropriate hempcrete kinds. However, thickness is an important factor in selecting the best material-element mix for each climate. Finally, in warmer regions, active cooling, internal loads, and solar heat gains impact the selection of the appropriate Hempcrete type.

Which ways can a workflow define the impact of hempcrete thickness on thermal and visual comfort in buildings across different regions?

To determine the effect of hempcrete thickness on thermal and visual comfort in constructions across locations, the workflow involves computational simulations and optimizations. This is the approach:

1. Data collection:
    - Local climate evaluation: Collection of climate data (epw) from 4 climate regions.
    - Gathering of information about hempcrete's thermal properties (thermal conductivity, thermal mass, density, etc)
2. Simulation and Optimization:
    - Energy performance simulation by using EnergyPlus with varying hempcrete thicknesses on different building elements.
    - Daylight simulation by utilizing Radiance to evaluate natural light distribution and check BREEAM standards.
    - By optimizing the model, thermal and visual comfort are equalized.
3. Comparative analysis
    - An interface which summarizes the results with a parallel plot diagram can help to compare the results. Furthermore, the tab with the comparison can be used by an engineer or a designer to analyze the results and actually investigate how thickness and other parameters perform in terms of thermal and visual comfort.

As previously stated in Chapter 7.5, the thickness of hempcrete in the building elements is a significant factor impacting energy performance and global warming potential (GWP). Figure 66 shows that in Oslo, BREEAM-successful designs have a 0.6 window-to-wall ratio (WWR) and an external wall thickness of 0.4 meters. Similar findings were reported in Milan, with a WWR ranging from 0.55 to 0.6 and an external wall thickness of 0.4 meters, followed by 0.2 meters. This is most likely owing to the low sunshine hours throughout the winter, especially in Oslo, which necessitates wider windows to maximize solar exposure. Cairo has a wider variety of findings, with WWRs ranging from 0.35 to 0.65 and thinner walls ranging from 0.1 to 0.2 meters. In contrast, in tropical regions such as Singapore, a WWR of 0.4 coupled with a wall thickness of 0.4 meters can provide sufficient daylight.

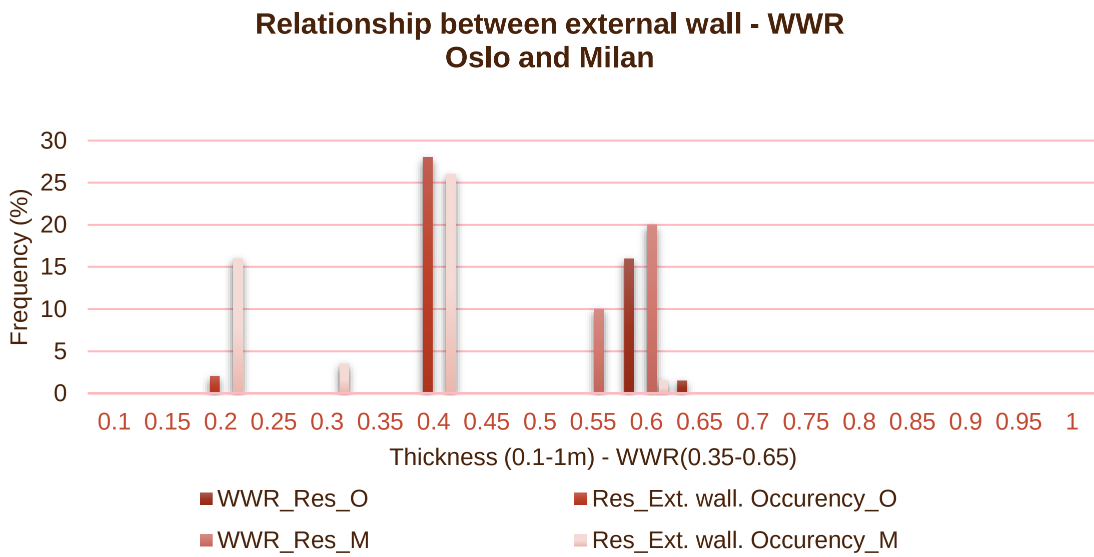


Figure 66. External wall thickness - WRR concurrency in Oslo and Milan Residential.

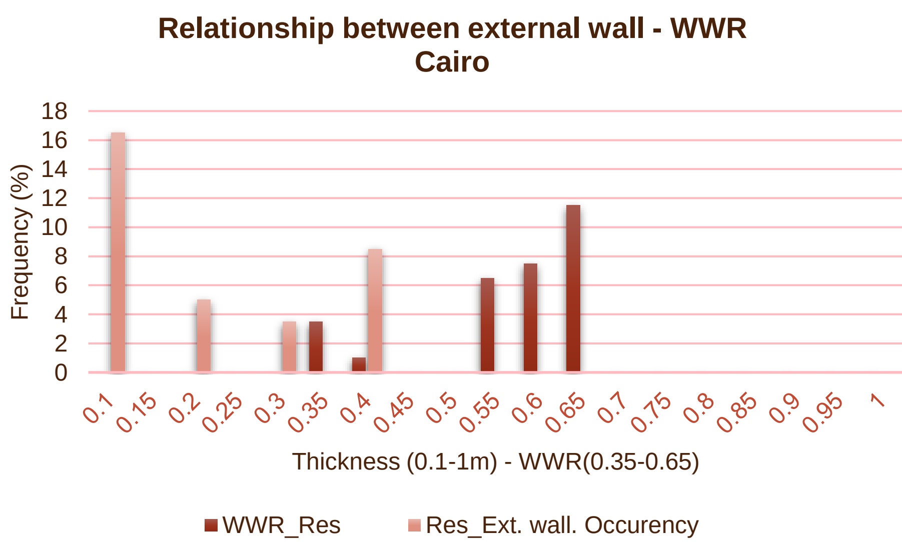
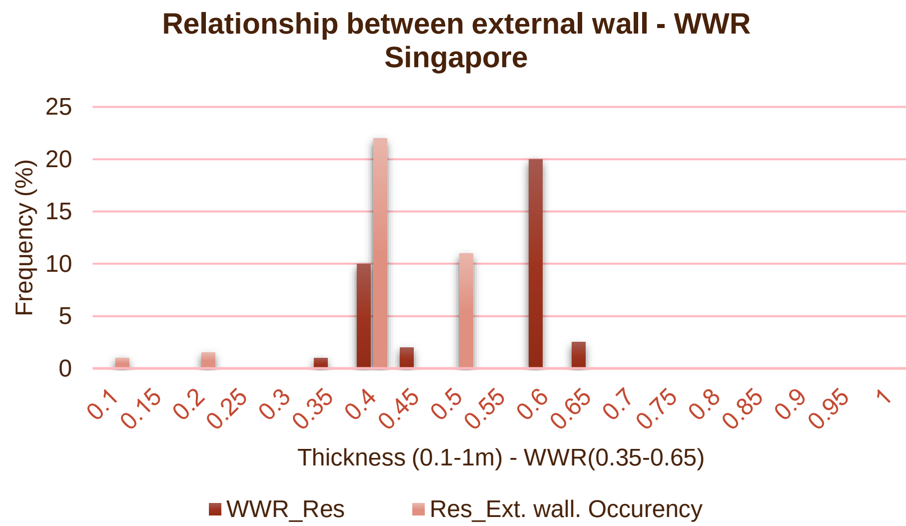


Figure 67. External wall thickness - WRR concurrency in Cairo Residential.



These findings indicate that thinner walls are unusual in colder places due to greater energy demands, forcing the usage of thicker walls during the optimization. Nevertheless, walls thicker than 0.4m did not enable enough sunlight to flow through the windows in most cases. A similar trend is seen in Cairo, with the exception that thinner walls are more common due to the high temperatures, and even smaller window-to-wall ratios were able to meet BREEAM criteria.

How may operational energy and global warming potential optimization influence hempcrete thickness in different contexts?

As already stated in Chapter 7.5, wall and roof thickness are major factors influencing energy demand and global warming potential. Increasing the thickness of external walls and roofs decreases energy consumption while increasing GWP. The optimization engine seeks to minimize energy demand and GWP, hence the most commonly utilized results are those that best accomplish this goal.

In climates such as Oslo and Milan, successful BREEAM-compliant designs typically have a wall thickness of 0.4 meters, with variances depending on the building use. Oslo's cooler climate, combined with reduced sunshine hours in the winter, requires wider windows for daylight, which has an impact on energy usage and heating needs. Simultaneously, larger window areas result in a higher GWP. Milan, although having more sunshine hours, prefers 0.4-meter-thick walls, showing a compromise between insulation and daylight requirements.

In contrast, tropical climates such as Singapore and Cairo show distinct tendencies in hempcrete thickness optimization. Cairo's greater range of wall thicknesses (0.1 to 0.4 meters) reflects the need to accommodate both daylight and cooling demands as temperatures rise. Singapore's successful designs demonstrate a tendency for thinner walls, roughly 0.2 meters, to balance sunshine with the high cooling demands of tropical climates. Despite this, successful designs in these regions frequently have greater energy demands, beginning at 190 kWh/m2, emphasizing the difficulty of attaining energy efficiency while fulfilling daylight needs.

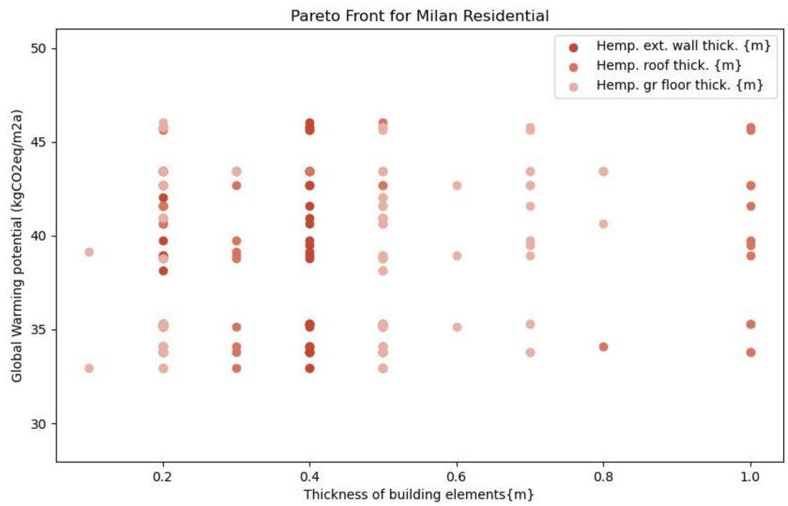


Figure 68. Pareto Front for Milan Residential. Relationship between Global warming Potential and thickness of building elements

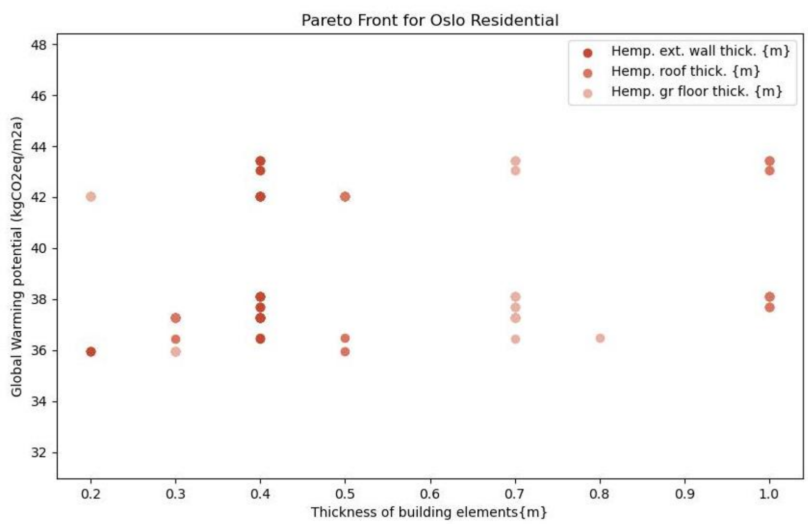


Figure 69. Pareto Front for Oslo Residential. Relationship between Global warming Potential and thickness of building elements

Figure 68, Figure 69, Figure 70, and Figure 71, which illustrate the relationship between GWP and building element thickness, indicate that there is no substantial impact. In Milan, the thickness of architectural materials varies, yet the global warming potential remains constant. For example, choices with 0.4-meter-thick walls have high GWP values, such as 45, whereas the same thickness can have values as low as 35. Similar findings are seen in every region, with Cairo being the most noteworthy example, where a 0.1-meter-thick wall can have a GWP of more than 40. Similar findings are seen in every region, with Cairo being the most noteworthy example, where a 0.1-meter-thick wall can have a GWP of more than 40. Although thinner elements have a lower GWP, the effect is not substantial, suggesting that other factors, such as windows or element construction, have a greater influence on GWP.

It is also worth noting that hempcrete has relatively low embodied energy and is considered a carbon-positive material, so its thickness may not have a substantial impact on the building's carbon footprint. This feature underscores the importance of taking into account other design and construction components while optimizing for GWP and energy performance.

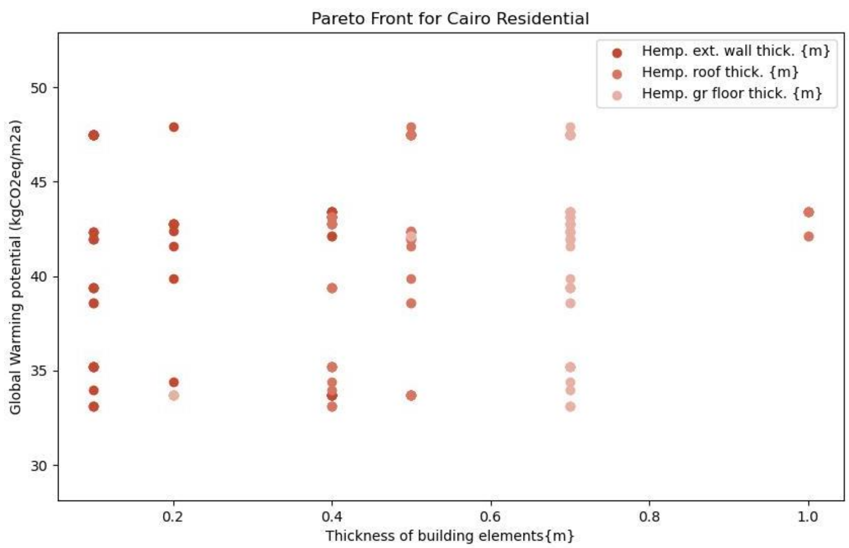


Figure 70. Pareto Front for Cairo Residential. Relationship between Global warming Potential and thickness of building elements

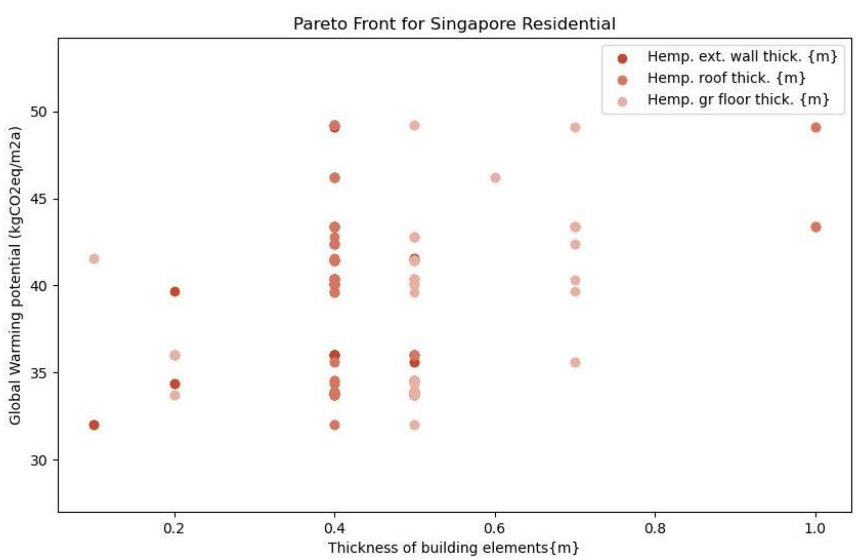


Figure 71. Pareto Front for Singapore Residential. Relationship between Global warming Potential and thickness of building elements

How can a computational workflow be used to establish a balance between energy efficiency and occupants comfort preferences, in hempcrete buildings?

A multi-objective workflow can address multiple objectives, some of which may be contradictory. As a result, this study focuses on achieving a balance between energy economy and daylight provision while complying with European comfort standards. The model is adjusted to achieve good or high efficiency in terms of indoor comfort, as shown in Table 11 and Table 12, in order to meet BREEAM daylight standards while minimizing energy use. The obtained results produce outcomes characterized by low energy consumption and compliance with daylight criteria, hence contributing to the development of high-performance buildings with appropriate occupant comfort levels.

In which way can this workflow be evolved into a useful tool for reducing the required time during the first design stages and promote the use of hempcrete?

While still in its early stages, this workflow shows potential for architects and engineers looking for quick insights on hempcrete construction, optimal solutions, and environmental impact. Individuals can gain access to ideal design solutions throughout the early stages of development thanks to Human UI's user-friendly interface. The introduction of hempcrete datasets into the workflow improves accessibility and knowledge distribution in the construction industry, saving research time for implementation. On top of that, the presence of many aspects required for Paris-proof structures makes the workflow more appealing to customers, potentially boosting hempcrete integration into other markets.

8.2. Workflow limitations

The workflow has constraints and boundary conditions that can affect the output. This includes:

- Consider the entire floor area as a single room with no interior partitions. Although the implemented core can be used for energy and daylight simulations, it is not considered during the optimization process. As a result, after choosing a design, the simulation may need to be repeated separately to incorporate the core and deliver final findings.
- The use of hempcrete in Honeybee does not account for its hygroscopicity, which may result in higher thermal and cooling demands than in real-world circumstances.
- The absence of internal walls causes increased internal airflows, which can have an impact on simulation accuracy.

- The lack of Computational Fluid Dynamics (CFD) analysis restricts the assessment of natural ventilation to one-sided effects.
- Climate data collected at airports may not adequately reflect circumstances in the city canter, where the building is likely to be located, thereby leading to differences in simulation results.
- The absence of mechanical systems in the Life Cycle Assessment (LCA) may result in an overestimation or underestimating of environmental impacts, depending on the systems that are ultimately implemented.
- Building shapes are limited to rectangular forms because the emphasis is focused on optimizing the building envelope rather than architectural design complexities.
- Time restrictions resulted in a limited database within the interface. Given the extensive computing needs, data generation for each building with specific attributes and 200 alternatives would take about two hours. As a result, the present interface is pre-populated with data for a certain building type and function across multiple climates to aid in initial testing and review.
- The results indicate whether the energy performance fulfils the BENG criteria. However, this is only used as a reference for climates near to the Netherlands. It is vital to highlight that the findings differ greatly by country, therefore BENG criteria cannot be used to properly compare outcomes across areas.

8.3. Workflow key aspects

Hempcrete integration

The integration of hempcrete datasets into the workflow improves accessibility while also facilitating the exchange of information within the building industry. By combining extensive datasets, the workflow accelerates the research process, saving critical implementation time. Additionally, including the many features required for Paris-proof architecture, which increases the workflow's attraction to clients. This holistic strategy handles not just sustainability and energy efficiency, but also ensures compliance with modern construction codes. As a result, the workflow has the potential to significantly accelerate hempcrete integration into various industries, opening the path for more sustainable and environmentally responsible construction methods.

Parametric modelling

The workflow combines human input with data-driven geometric modification to enable multi-objective comparison and optimization processes. The methodology allows for easy and data-driven design explorations by utilizing parametric modelling and climatic simulations with the Grasshopper and Honeybee plugins. This connection reduces the need for constant redesigns, which improves the design process and increases efficiency.

Consideration of future climate data

Reducing energy use through smarter, more energy-efficient solutions is critical for mitigating the effects of climate change, as rising CO2 levels increase its effects. Climate-proof designs incorporate local climate variables into building functionality to maximize energy management by combining energy gains and losses to improve thermal comfort. With climate continually changing and global warming increasing the consequences, it is critical to consider future climatic conditions when constructing buildings that will endure several decades. Integrating climate morphing into the design process enables the use of climatic forecasts for future years, such as 2080, guaranteeing that hempcrete construction is successful throughout a building's life cycle while anticipating the effects of climate change. Nevertheless, there is an option to use current climatic data for temporary constructions, which allows the user to get the most efficient layout for a shorter period.

Compliance with standard

The workflow aims to inform the user about the design's potential compliance with existing standards and certifications, particularly addressing specific factors such as daylight, as described by BREEAM. Given the BREEAM certificate's strict benchmarks, early validation of complying with these requirements can help to produce a final design that is both efficient and comfortable.

User-friendly interface

The Human UI interface improves accessibility and usability, enabling designers and engineers to interact the workflow and explore design alternatives more efficiently. To achieve optimal outcomes, the user can choose from several functions, climates, efficiency levels, and overall building proportions. Following that, the user can examine, compare, and select the optimal solution.

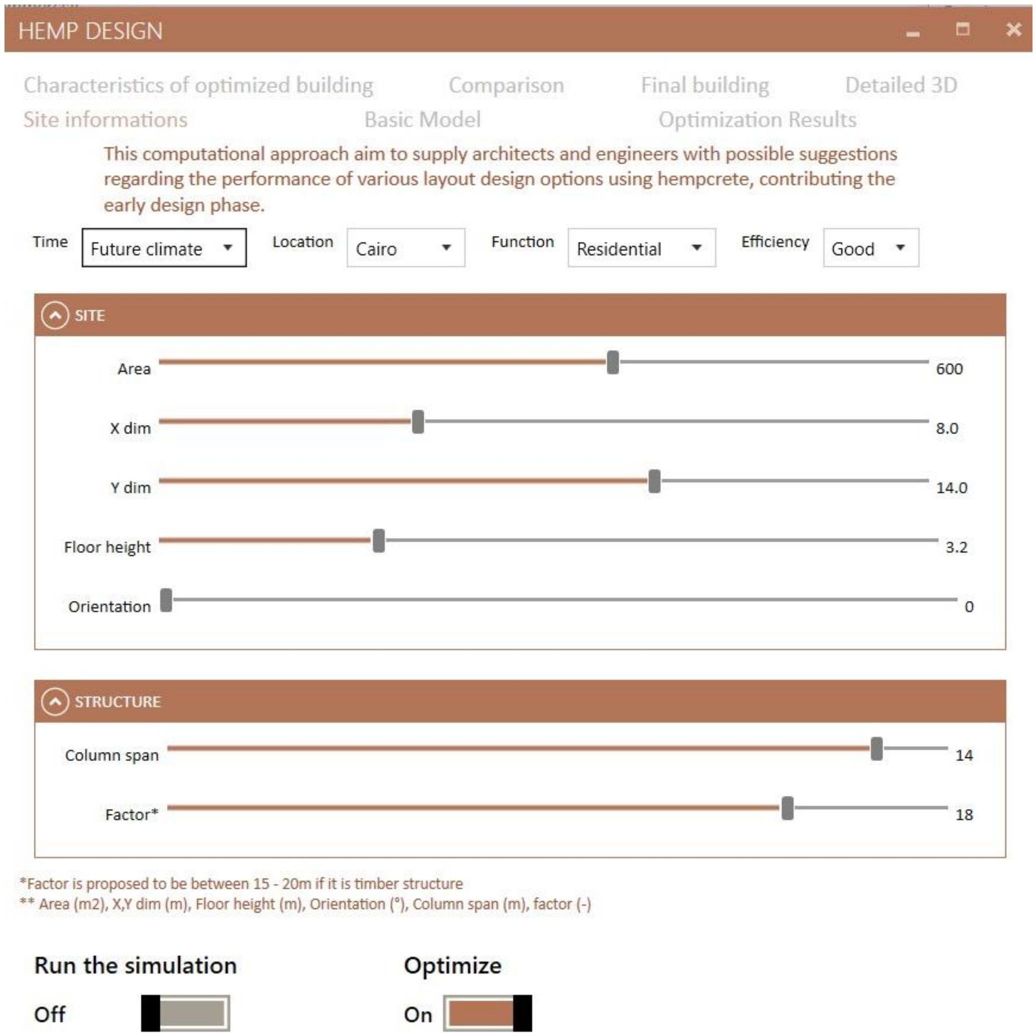


Figure 72. Hemp Design interface made by using Human Ui plug-in of Grasshopper

8.4. Reflection

The goal of this research was to provide an efficient optimization workflow for energy-efficient and environmentally friendly hempcrete structures that could be used in the early stages of design. The goal was to suggest ideal designs for a wide range of buildings and climates. As part of the master's degree in Architecture, Urbanism, and Building Sciences, the thesis focuses on the early stages of the design process, with the goal of providing architects with insights into their designs and contributing to the design process. This workflow connects architects and engineers, combining design and technological considerations.

Given its objective, this topic is strongly tied to Computational Design and Climate as part of the Building Technology program. It incorporates efforts to reduce energy consumption and carbon emissions in the building sector by promoting carbon-positive materials and creating related workflows. When combined with parametric modelling and optimization techniques, these attempts show promise for preliminary designs.

Graduation process

The methodology used in this study was guided by a thorough literature evaluation, which helped shape and influence the research. While there was much of research on multi-objective optimization methods for windows and layouts, the difficulty was a lack of equivalent studies focusing on hempcrete. Specifically, there was a shortage of research on multi-objective optimizations with hempcrete or optimizing hempcrete thickness within wall components. Despite these limits, the previous examples served as great sources of inspiration, providing ideas that eventually helped the development of a workflow customized to the specific needs of hempcrete optimization. Thus, the research approach was useful in both data collecting and the subsequent implementation of findings into the process, demonstrating the vital role.

Research and design are interconnected processes that each influence and shape the other in a dynamic relationship. In the context of this study, the methodology involves obtaining current knowledge on hempcrete buildings, types, and standards such as BREEAM and BENG, as well as EU comfort standards. Despite an extensive amount of literature on hempcrete, particularly on construction techniques in Europe, there was a noteworthy lack of relevant information. Aligning with European norms became difficult due to the accessible literature, which was often in French or from Australia. Subsequently, simulation setup and optimization became critical components of the research process. The initially designed procedure was modified in response to research findings. Significantly, the front-end user interface evolved as an essential part of the workflow, allowing for easier comparison of design ideas. As a result of the study findings, data were acquired and used to construct the workflow, highlighting the fundamental link between research and design in improving knowledge and practical applications.

Societal impact

The findings have practical implications for architectural design, especially when it comes to comprehending how daylighting and energy use affect buildings' carbon emissions and global warming potential (GWP). It is important to recognize that the approach might not accurately replicate real-world environments because it does not account for all aspects of architectural design. In order to maximize the practical applicability, site-specific optimizations need to take into account elements such as neighbourhood impacts and internal partitions, which could necessitate more time for optimization.

The innovation is partially the creation of a user interface that enables engineers and architects to quickly produce initial designs that incorporate sustainable features, such as eco-efficiency and energy efficiency. With the use of this application, users may create optimum designs in a matter of hours as compared to days by having access to an extensive library of hempcrete materials and construction techniques. Through the use of this interface, practitioners can accomplish sustainable goals and accelerate the first design phase, which is a major step forward in the integration of sustainable practices into architectural and engineering workflows.

The project has practical applications, particularly in the field of sustainable building design. The creation of an optimization workflow customized to hempcrete constructions provides architects and engineers with a valuable tool for incorporating eco-friendly materials into the early stages of design. While the anticipated innovation of adding hempcrete optimization has been realized to a significant level, more validation through real-world applications may increase its usefulness. Nonetheless, the initiative makes a significant contribution to sustainable development by increasing energy efficiency and lowering carbon emissions in the built environment.

The project has an impact on sustainability from an environmental, economic, and social perspective. Through the use of eco-friendly and cost-effective options, the project promotes economic development by reducing the environmental impact of construction operations and giving priority to materials that reduce carbon emissions, such as hempcrete, and optimizing building designs for energy efficiency. Furthermore, encouraging ethical architecture techniques that put social welfare and environmental stewardship first highlights ethical considerations.

The project's socio-cultural impact is in line with larger social activities that aim to prevent climate change and further sustainable development objectives. The project's integration of natural resources and climate-responsive design principles helps to a greater cultural change towards environmentally conscious and sustainable building practices. Ultimately, the project has a huge impact on architecture and the built environment by offering cutting-edge techniques that put sustainability first and steer architectural design in the direction of more environmentally friendly and eco-efficient solutions.

8.5. Future improvements

Enhanced database

Potential paths for future project improvements include the ongoing update and enlargement of the database about hempcrete materials and construction techniques. This improvement would ensure that the project stays up to date with the most recent developments in sustainable construction methods, as well as improve its practical application by embracing a wider range of options and guaranteeing relevance to evolving industry requirements.

Advanced parametric modelling

Future work on the project could focus on improving parametric modelling tools to allow for more complicated design explorations that will accommodate a wider range of architectural styles and project difficulties. Incorporating hempcrete hygroscopic analysis would further improve the project's accuracy in modelling material behaviour in a variety of environmental scenarios.

Site-specific

Including site-specific factors in the optimization workflow requires taking into account things like neighbouring impacts. This improvement makes sure that the design process takes into account the particular needs of each project area and matches real-world realities. Allowing users to choose any location in the world would also be an improvement, as this would allow the optimization method to adjust to various environmental situations and regulatory frameworks.

User interface enhancements

The goal of UI improvement is to consistently improve usability, accessibility, and user experience. Using machine learning capabilities to generate all potential optimizations with each building variable could be an extra development. This development would greatly accelerate the design process, enabling engineers and architects to produce optimum designs instantly. The interface can evaluate enormous volumes of data and produce customized design solutions in a fraction of the time it would take by hand by utilizing machine learning techniques.

Analysis of results

The purpose of this thesis was to develop a workflow that would assist architects and engineers in making decisions early in the design process. The tool developed includes a database including numerous hempcrete construction aspects that can be utilized in future study to determine how hempcrete composition or construction type effects building performance in different climates or functions. Although relevant research has previously been completed, this tool can be applied to a variety of places and scopes. Additionally, the relationship between hempcrete and the window-to-wall ratio (WWR) can be investigated.

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Appendix

ISOHEMP NATURAL BUILDING

TECHNICAL DATA SHEET
ISOHEMP HEMP BLOCK

Version: February 2019

1. Definition

The Belgian-made hemp block is a free-standing masonry element that does not fulfil any structural function. It is comprised of hemp chips and a mixture of air and hydraulic lime. The product is moulded, pressed and then cured and dried in the open air without the need for any heat input.

IsoHemp blocks are used for thermal, hydric and acoustic regulation in new builds (with structure), and interior and exterior renovation. They are used in the form of masonry for filling framework, building envelopes or as partition walls or floor insulation. They are not at all suitable for supporting a floor or roof.

2. Characteristics and dimensions

The IsoHemp hemp blocks have a colour ranging from beige to off white with a porous surface between the plant strands which is highly suitable for easy application of the outer coating.

The blocks have modular dimensions:

- **Thickness**: 6, 9, 12, 15, 20, 25, 30 and 36 cm
- **Length:** 60 cm
- **Height**: 30 cm

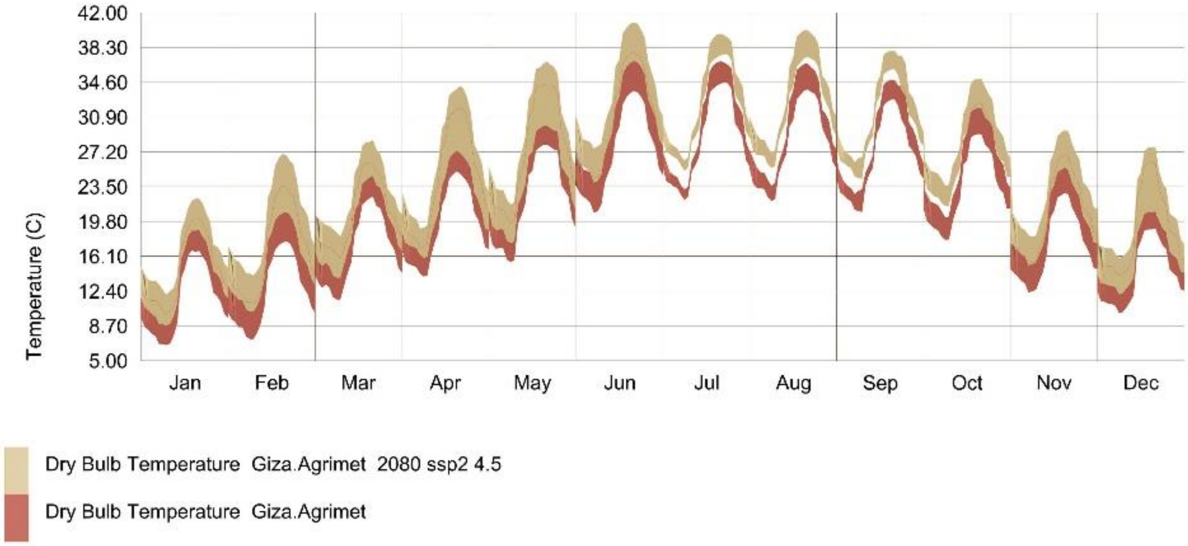
3. Technical specifications

Product range	**60**	**90**	**120**	**150**	**200**	**250**	**300**	**360**
Modular dimension [mm]	600X300	600X300	600X300	600 X 300	600 X 300	600 X 300	600 X 300	600 X 300
Thickness [mm]	60	90	120	150	200	250	300	360
Number of blocks per m² [-]	5,55	5,55	5,55	5,55	5,55	5,55	5,55	5,55
Dry bulk density [kg/m³]	340	340	340	340	340	340	340	340
Dry thermal resistance [m²K/W]	0,9	1,34	1,79	2,24	3	3,5	4,5	5,4
Thermal resistance 50%RH [m²K/W]	0,85	1,27	1,69	2,11	2,82	3,7	4,23	5
Thermal conductivity λ	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,071
Equivalent air layer thickness Sd [m]	0,17	0,25	0,34	0,42	0,56	0,7	0,84	1
Phase shift [h] (ISO 13786)	3,9	5,9	7,9	9,8	13,1	16,4	19,7	23,6
Sound reduction index Rw [dB]*	37	38	**39**	40	42	43	44	45
Sound absorption coefficient α	0,85	0,85	0,85	0,85	0,85	0,85	0,85	0,85
Fire resistance * [min]		-	60	-	120	-	-	-

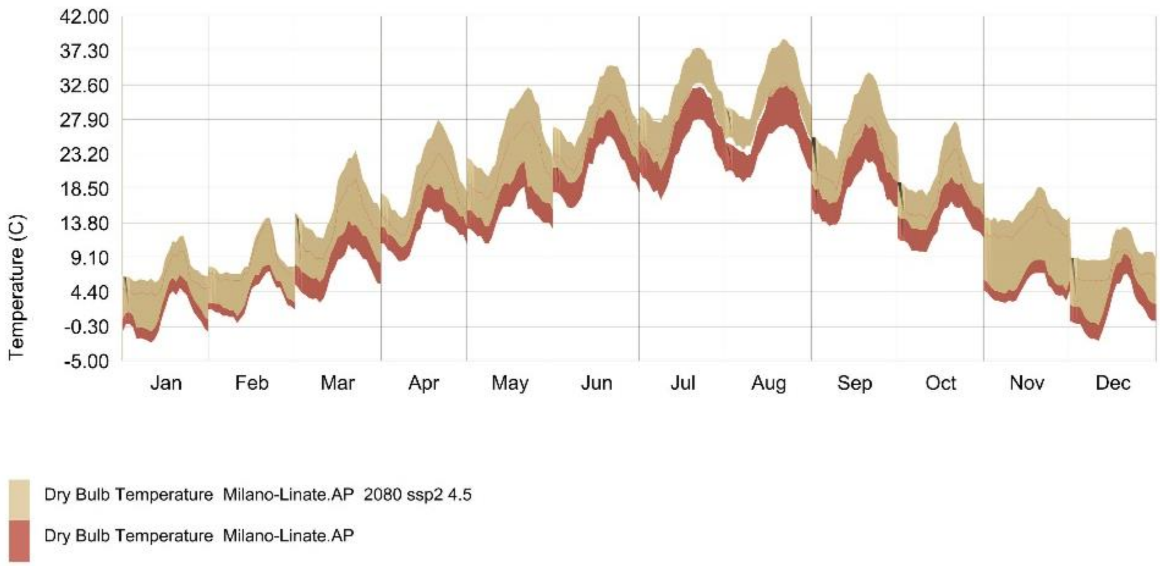
*Masonry wall with redder on one side: **certified value** / extrapolated value

IsoHemp S.A. – 18, Rue du Grand Champ – 5380 Fernelmont **Page 1 of 2**
www.isohemp.com – +32 (0) 81 39 00 13 – info@isohemp.be

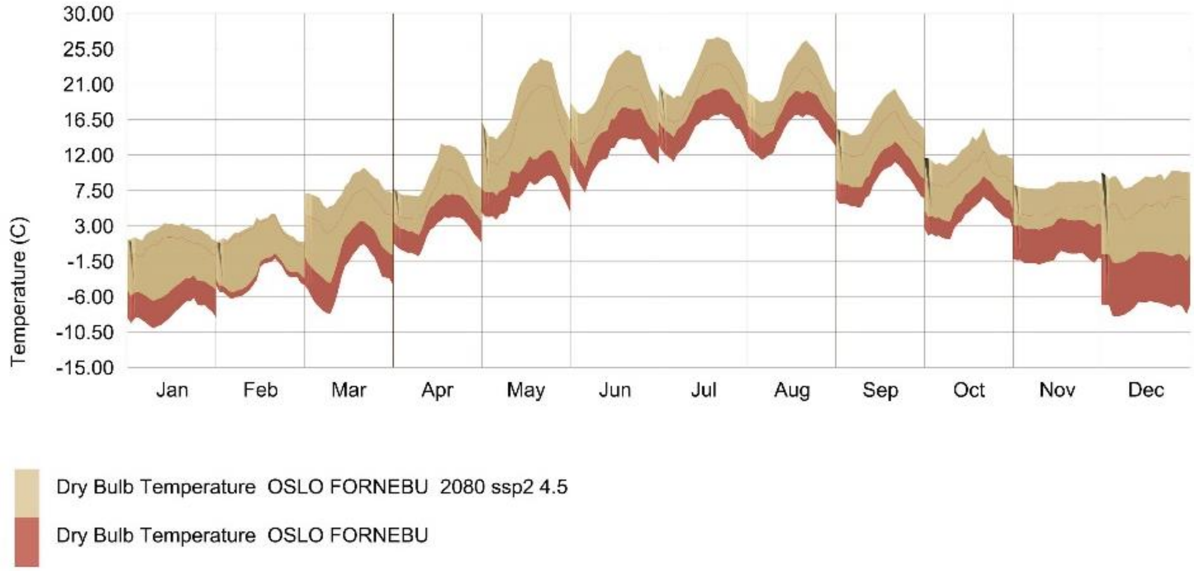
Appendix Figure 1. Technical Data Sheet IsoHemp Hemp block. Reference: TECHNICAL DATA SHEET ISOHEMP HEMP BLOCK, n.d.



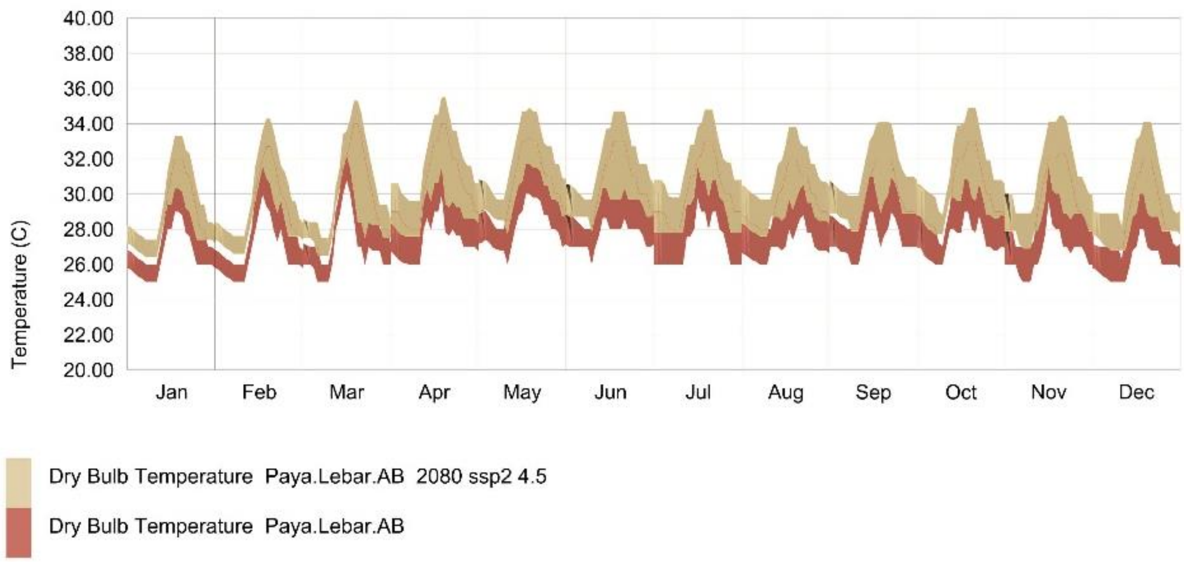
Appendix Figure 2. Dry Bulb temperature Giza data 2007-2021 and Giza data 2080



Appendix Figure 3. Dry Bulb temperature Milan data 2007-2021 and Milan data 2080



Appendix Figure 4. Dry Bulb temperature Oslo data 2007-2021 and Oslo data 2080



Appendix Figure 5. Dry Bulb temperature Singapore data 2007-2021 and Singapore data 2080