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BIOMIMICRY AND BIOMIMETIC DESIGN

THE HOUSE IN A GREENHOUSE MODEL

ENERGY ANALYSIS, BIOMIMETIC OPTIMIZATION, AND PRACTICAL APPLICATION

Master Thesis
Architectural Engineering

Eleonora Rubinacci

Supervision
Prof. Dr. Ahmed Z. Khan

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Eleonora Rubinacci

Academic year 2021-2022

Master Thesis submitted under the supervision of Prof. Dr. Ahmed Z. Khan, in order to be awarded the Master's Degree in Architectural Engineering

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ABSTRACT

This Master Thesis is submitted by Eleonora Rubinacci in order to be awarded the master's degree in Architectural Engineering at the Brussels Faculty of Engineering (BruFacE), during the academic year 2021-2022. The title of the thesis reads as follows:

"Biomimicry and Biomimetic design: The House in a Greenhouse Model: Energy Analysis, Biomimetic Optimization, and Practical Application".

Building envelope inefficiency accounts for a substantial portion of the construction sector's energy losses, one of the primary causes of climate change. This master thesis studies an effective alternative to traditional façades insulation methods. In that context, it analyses, optimizes, and studies practical applications of the *House in a GreenHouse* (HGH) concept, a core house enclosed in a greenhouse. First, energy simulations prove that surrounding a house with a greenhouse is equivalent to using a traditional insulating composite in terms of quantitative energy performance. Second, a biomimetic research-by-design process is followed to counter the five identified weaknesses of the HGH: high illuminance levels, insufficient passive heating in the coldest days and overheating in the warmest days, high humidity levels, and a margin to optimize the energy collection. As a result, two combined biomimetic optimized solutions are proposed to improve the HGH. These are inspired by the properties of the termite mounds, the desert rhubarb, the strelitzia reginae, the sunflower, the chameleon skin, as well as the geodesic dome. Subsequently, this thesis studies the practical application of these two solutions to existing insufficiently insulated Brussels villas in three different setups: a full, semi or rooftop greenhouse. Provided certain conditions are met, the optimized HGH may be a concrete alternative to standard insulation methods. To conclude, the HGH concept is efficient in terms of thermal insulation, is an alternative to fuel-based insulation materials, can be further optimized through biomimetic design, and may be applied to retrofit Brussels villas. It also goes beyond insulation by providing in-situ food production, water autonomy, and enhanced mental health through greater proximity to nature.

Key words: Biomimicry, building envelopes, Energy Performance of Buildings, insulation retrofit, architectural engineering.

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INTRODUCTION

"Biomimicry is a practice that learns from and mimics the strategies found in nature to solve human design challenges — and find hope along the way."

(Biomimicry Institute 2006).

INTRODUCTION

1. Problem statement

Climate change is one of the biggest challenges of the 21st century. This phenomenon is mainly driven by the rising emission of greenhouse gases (GHG). Indeed, human activity increases the concentration of the greenhouse gases in the atmosphere, in particular carbon dioxide (CO_2) (refer to Appendix 1 – Climate for more details p.168).

First, the building sector is the world's greatest user of raw materials, it accounts for up to 40% of the EU energy consumption and represents almost 10% of total domestic carbon footprint (European Commission 2022) (Webb, Aye and Green 2018). In this context, wiser planning and more energy-efficient design are crucial to reducing the construction sector's detrimental influence on the environment (Barozzi, et al. 2016). For this reason, the EU and the reports of the Intergovernmental Panel on Climate Change (IPCC) call for a drastic reduction in GHG of 50-80% by 2050 compared to 2020 (Cruz 2016) (European Commission 2022). In other words, primary energy consumption, which accounts for the largest share of carbon emissions, must be reduced through the improvement of building's energy performance. This involves lowering heating and cooling use, which can be achieved through insulation (Bianco, et al. 2019).

Second, the average level of insulation of Brussels houses is very poor as most of them were built before the 1960s and their current pace of renovation is too slow (Brussels Environnement 2022). In addition, the building stock would certainly benefit from alternate insulation techniques, as standard systems are quite limiting. Indeed, the insulation retrofit of buildings nowadays is most often conducted by adding non regenerative petrochemical-based materials either inside, outside, or in-between the cavities in the walls. Each of these solutions are complex and expensive to implement, as they bear a risk of thermal bridges, condensation, denaturing of frames, covering of architectural qualities, etc. (Carton 2009).

Ergo, there is room to propose new and innovative insulation solutions in the construction sector. To that end, this Master Thesis will study, analyze, apply, and optimize the House in a GreenHouse (HGH) model.

2. Main concepts

Climate change and climate zones

As explained in the problem statement, innovative solutions to reduce the contribution of the construction sector to the causes of the climate change are a key challenge for today's engineers and architects (refer to Appendix 1 – Climate for more details p.168).

Climate change does not only affect the temperatures, but also increases the risks of natural disasters because of the modified precipitations and sea level (Pepermans and Maeseele 2017) – as demonstrated, for example, by the floods in Belgium after the heavy rains during the summer 2021.

According to the Köppen climatic classification system, Belgium sits in a temperate oceanic climate zone, defined by *Cfb*. A temperate region is characterized by wide temperature ranges and distinct seasonal changes where mean temperatures evolve between -3°C and 18°C. Oceanic temperate regions (Cfb) present mild summers, cool but not cold winters, relative humidity and precipitation spread throughout the entire year. These zones are also frequently cloudy (Beck, et al. 2018).

House in a Greenhouse (HGH)

The House in a GreenHouse (HGH) model is based on a specific type of double-skin envelope, namely the enclosing of a house in a glazed greenhouse. HGH has many advantages. Besides providing an insulating air layer between the outside and the inside of the home, it also provides its occupants with possibilities for local food production under the greenhouse, more area for the implementation of renewable sources of energy and proximity to nature. The latter has been proven to enhance mental health (Superior Health Council 2021) (further details in annex p.168).

Yet, as it will be shown in the following chapters, the very design of the HGH model also presents weaknesses, such as high illuminance levels, scarce passive heating in the winter and overheating in the summer, high humidity levels, and a margin to optimize the energy collection.

Biomimicry and Biomimetic Design

Biomimicry applied to architecture is a science that imitates nature to find design solutions. Indeed, organisms have managed to achieve what humans do without consuming fossil fuels, harming the environment, or risking the future – therefore being "sustainable"[1]. Whereas nature only uses renewable resources and reuses as much as possible while using the path of least resistance, hence saving energy, humans operate with a lot of non-renewable sources of energy and produce a lot of waste (Appendix 2 – Biomimicry p.173).

Biomimicry comes from the Greek *bios,* life and *mimesis,* imitation. According to the book *Innovation inspired by nature* written by Janine M. Benyus (1958 –) in 1997, this science is based on three pillars:

1. *"Nature as* model*: Biomimicry is a new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems, e.g., a solar cell inspired by a leaf.*
2. *Nature as* measure*: Biomimicry uses an ecological standard to judge the rightness of our innovations. After 3.8 billion years of evolution, nature has learned: What works. What is appropriate. What lasts.*
3. *Nature as* mentor*: Biomimicry is a new way of viewing and valuing nature. It introduces an era based not on what we can extract from the natural world, but on what we can learn from it."* (Benyus 1998)

According to the *Biomimicry Institute*, the most up-to-date source of this science, bioinspired design is a well-recognized term describing design and engineering techniques that use nature as a resource. Biomimicry is a form of bioinspired design. Indeed, Biomimicry learns from, and copies regenerative strategies found in nature for *functional problems*; whereas an entity that is bioinspired refers to a *design* inspired by or based on biological structures, a more formal process. The latter's definition is larger (Biomimicry Institute 2006).

Biomimetic design is biomimicry applied to design. For that purpose, several methodologies have been defined such as the top-down and bottom-up approaches (Sabry Aziz et El sherif 2016).

[1] "*Sustainable*" in this context means: "able to be used without being completely used up or destroyed"; "involving methods that do not completely use up or destroy natural resources"; "able to last or continue for a long time" (Merriam-Webster 2022)

Biomimicry and building envelopes

The initial aim of architecture is to shelter humans from weather conditions. Therefore, architecture requires an awareness of how to respond to changing climatic conditions, such as people who, over time, have adapted to their surroundings by dressing for the weather and living in ways that are tailored to their local environment (Kaslegard 2010).

The building envelope or building skin – its outer walls and roof – is the boundary through which the building interacts with the environment and where most energy and material exchange occur. It is similar to natural skin as it consists of filters that react to light, air, moisture, sound, and heat. The main purpose of a skin is its capability to maintain internal conditions while the external environment is changing in terms of temperature regulation (Radwan and Osama 2016).

Traditional façades are built with static components and require human involvement to maintain the building's temperature (e.g.: open and close windows or curtains). Adaptive and/or responsive façade systems can change function, form, and behavior in response to changing external circumstances and may provide adjustable heat exchange, shade, humidity, ventilation, energy storage, etc. (Sandak, et al. 2019).

A first observation is that the HGH model is an example of a biomimetic design solution. The greenhouse that surrounds the house operates in a comparable manner as a skin layer: the objective is to insulate and protect the home and its residents from the outdoors, like one would wear a jacket when it gets colder outside. In that way, the greenhouse acts as an adaptive thermal comfort solution, a *climate shell*, and provides a buffer zone between the outdoors and the living space.

3. Research goals

This thesis will study the behavior of a HGH prototype to achieve a higher energy efficiency in regions with cold or temperate climates. This model and derivatives have already been built and studied by others, like Lacaton and Vassal's wintergardens or the popular Swedish concept *Naturhus*. After describing and analyzing real-life examples, this thesis will review ways to optimize it through biomimicry via a research-by-design process. The application of the concept to insufficiently insulated Brussels villas will then be studied.

Therefore, the main research question is:

Is the House in a GreenHouse concept valuable for Belgium? How can we improve its energy performance through biomimetic design and apply this solution to the retrofit of Brussels Villas?

The research will be conducted through a HGH prototype, V^2, designed specifically for this thesis. It is based on several case studies. To fulfil the thesis target, the following objectives will be sought:

- What are double-skin façades? (How) do they improve a building's energy performance?
- Which types of biomimetic envelopes already exist? (How) do they improve a building's energy performance?
- What is the impact of an outer glass skin on the thermal efficiency of a house? How could it be improved by copying some natural bioprocesses?
- How could the thermal efficiency of Brussels Villas be improved through the addition of a biomimetic outer glass skin such as a greenhouse?

4. Research methodology

To answer the aforementioned questions, the following methodology will be used.

Firstly, a literature review will be performed, both on a historical overview and the state-of-the-art of research on the main concepts. This initial chapter will be completed by several case studies to identify the main weaknesses of the HGH concept, as well as looking for initial paths for improvements. These two chapters will help defining this thesis' HGH prototype.

Secondly, experiments will be conducted. First, by designing the prototype mentioned before. Second, by conducting energy simulations using the OpenStudio software, based on five scenarios to determine the insulating properties of the HGH concept. Third, by conducting a research-by-Design (RbD) analysis of eight different biomimetic envelopes to optimize the prototype based on the issues identified in both the research and the simulations. Last, by performing another RbD development to apply the concept in a practical manner. The goal is to use the HGH concept to insulate the building stock of detached houses in Brussels.

Finally, conclusions will be drawn and potential further research on the subject will be identified.

5. Master Thesis outline

Chapter 1 frames the context based on a literature review, by providing a historical overview and the state-of-the-art findings on this thesis' key aspects: biomimicry, thermal efficiency, climatic design, and building skins.

In Chapter 2, six case studies are presented. Three are used as introductions to the subject: the Greenhouse Living Concept, the Edge, and the One Ocean Building. The other three case studies (Naturhus, Kaseco, and the Dome over Manhattan project) are described in depth and critically analyzed.

Chapter 3 contains the basic assumptions used as well as the build-up of the HGH prototype designed specifically for this paper.

Chapter 4 presents the results of the energy simulations conducted on five different scenarios to determine whether the greenhouse can act as an insulation solution.

Chapter 5 describes the biomimetic Research by Design process performed to optimize the HGH model. To this end, eight bio-inspired options for the outer skin façade were analyzed based on the findings of the previous chapters.

Chapter 6 goes over different Research by Design scenarios for the practical application of the concept optimized in chapter 5. The optimized greenhouse is placed over typical Brussels villas, and the feasibility of this application is discussed.

Finally, the conclusion summarizes the main findings in comparison to the initial objectives, the contribution of this thesis to the ongoing research, its limitations and potential further research on the subject.

Figure 1 illustrates this thesis' structure.

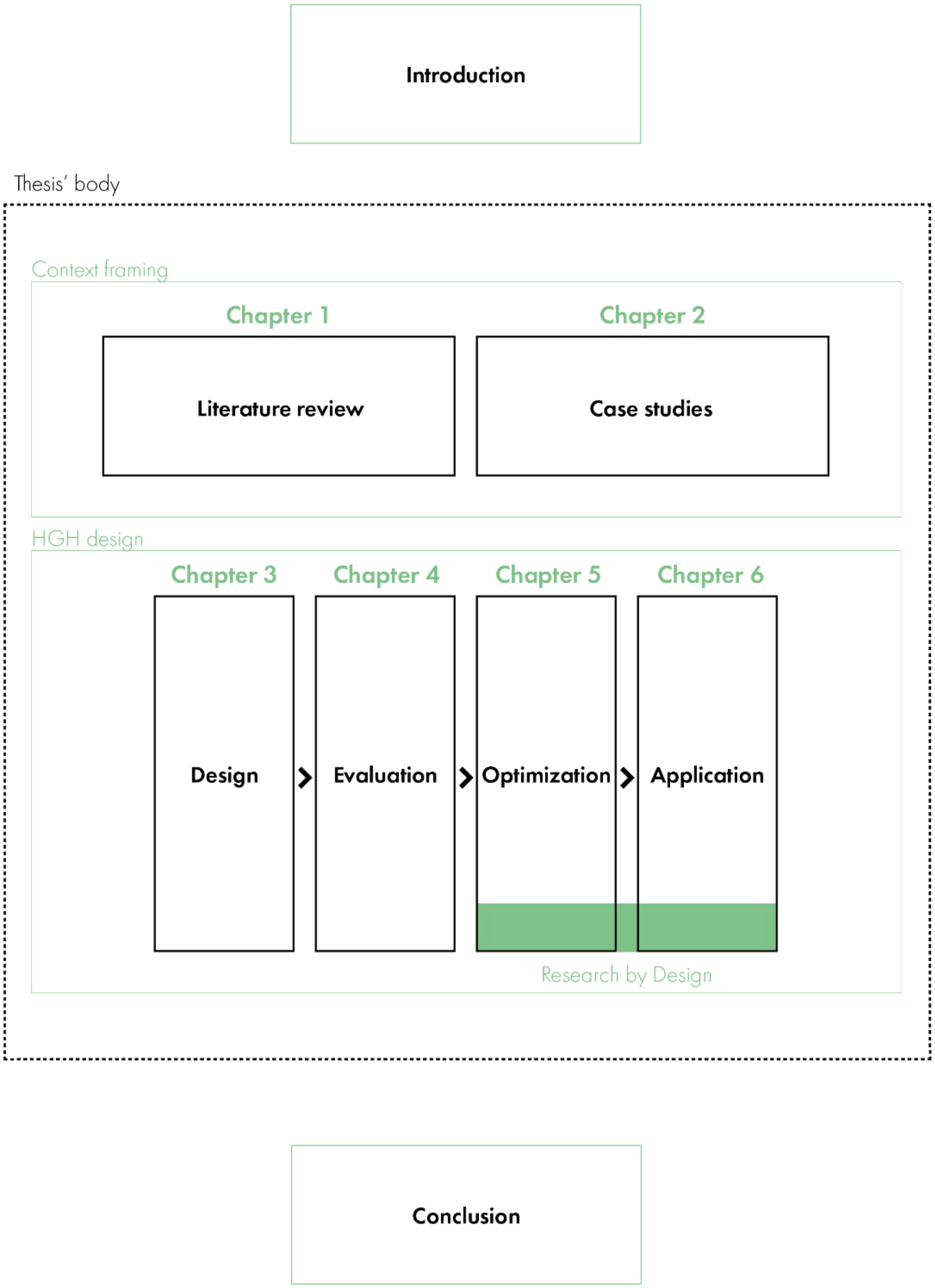

Figure 1: Master Thesis' outline (Author, 2022)

1

CHAPTER 1

LITERATURE REVIEW

This first chapter aims at providing a state of the art on the different subjects involved in this thesis. It starts with the definitions and/or an historical review of the key elements framing this research namely climate change and climate zones, the thermal/energy efficiency of a building, climatic design, building skins and of course biomimicry and its application in terms of building envelopes.

After the definition and the historical background, the state of the art will highlight the most recent and optimized developments in Biomimicry (resources, principles, ideas, degrees) as well as in double skin façades (efficiency, buildings in diverse climates, passive solar design, and greenhouses) available in the scientific literature. It will also present the biomimetic research by design process that has been followed to improve the overall efficiency of the HGH model and its application on the Brussels villas.

I. CHAPTER 1 – LITERATURE REVIEW

1. Historical overview

Biomimicry

One of the first instances of Biomimicry was the study of birds to enable human flight by Leonardo da Vinci (1452–1519). In the many notes he left about his findings, he developed the well-known concepts for *flying machines*. Despite never being able to build one himself (Leonardo da Vinci 2019), his observations of pigeons in flight are claimed to have inspired the Wright Brothers (respectively 1867-1912 and 1871-1948), who piloted the first airplane in 1903 (Benson 2021).

In the 1950s, the American biophysicist Otto Schmitt (1913 - 1998) was the first to introduce the term *biomimetics*. In his research, he developed the *Schmitt trigger*[2] by analyzing squid neurons and attempting to construct a device that replicated the organic mechanism of nerve transmission (Sullivan s.d.). He continued to work on technologies that mimic natural processes which he labeled *biomimetics* (Vincent, et al. 2006) (De Rossi and Pieroni 2013). Simultaneously, in 1962, the similar term *Biomimicry* emerged in the scientific literature (Pawlyn 2016).

In the late 1990s, the term was officially re-introduced to the public in Janine Benyus' book *Biomimicry: Innovation Inspired by Nature* (Standford Daily 2008). It has not stopped gaining visibility and popularity since then, especially in the last two decades where more innovations towards sustainability are taking place.

[2] Schmitt triggers are comparator circuits that employ positive feedback to implement delayed action (slight changes in the input cause significant variations in the output in the same phase) and are used to eliminate noise from an analog signal whilst turning it to a digital signal (Components 101 2019)

Building envelopes

Traditional façades

Circa 1950, James Marston Fitch (1909–2000) characterized the building envelope as a two-way filler – a selective, permeable membrane. He compared the envelope to our skin, which enables our bodies react to their surroundings and maintain ideal operating conditions (Furness, et al. 2019).

As mentioned in the problem statement, building envelopes are responsible for more than 40% of a building's energy losses. If most of the population is beginning to recognize the dire repercussion of climate change and making small changes at an individual level by, e.g.: reducing their heating consumption, they also demand higher and higher levels of thermal comfort in their homes (Webb, Aye and Green 2018). Of course, construction techniques for building envelopes are highly influenced by the building's geographical location and its nearby climate conditions (Antoniadou, et al. 2020).

Notwithstanding, Marta Barozzi et.al. argue in their article *The Sustainability of Adaptive Envelopes* that buildings could operate without high-energy-consuming equipment if façade features were carefully designed (Barozzi, et al. 2016). Double skin façades are one of those solutions, as they can provide both enhanced indoor environment and energy savings (Souza 2019).

Nowadays, the envelope efficiency of the building is primarily ensured by its insulation. Traditionally, thermal storage techniques were used to provide thermal comfort in the summer – such as double brick layers. Since the 1960s, external thermal insulation composite systems have been used throughout Northern Europe. The positioning of the insulating material, either external or internal, is the fundamental difference in traditional building elements (Antoniadou, et al. 2020).

Double skin façades

Double skin façades are façade systems consisting of two layers, usually the outer one being in glass, wherein air flows through the intermediate cavity[3] (Furness, et al. 2019). This means that these systems are ventilated. They have been used mostly in colder climates in the past, such as in Scandinavia. However, they have become increasingly popular in warmer areas of the world, such as in Belgium or even in Greece (Antoniadou, et al. 2020). If appropriately built, double skin façades can provide both enhanced indoor environment, energy savings and better indoor natural light features.

Figure 2 and Figure 3 illustrate the first roles of double skin façades, respectively daylight improvements (early 1900s) and ventilation (1920s).

- Figure 2 was taken in the Post Office Savings Bank designed by Otto Wagner in 1903. It uses a type of double skin façade to provide lighting inside the building from the ceiling.
- Figure 3 represents the 1925 construction named the Tsentrosoyuz building by Le Corbusier (1887-1965) and Nicolai Kolli (1894-1966). The architects worked on an *innovative curtain wall*, provided with ventilation systems in between the layers of glazing.

After the first double skin façades in the 1920s, little progress was made for decades. However, in the 1990s, growing environmental concerns started to influence architecture again. Since then, the goal of a double skin façade is usually to design the most energy-efficient building possible (Poirazis 2004).

[3] Please refer to Appendix 3 p.170 for further details

Figure 2: Double-skin façades for daylight improvements: Post Office Savings Bank, Vienna, Otto Wagner 1903 (Pablo Rodriguez)

Figure 3: Double-skin façades for ventilation: Tsentrosoyuz building, Moscow, Le Corbusier and Nicolai Kolli 1925 (Cemal Emden)

2. State of the art

Biomimicry

Solution resources

The two diagrams on Figure 4 show quantitatively the capability of nature-inspired design to generate more sustainable solutions for technical problems. They compare the consumption of resources (energy, information, material, etc.), arranged according to size, employed by humans (Figure 4.a) and by nature (Figure 4.b) to solve problems (Gallo 2018). These diagrams clearly show that humans use a lot more energy and substance than nature in their problem resolutions. Biology focuses more on information and structure, relying only on natural energy (solar, hydraulic, geothermal, wind, …) since it does not have access to non-renewable resources like fossil fuels. Moreover, living organisms have sustained themselves without over-the-top technologies for almost four billion years.

1.1. Principles

According to Janine Benyus, there are nine principles that underpin nature's designs. She claims that nature (Benyus 1998): "

- *Runs on sunlight*
- *Uses only the energy it needs*
- *Fits form to function*
- *Recycles everything*
- *Rewards cooperation*
- *Banks on diversity*
- *Demands local expertise*
- *Excesses are suppressed from within.*
- *Taps the power of limits*"

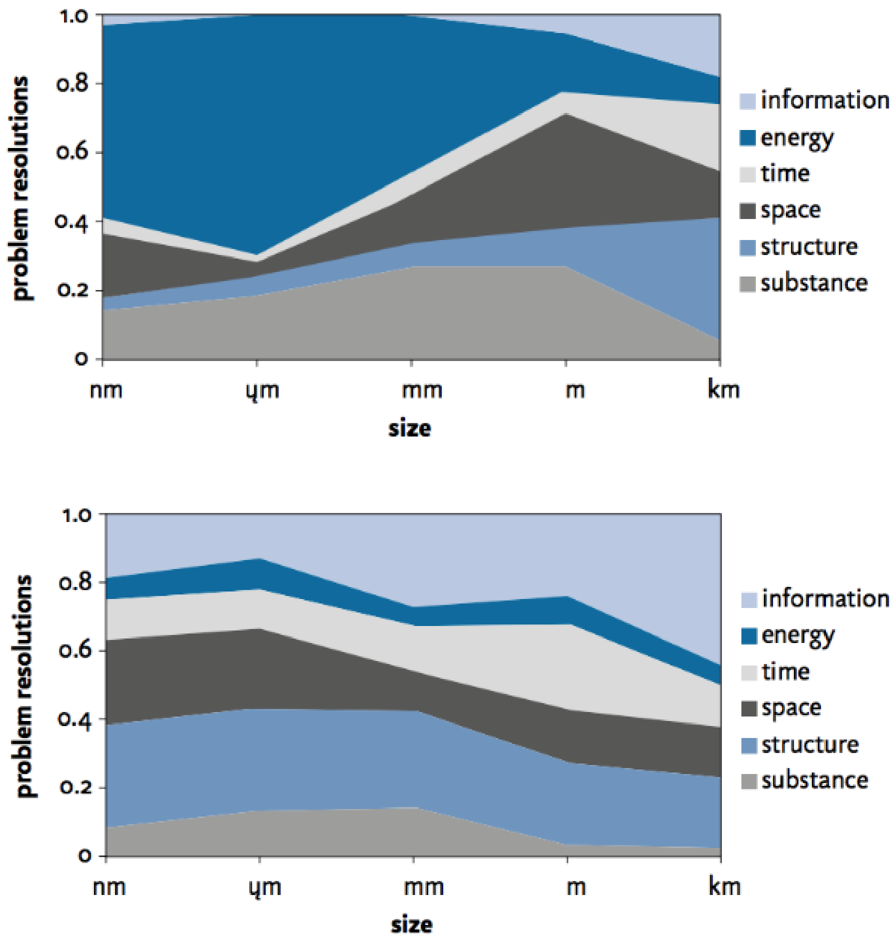

Figure 4: Problem solutions arranged according to size hierarchy: comparison between engineering solutions (top graph) and biological solutions (bottom graph). The engineering solutions use much more energy and substance, while the biological ones focus on information, time, and structure (Gallo 2018)

1.2. Ideas

Gallo's book states that there are two major ideas that underpin biomimetic design (Gallo 2018).

- The first is ***autopoiesis or conativity***[4], referring to a natural organism's ability to reproduce and maintain itself. All living beings are driven by the desire to maintain their own integrity and existence.
- The second is about *how* they go about achieving their conative goals in a specific way. They do so in a way that requires the least amount of work from them. The idea is called ***of least resistance*** and is focused on avoiding difficulties rather than confronting them head-on.

Research by Design and Biomimicry

Biomimicry approaches as a design method generally fall into two categories (Figure 5): problem-driven/ top-down or solution-driven/ bottom-up (Sabry Aziz et El sherif 2016). In his book, M. Gallo confirms these concepts. (Gallo 2018).

In parallel, there are two similar Research by Design processes described in the Biomimicry Guild's papers (Figure 6).

- *Top-Down approach* or *Challenge to Biology*: identifying a human requirement or design challenge and finding a solution based on how other organisms or ecosystems solve it. This approach is problem driven.
- *Bottom-Up approach* or *Biology to Design*: recognizing a certain feature, activity, or function in an organism or ecosystem and converting it into human concepts. This approach is solution driven.

Both processes are applied in Chapter 5 and 6, respectively.

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[4] *Conation* from Latin *conatus*; any natural tendency, impulse or directed effort (Kolbe 2009)

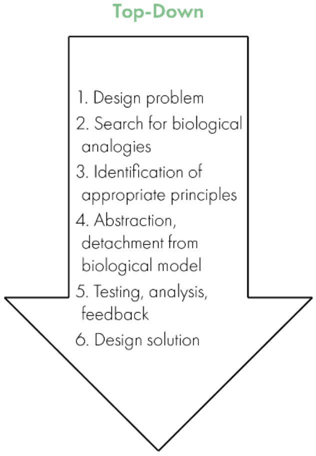
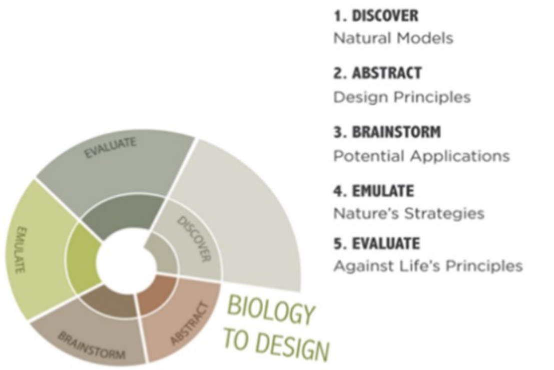


Figure 5: Top-Down and Bottom-Up approaches to Biomimicry (Sabry Aziz et El sherif 2016)



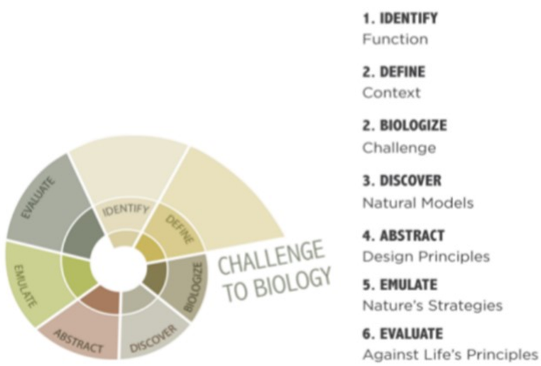


Figure 6: Biomimicry Design processes: Design Spirals (BDS): Biology to Design and Challenge to Biology (C2B) (Peters 2011)

1.3. Degrees

Lastly, there are three degrees of Biomimicry that may be used for design issues in addition to the two approaches already presented. The three stages of imitation are evident and well noted from biomimetic technologies and techniques: organism level, behavior level, and ecosystem level (Sabry Aziz et El sherif 2016) (Benyus 1998).

- *The* ***organism*** *level* depicts the imitation of a specific organism or a portion of a larger organism.
- *The* ***behavior*** *mimicry level* replicates the behavior of every organism.
- *The* ***ecosystem*** *level* mimics the entire ecosystem, which is regarded the most difficult because it focuses on functionality, a complicated issue to replicate.

For each level, there are five sub-levels that define the degree of imitation. This can be in terms of how it appears (shape), what it is made of (material), how it is created (construction), how it functions (process), and what it can do (capacity), and its capabilities (function) (Sabry Aziz et El sherif 2016).

Biomimetic processes and building skin applications

L. Badarnah studied different morphologies found in nature and their processes. She explains their mechanism and their building application. Table 1 summarizes elements of her research. She based this study on the four elements to control in a building: heat (and cool), air, water, and light (Badarnah 2017).

Her work shows that there are multiple strategies in nature that can be mimicked to improve a building system efficiency. Heating, ventilation, and cooling processes are indeed frequently observed in nature, e.g.:

- At ***organism level:*** wrinkles on the surface of the skin
- At ***ecosystem level:*** mounds and funnels built by insects and animals

Further details are available in Appendix 2 – Biomimicry, p.173.

*Table 1: Distinct morphologies, corresponding processes, their underlying mechanisms, and potential applications for environmental adaptation. * The relevant environmental aspects involved in a process: Heat ( ), Air ( ), Water ( ), and/or Light ( ) (Badarnah 2017).*

Morphology	Processes (, , ,)	Mechanism	Applications
Wrinkles	Evaporation , reflection , convection	Provision of enough surface area (holding moisture and promote evaporation) Creation of self-shaded areas (reduced heat loads) Generation of convective currents for enhanced heat losses	Cooling external cladding
Hexagons	Flow , condensation , interception	Decrease of contact angle (due to micro-structuring of surfaces) → super-hydrophilic surface Creation of optimal pattern for capillary water flow Enhancement of light interception (for hexagonal array of facets on a spherical plane)	Moisture and light harvesting
Spikes	Condensation	Creation of boundary layer that improves water collection from fog (spiky leaves)	Moisture harvesting
Lamellae	Reflection , absorption	Reflection of wavelengths (tightly packed ridges with horizontal lamellae and micro ribs) 96% absorption of the incident solar radiation (due to variations in film thicknesses)	Light control and energy generation
Mounds and funnels	Flow , velocity gradient	Generation of velocity gradients on the surface resulting in a pressure gradient for wind induced ventilation	Ventilation

Double skin façades

Double skin façades are usually considered *high performance*. Such façades have the end goal of being energy efficient and environmentally sustainable, all whilst assuring the well-being of the habitants.

In pages 66 to 68 of his literature review report, Harris Poirazis studied the advantages and disadvantages of double skin façades based on various sources (Poirazis 2004). The most striking ones are that buildings with such systems benefit from increased acoustic and thermal insulation, better ventilation, and thermal comfort. However, their construction, maintenance as well as operational costs are higher in general, and they are more susceptible to overheating problems.

Energy-wise, they are interesting for their versatility as they may be used in both cold and hot climates. In colder regions, the air buffer acts as a heat barrier. The cavity's sun-heated air warms up the spaces outside the glass, reducing the need for interior heating systems (Figure 7(1)). In hot regions, the hollow can be vented outside the building to reduce the cooling demand. The chimney effect, in which variations in air density generate a circular motion that enables warmer air to leave, is used to drain excess heat. As the temperature in the hollow rises, the air is forced out, creating a small breeze while isolating the area from heat accumulation (Figure 7(2) ; Figure 7(3)) (Souza 2019).

Further details can be found in Appendix 3 – Double Skin Facades, p.174.

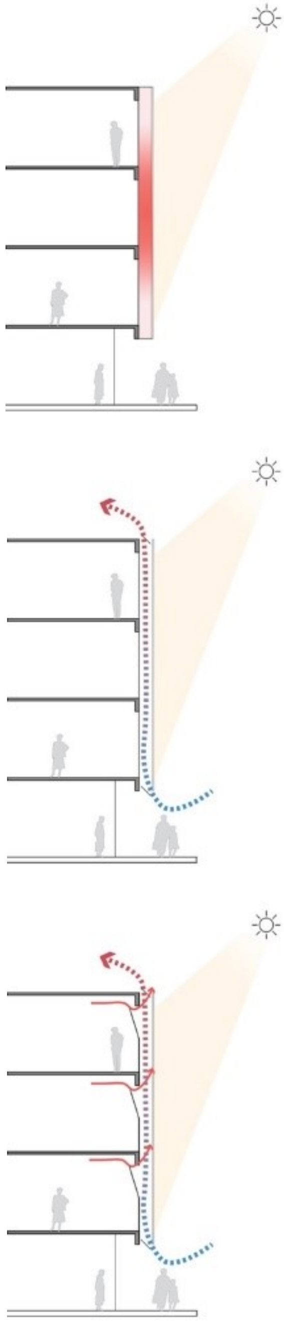


Figure 7: Double skin façades. From top to bottom: (1) Winter: passive heating thanks to solar energy heating up the air in between the glass layers; (2); (3) Summer: natural ventilation thanks to the buoyancy effect: warm air goes up; hence the building is naturally ventilated. (ArchDaily, 2019)

Efficiency of double skin façades

The use of ventilated and double-skin façades can result in a variety of favorable consequences.

The first is a reduction in energy usage – both in heating and cooling. Because of the heat gains and lower heating load, overall energy requirements are reduced. During the warmer seasons, the ventilation of the air gap inside the double skin façade and the extraction of the warm air might reduce the temperature in the buildings, therefore reducing the cooling costs and energy consumption. Furthermore, the air gap's ventilation provides user comfort and reduces humidity, particularly on wet days – mostly thanks to the amount of light and heat coming through the external layer but also the ventilation system. The vented double skin façade may also be used to provide noise isolation, as the increased air gap works as a sound barrier against the noise of cities and congested places. (Antoniadou, et al. 2020).

Despite the advantages of ventilated and double-skin façades, there are several problems that should be considered, particularly in terms of economic and safety evaluation. For instance, as the air gap causes rapid air flame dispersion across the façade, fire safety is compromised, necessitating more ventilation to eliminate flames. Moreover, because a second skin is required, the initial cost is higher than with other insulation options (Antoniadou, et al. 2020).

Finally, it is important to consider the direction and suitable positioning of exterior construction characteristics, so that solar radiation may be employed efficiently. As a result, South-facing orientations are determined to be the best for ventilated double-skin façades in Belgium.

Building according to the climate

Thermal efficiency of a building in different climate zones

Sustainable construction is defined by the Environmental Protection Agency (EPA) as the process of creating structures and employing methods that are environmentally responsible and resource-efficient throughout a building's life cycle, from siting to design, building, execution, upkeep, restoration, and dismantling. The protection of the natural environment, the use of non-toxic building materials, the reduction and reuse of resources, waste minimization, and the use of life-cycle cost analysis are all important concepts. One of the most important characteristics of sustainable structures is their energy efficiency (EPA 2022).

Over time, a variety of simple passive architecture strategies have been followed to increase the energy efficiency and therefore the sustainability level of a single house in relation to its climate zone (EPA 2022):

- Appropriately choose the site and orientation of the building.
- Organize the room layout and/or window sizing according to the orientation and street. Because glass is a poor insulator, special consideration must be given to the windows. In northern nations, this strategy usually results in the installation of more South-facing windows and fewer north-facing windows.
- Insulate the building to keep the heat inside the house and thereby improve the heating, ventilation, and air conditioning (HVAC) system's efficiency. These systems are the largest energy consumers. A more energy-efficient construction requires less energy to create or dissipate heat, but it may require more ventilation capacity to eliminate stale interior air.
- In hotter areas, cooling is a significant consideration; however, passive solar designs can also be quite successful. The use of high thermal mass building materials is also critical for retaining the chilly temperatures of the night during the day. Buildings are also frequently built to catch the winds for better ventilation and cooling.

Climatic design refers to the methods and ideas utilized to maximize the benefits of the climatic conditions surrounding the structure. Constructions under the climatic design paradigm try to get the most from their local environment, *much like organisms rely on the resources offered by nature*. Heat accumulating or rejecting strategies, air humidity, natural ventilation, wind, greenhouse effect, and shade are all factors to consider.

Greenhouse and passive solar design

A greenhouse is a structure that has glass walls and a glass roof. Its goal is to take use of passive solar technology, which turns sunlight into usable heat without the use of active mechanical devices. Passive solar design is a form of climatic design. During the day, solar radiation penetrates and heats the air within because of the poor thermal conductivity of the glass, which prevents heat from escaping properly. Because the glass walls retain heat, the greenhouse remains warm even on colder nights (Goddard 2014).

The heating qualities of a greenhouse are an intriguing advantage in cold and temperate areas. The notion has been adopted by a few builders who decided to build a house within a greenhouse to profit from its passive solar system.

According to the US Department of Energy, passive solar design strategies require (US Department of Energy 2000):

- Using energy-efficient design strategies: the house must be well-insulated to benefit the most from the solar heat gains
- Site orientation: Orient the house with the long axis running East-West.
- Windows: select, orient, optimize glazed surfaces to maximize winter heat gains and minimize summer heat gains
- Shading: provide overhangs or other shading devices in the South direction to avoid overheating in summer but let the winter sun get in
- Thermal mass: add thermal mass in floors or walls for heat storage (heat travels through masonry or concrete at the average rate of 2,5 cm per hour. This means that it takes around eight hours for the noon warmth to reach the other side of a 20-cm thick wall (Energy saver 2022))
- Ventilation: use natural ventilation
- Daylight: prefer natural daylighting

3. Chapter summary and conclusion

To summarize, this chapter defined biomimicry and biomimetic design, double skin façades and building envelopes, as well as climatic building design from both a historical and state-of-the-art approach.

The main conclusions are that:

- The design of the envelope of a building is a key element determining its energy efficiency
- Applying biomimetic principles to its design could further improve the building thermal behavior. Indeed, several nature strategies exist and may be copied to improve a building efficiency in terms of heating, cooling, moisture, energy generation and / or ventilation
- Double skin façades benefit from passive solar heating and ventilation and are more energy efficient than traditional ones. A HGH is a design similar to a double skin façade.
- Several climatic design strategies exist to increase the energy efficiency of a single house depending on its climate zone.
- A greenhouse uses the passive solar technology to warm up during the day and stay warm during the night.
- Two biomimetic Research by Design methodologies have been defined, one problem-driven and one solution-driven. Both will be used later in this thesis.

This literature review will be completed by some case studies in the next chapter. Together, they will help design this thesis' prototype on which experiments will afterwards be conducted (energy simulations, optimization, application).

2

CHAPTER 2

CASE STUDIES

Chapter 2 will present six case studies of buildings based on biomimetic design or enclosed in a greenhouse or holding a glazed atrium: the greenhouse living concept, the Edge building, the One Ocean Building, Naturhus in Sweden, Kaseco in Belgium, and the Dome over Manhattan project. The purpose is to describe the different constructions, discuss the systems as well as the additional processes used by the different architects to regulate the temperature or ventilation inside the glass shell. The different examples will also help to set up the detailed characteristics of our HGH prototype, and to already identify matters for improvement that will be solved via a biomimetic design process.

II. CHAPTER 2 – CASE STUDIES

1. Introduction

Greenhouse living concept – Greenhouses

Concept: Living in a greenhouse
Function: Residential or productive
Localization: Anywhere
Architect: Greenhouse living group

The *Greenhouse Living concept* (Figure 8) has been receiving evermore attention in the last years, not only in Nordic countries but also in Western Europe. Two building-scale key concepts derive from *Greenhouse Living*, namely Nature Houses and Urban Food Production (Greenhouse Living 2021).:

Nature Houses (residential) consist of the combination of a greenhouse, a core-house, and an eco-cycle system, as displayed in Figure 8(1). The concept is inspired by the Swedish architect Bengt Warne. The inhabitants live inside the core house, a traditional home with closed walls and windows. Around it, there is a greenhouse which creates a warmer climate and comfortable covered outdoor area accessible at any time. The greenhouse enables to grow plants, fruits, and vegetables (Greenhouse Living 2021). Different designers thought of diverse ecological cycles in the house:

- In Sweden, Anders Solvarm uses filtered wastewater to provide nutrients to the plants.
- In Belgium, Koen Vandewalle focused on rainwater collection and ventilation.

Urban Food Production (services) consists of the implementation of greenhouses on top of buildings in an urban context, as shown on Figure 8(2). About one third of household's climate impact comes from the food that is consumed. Ergo, local food production is crucial. Those will need to be supported by closed cycles of water and nutrients – whilst breaking free from pollutant fertilizers and pesticides (Greenhouse Living 2021).

Goal of this case analysis: This thesis focuses on HGH, related to this concept. Nature Houses already follow a biomimetic design since there are based on the multilayer principle just like the human skin, or clothes layering for example. This broad definition and concept help framing the thesis prototype's characteristics (Chapter 3).

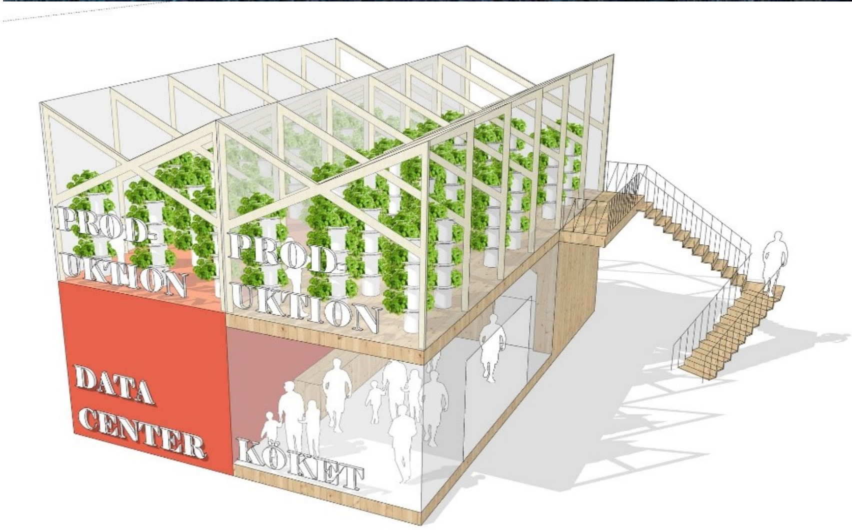


Figure 8: Greenhouse living concept examples: from top to bottom: (1) Nature house, Uppgrenna Nature House by Tailor Made arkitekter, 2015 (Ulf Celander) (2) Urban food production, Digitala Tomater / Digital Tomatoes project (Greenhouse Living 2021)

The Edge — Amsterdam, Atrium

Concept: Atrium for energy savings
Function: Offices, Deloitte's Headquarters
Localization: Amsterdam, the Netherlands
Architect: PLP Architecture

The Edge (Figure 9) is a smart building in two ways, technology-wise and in its energy use. It is not an HGH, but its main design feature, the atrium, works in a comparable manner. The building is energy positive. Designed in 2014, it scored the highest BREEAM[5] score ever at the time (Bakker, Ramage and Jalia n.d) (Tracy 2016). The atrium offers a lot of light and air in the common zone. It also acts as a buffer zone for insulation and noise reduction according to the architects (Boston Consulting Group n.d.).

As shown on Figure 9(1), the volumetry was thought about carefully. First, the Southern wall is thick with minimal openings, optimizing the thermal comfort. Second, the Northern façade provides stable natural daylight in the offices throughout the day. Third, the roof does not only host many solar panels for hot water and electricity, but also collects rainwater for indoor use. The Edge also uses geothermal energy for thermal comfort and ventilation. The excess office air is used to ventilate the atrium (Figure 9(2)). The building is very high-technology and smart, which avoids electricity and heating or air conditioning excesses (Bakker, Ramage and Jalia n.d) (López García-Alcaide n.d.) (Tracy 2016) (Boston Consulting Group n.d.).

Goal of this case analysis: Determining what benefits are gained from a space within a glass skin. The idea of regulating the daylight according to the building's orientation and using an element both for aesthetic and functional purposes as well as for saving energy is close to the main aim of the HGH concept. The Edge inspires for its climatic design strategies as well as the thermal and ventilation benefits of the glass atrium itself even if it does not surround the entire building.

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[5] *BREEAM* or *Building Research Establishment Environmental Assessment Method* is a thorough and recognized assessment of a building's environmental performance. It evaluates a building's specification, design, construction, and use recognized performance indicators that are compared to established standards. The measures used represent a broad range of categories and criteria from energy to ecology (BRE Global 2011).

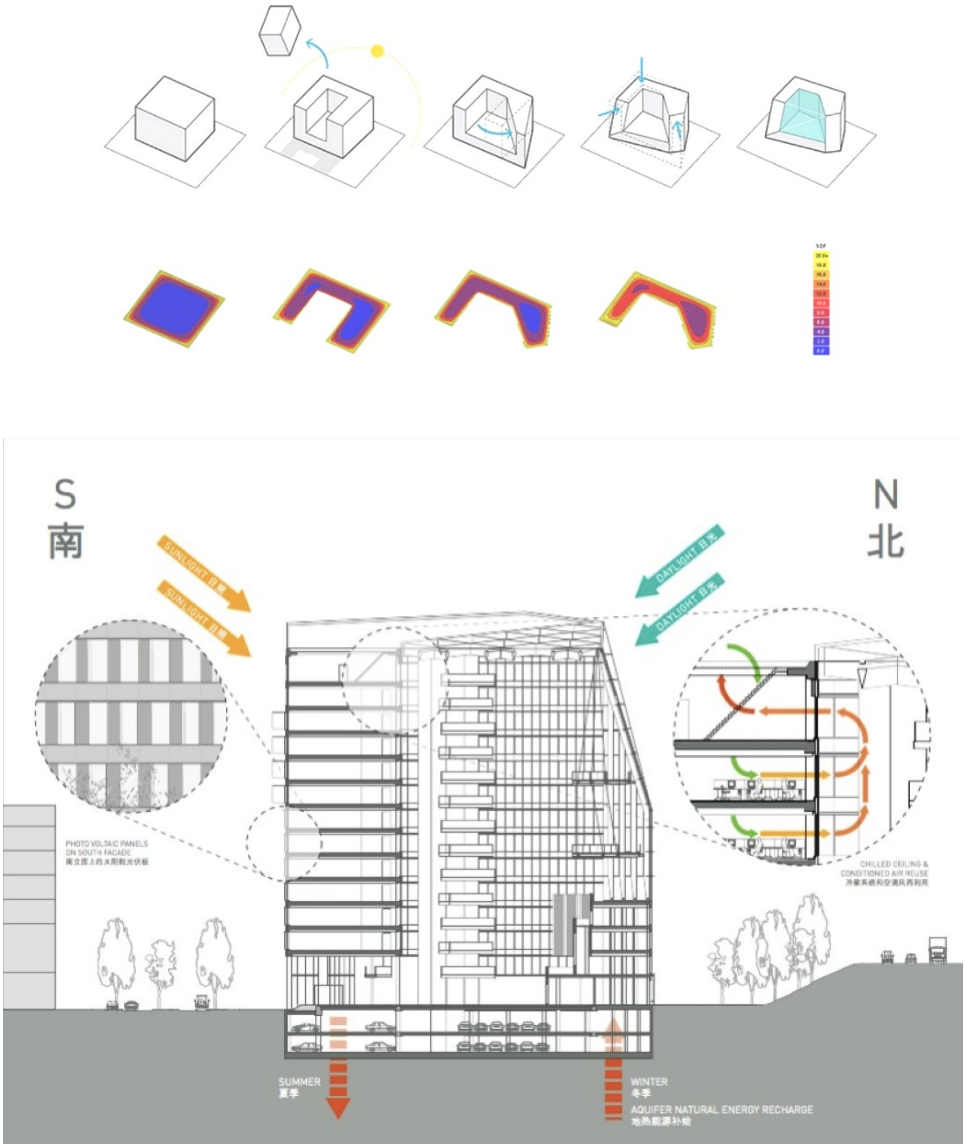


Figure 9: (1) The Edge volumetry development and atrium advantages (top) and (2) The Edge's energy strategies (building and atrium) (bottom) (PLP Architecture)

One Ocean Building — Yeosu, Biomimicry

Concept: daylight control via biomorphic façade
Function: Exhibition pavilion
Localization: Yeosu, South Korea
Architect: SOMA Lima

The *One Ocean building* is located in Yeosu, South Korea. It displays a kinetic adaptative façade system, where lamellae can move and create patterns. This pavilion is a result of formal biomimetic design inspired on the ocean (Soma Architects 2012) (ArchDaily 2012).

On the one hand, more than a hundred lamellae mimicking the opening-closing system of fish grills surround the main entrance. On the other hand, the waterfront is composed of pebble-like elements. The concrete cones facing the sea suggest a new coastline and are linked to the main entrance with pathways emerging from the ground on the other side of the pavilion (ArchDaily 2012).

The lamellae are made of glass fiber reinforced polymers (GFRP), a material that can be molded into a variety of dynamic designs. They are used as mobile sun-shading devices that can be programmed to adapt to changing lighting conditions, follow a predetermined dance and react to specific occurrences. Consequently, light can radiate in and out of the structure and provide views in both directions (Figure 10(1)), or the structure can stay closed-up (Figure 10(2)) (ArchDaily 2012) (Knippershelbig 2012).

They are based on the *flectofin* system: the asymmetrical bending is facilitated by actuators at the top and bottom (Figure 10(1)) (Soma Architects 2012) (Knippershelbig 2012).

Goal of this case analysis: From this case study, it is most insightful to look into the way this Flectofin system was implemented and used. Indeed, the One Ocean Building is a perfect example of a biomimetic adaptative skin that contributes to the regulation of the temperature and the ventilation inside the building and therefore to an improved energy efficiency. The system is also remarkable in the sense that it allows to automatically monitor the shading in the building according to the evolution of the external temperature. These principles will be used in Chapter 5.

Figure 10: One Ocean Building front entry façade: flectofin system for the lamellae. (1) the lamellae are open, letting air and light inside (top); (2) the lamellae are closed (bottom) (ArchDaily 2012)

2. Naturhus — Sweden, Nature house

Concept: *House in a greenhouse*
Function: *Housing*
Localization: *Sweden*
Builder and idea: *Anders Solvarm*
Original concept: *Bengt Warn*

Naturhus (Figure 11) is one of the most well-known cases of the HGH concept. This house was constructed by the engineer Anders Solvarm for himself and his family. In an interview for the TV show *HOME* on Apple TV+ (2020), he explained how his concept was inspired by Bengt Warne to create a perpetual Mediterranean climate in his home country, Sweden.

According to him, the greenhouse provides a *climate shell* around the house and is a radical way to lengthen the summer season despite the harsh meteorologic conditions of the region (Naturhusvillan 2021) (Apple TV+ 2020).

Naturhus is built around the idea of enhancing the relationship between people and plants (Apple TV+ 2020). The household allows its inhabitants to live closer to nature and develop their environmental consciousness. The construction provides a comfortable and relaxing environment, enhances health benefits, and functions as a resource for both food and energy. The core house takes the form of a traditional Swedish cabin, entirely built with wood from the forest near the site (Naturhusvillan 2021). A remarkable benefit is also the scheme of the water cycle. Indeed, the grey water of the house is filtered before being used directly on the plants of the greenhouse! This wastewater is richer in nutrients, and this process imitates nature by using renewable resources. Moreover, firepits with chimneys are used to heat the house as needed. No electrical heating is needed as the firepits combined with the climate shell provide a sufficient thermal efficiency to stay comfortable during the Swedish winters (Apple TV+ 2020).

All the aforementioned aspects of NATURHUS are illustrated on Figure 12.

Figure 11: Naturhus: the first Nature House in Sweden developed by Anders Solvarm (Naturhusvillan 2021)

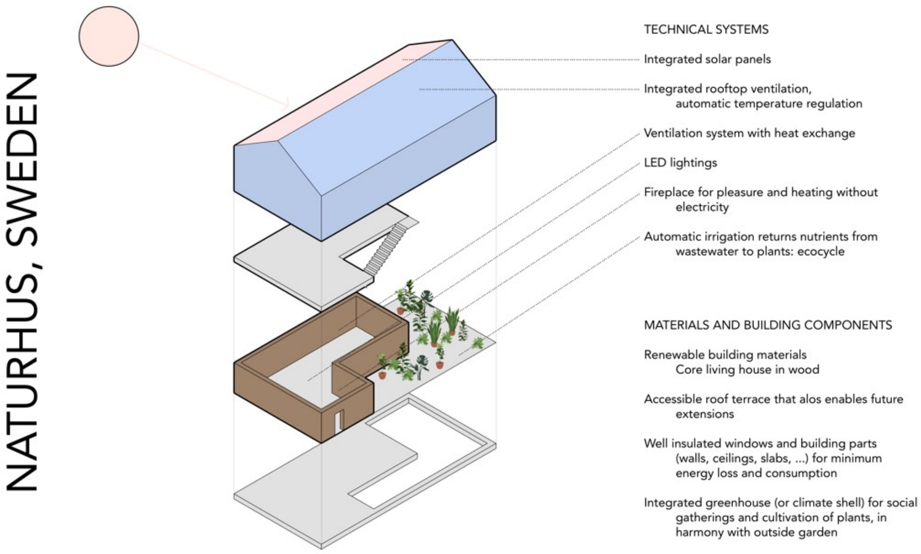


Figure 12: Naturhus organization, built-up and systems (Author, 2022)

Pros and cons of Naturhus

The following table highlights some advantages and disadvantages of this house in the particular Swedish weather. These results come from a personal analysis based on the literature review, comments expressed in the presentation episode by the architect himself as well as on the official company's website. In addition, some arguments derive from topics addressed in the *Energy Performance in Buildings* and *Low-Energy Design for sustainable buildings* (EPB) classes given at the Vrije Universiteit Brussel (VUB) respectively in 2020-2021 and 2021-2022 by Professor Filip Descamps.

Table 2: Pros and Cons analysis of NATURHUS (Author 2022)

Category	Advantages	Disadvantages, questions
Thermal comfort	Mid-season: no need for extra heating as the greenhouse insulates.	Warm days: the greenhouse is prone to some overheating and needs to be carefully ventilated. Cold/cloudy days: firepits with local wood are needed to heat up the interior.
Daylight	The greenhouse is very well lit, the garden space can be used throughout the year.	The interior of the house is less lit as the sunrays have to cross several barriers before reaching the inside. Sweden has early nights from October to March, so there is a need for sufficient daylight.
Water supply	The house has an ingenious waste-water-to-plants cycle system.	What happens when there is not enough grey water for the plants? There is a need for extra maintenance to clean the grey water filters.
Solar gains	There are solar panels on the South part of the roof for the electrical needs of the family.	When the days are short in Sweden, is it sufficient? Is there enough electricity all year around?
Materials	The cabin was made in the wood of the forest right next to the site.	For the greenhouse, a lot of extra materials were used – especially glass (large CO_2 footprint).
Maintenance	/	The glass gets dusty easily and needs a special team or expensive equipment to be cleaned. Self-cleaning glass (Biomimicry) can be an option to explore?

Space, user's comfort, architecture	Living within nature. Good thermal performance even during the winter. Energy savings from the double skin.	The greenhouse gets loud when it rains or hails. The humidity levels might not be comfortable, especially in summer → Choose the plants and materials carefully. High cost compared to the dimensions of the house → inaccessible to most people. If the greenhouse is not ventilated enough there can be smell issues from the plants or the kitchen.
Health	Comfortable, relaxing environment	Living close to sunrays and in a high humidity environment might result in health problems (Arundel, et al. 1986)[6]

Overall, Naturhus is a very impressive project. The advantage of having such architecture in Sweden is that the average yearly temperatures are lower than in Belgium and thus the double skin can really be used at its full potential as a climate shell. On the other hand, the days are noticeably short in the Scandinavian winter which means that the passive solar gains may then be smaller than in Belgium.

The principal areas for improvement identified are the following:

- Overheating during warm days, insufficient heating during cold or cloudy days, high daylight levels during sunny days, increased humidity and energy harvesting can be problematic
- Relying almost only on the sunrays for electricity can be insufficient, as the days in Scandinavia are extremely short in winter
- The choice to have a greenhouse around the core house adds to the amount and cost of materials, as well as the embodied carbon footprint

Goal of this case analysis: This case study is related to the prototype developed in chapter 3 and aims at determining the pros and cons of this house as well as potential paths for improvement. Since the house is located in Sweden, particular care will be applied when using it to design the prototype as a different climate involves diverse considerations in terms of light, temperatures, precipitation, etc.

[6] Please refer to Appendix 4 – Additional case studies, p. 172 for more information

3. Kaseco — Belgium, Nature House

***Concept**: House in a greenhouse*
***Functions**: Housing, office*
***Localization**: Belgium*
***Builder and idea**: Koen Vandewalle*
***Original concept**: Bengt Warne and Mike Reynolds*

Kaseco (Figure 13) is the first autonomous bioecological HGH in Belgium, constructed in 2018 and designed by the architect Koen Vandewalle for him and his family of 7. It is situated in Rekkem, West Flanders.

K. Vandewalle has always been fascinated by the concepts of minimal energy usage, circular construction, and the cradle-to-cradle principle while studying bio-ecological building at KAHO Gent. This house was inspired by the concepts of the American designer Mike Reynolds' Earthships and Swedish architect Bengt Warne's Naturhus (KASECO+ 2017). Kaseco can be described with terms such as *ecological*, *sustainable*, *self-sufficient*, *unique living concept* in Belgium and abroad (IMMO DOCHY 2021).

According to Vandewalle, all the materials can be recycled easily. The basement of the house is made of concrete. The greenhouse covers 360 m^2 – of which 120 are for plant growing activities – and can be taken apart. The house has a wooden frame and cellulose insulating panels, chosen because of their biodegradability. The house is built on three levels: the ground floor includes all living quarters; in the upper floor there is the office and the lower floor (halfway underground to use the ground's thermal mass for thermoregulation) accommodates the sleeping rooms and bathrooms (Vandewalle 2021).

Kaseco has a double skin (Figure 13): the greenhouse is the outside layer and the house the inside layer. The space between the two acts as an insulating material and creates a well-lit living space as well as enabling the growth of local foods. The greenhouse surrounding the dwelling also acts as a *microclimate*, creating an everlasting spring. It makes possible the interior to be around 20 to 25°C when the temperatures outside do not reach more than 10°C (Vandewalle 2021). This phenomenon allows the inhabitants to drastically reduce their energy consumption and costs for heating.

Figure 13: KASECO architecture. View from the exterior (top); and from the interior (bottom (IMMO DOCHY 2021)).

Moreover, the Kaseco is designed to be energy-autonomous, meaning that it is not linked to the electrical, heating and water grids. That is possible thanks to some novel strategies and investments the architect decided to include (Deboyser 2019).

First, 72 solar panels on the roof of the greenhouse are used for electricity and heating generation (Figure 14). They are combined with 48-volt salt-water-based batteries (Deboyser 2019) (KASECO+ 2017).

Second, the collected rainwater is passed through several filters before being stocked and used throughout the house for all needs. The grey water is then directed towards another purification station before going back into a nearby water stream (Deboyser 2019) (Vandewalle 2021).

Third, the windows of the house are thermally interrupted with an aluminum front and triple glazing (KASECO+ 2017) (Deboyser 2019) and the façade is ventilated during the summer to avoid overheating (Vandewalle 2021).

Moreover, when the indoor temperatures reach more than 25°C, the windows on the roof of the greenhouse automatically open (the mechanism can be seen on Figure 14). This provokes a natural airflow and allows fresh air from a Provençal well to circulate in the greenhouse and cool the atmosphere (Deboyser 2019). Last, the greenhouse hosts a lot of eatable plants and herbs, used for cooking (Vandewalle 2021).

All the aforementioned aspects of KASECO are illustrated on Figure 15.

Figure 14: Solar panels and Provençal well principle in KASECO (KASECO+ 2017)

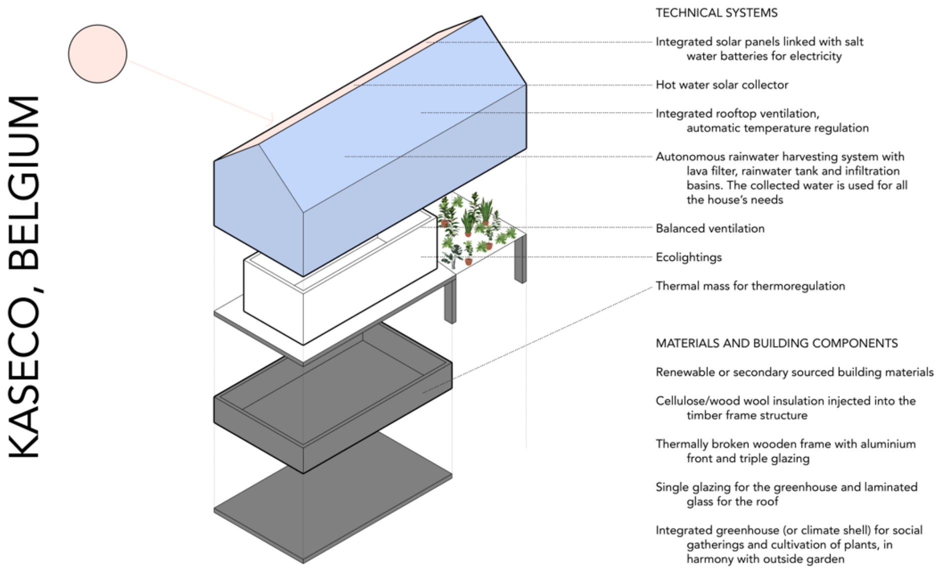


Figure 15: KASECO organization, built-up and systems (Author, 2022)

Pros and cons of Kaseco

The following table highlights some advantages and disadvantages of this house in the particular Belgian weather. These results come from a personal analysis based on the literature review, comments expressed by the architect himself in the several sources stated above as well as on the official company's website. In addition, some arguments derive from topics addressed in the EPB classes given at VUB.

Table 3: Pros and Cons analysis of KASECO (Author 2022)

Category	Advantages	Disadvantages, questions
Thermal comfort	Winter and mid-season: no need for extra heating as the greenhouse provides solar gains.	During warm days, the greenhouse is prone to overheating and extra energy is used in an A/C system.
Daylight	The greenhouse is well lit, and the garden can be used throughout the year.	The interior of the house is less lit as the sunrays have to cross several barriers before reaching inside – especially during Belgium's cloudy days.
Ventilation	Provençal well to ventilate when the temperatures get over a set number.	Extra ventilation and extra cooling are needed because of the overheating and humidity levels. The plants and people in the greenhouse create a lot of humidity inside by breathing.
Water supply	Rainwater collection and filtration to cover all needs.	/
Solar gains	Solar panels on the South part of the roof for electricity and heating, enough for a family of 7 living full time in the house.	When the days are short or grey in Belgium, is it sufficient? Is there enough electricity all year around?
Technology	The house is high tech, meaning that it can be controlled easily.	The house is high tech, which uses a lot of extra energy (even if it is renewable, a lot of embodied carbon is emitted when manufacturing the batteries, solar panels, ventilation systems, etc.).
Materials	A lot of the materials are biodegradable or secondarily sourced.	Lots of glass resulting in a large CO_2 footprint. The entire basement is of concrete. The house is in wood but did not have time to dry (visible cracks under finishes).

Maintenance	/	The glass gets dusty easily and needs a special team or expensive equipment to be cleaned.
Space, user's comfort, architecture	Living within nature. Good thermal performance even during the winter. Autonomous house.	The greenhouse gets loud when it rains or hails. The humidity levels are not comfortable (plants, people, insufficient ventilation). There are no windows in the bathrooms. The spaces are kept to a minimum. There is no extra space for more activities – compared to its price. If the greenhouse is not ventilated enough there can be smell issues from the plants or the kitchen.
Health	Comfortable, relaxing environment	Living so close to sunrays might result in some unforeseen health problems, like skin cancer. Another disadvantage may be that living where relative humidity levels are high, can cause lung problems.

Overall, Kaseco undeniably has a lot of advantages. However, the extra skin and the concept also causes problems, such as overheating during warm days resulting in higher technology needs in the home – hence a bigger carbon and ecological footprint –, some noise and smell issues, as well as humidity problems due to the plants. The overheating problem is more significant here than in the previous example, Naturhus in Sweden. Indeed, the Belgian climate is on average hotter than in Scandinavia, and the problem will persist especially considering the direction of climate change as well as the increasingly frequent heat waves during the summer.

Goal of this case analysis: This case study is related to the prototype developed in chapter 3. The goal here is to determine the pros and cons of this house, and potential paths for improvement. Since the house is located in Belgium, it is even more relevant to analyze, as some principles can directly be applied to the prototype and avoid making the same mistakes.

4. Geodesic Dome over Manhattan – USA, Nature City

Concept: Enclosing Manhattan in a geodesic dome
Functions: City
Localization: USA, New-York City, NY
Builder and idea: Richard Buckminster Fuller
Original concept: Richard Buckminster Fuller

Richard Buckminster Fuller (1895-1983) was a visionary, well-known for his geodesic domes. In 1960, he proposed the idea of putting a Dome over Manhattan (DoM) in New-York City, NY, USA (Figure 16).

Fuller envisioned architecture as a form of organism, and by considering the flows and fluxes, he mapped triangles and tetrahedra. This led to the theorization of the geodesic dome (Budds 2016) (Martin 1997). He liked demonstrating the strength of a triangle by applying pressure on it comparatively to a rectangle. The rectangle would fold up and become unstable, but the triangle withstands the pressure. The geodesic dome is thus a spherical structure made of triangles and has unrivaled strength (Buckminster Fuller Institute s.d.).

The sphere employs the *doing more with less* principle by enclosing the greatest volume of internal space with the smallest amount of surface area, hence conserving material, and money.

In the 1950s, Fuller had the opportunity to show his idea for the design of the enclosed center court design of the Ford Rotunda in Michigan. The weight of a standard steel frame was determined to be 150 tons whereas Fuller's design weighed just 8 tons (Tingley 2020).

Fuller's idea was to cover midtown Manhattan in a 3.21-km-diameter (2 miles) hemispherical geodesic dome (Figure 16). He calculated the total surface of buildings in New York covered by the dome in this superimposition and determined that the dome would cover eighty times more surface than its own, hence minimizing heat losses in New York by eighty times. That represents a decrease of around 20% of the energy intake at that time (Reznich 2017). He also calculated that the electric lights in New York City alone would provide enough heat to cover all the needs under the dome. He argued that the economy of not having to remove the snow under the covered area for ten years would pay for the dome and confirmed that guttering would collect rainwater (Budds 2016).

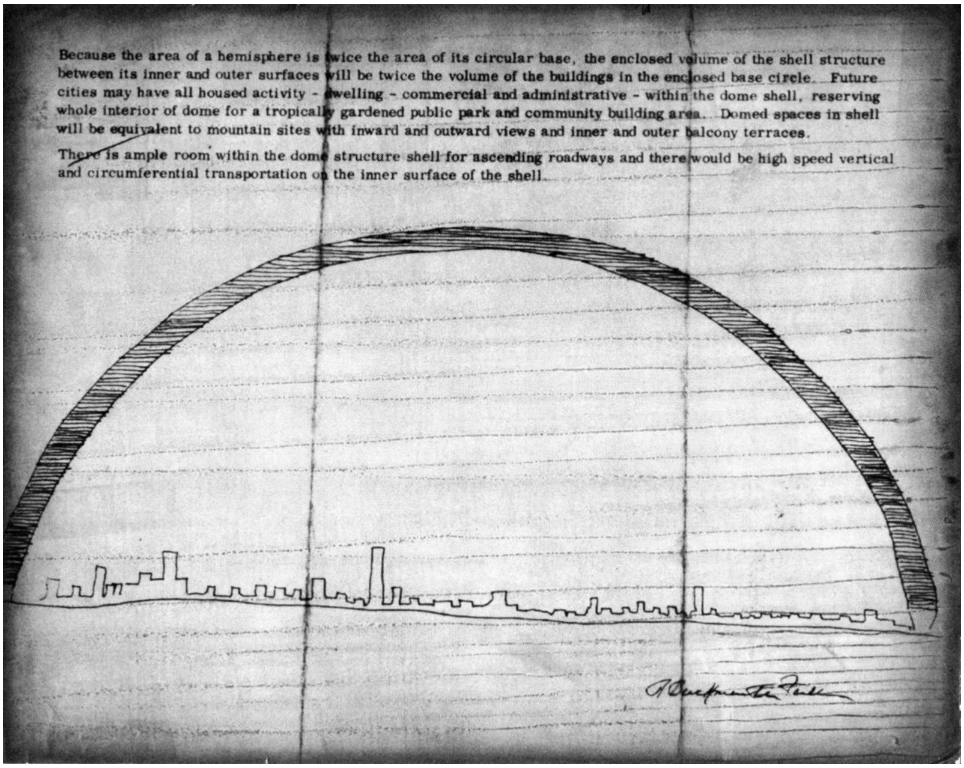


Figure 16: Sketch for Dome Over Manhattan by R. Buckminster Fuller (1960) (Reznich 2017)

Pros and cons of the Dome over Manhattan

The following table and text highlight some advantages and disadvantages of this concept. These results come from a personal analysis based on Laura Kurgan's comments and other arguments stated in the several sources cited in this section. In addition, some arguments derive from topics addressed in the EPB classes given at VUB.

Fuller's arguments

The dome, in particular, is energy efficient for a variety of reasons (Buckminster Fuller Institute s.d.):

- Its smaller surface area necessitates the use of fewer construction materials, thus also weighs less.
- Because of its spherical structure, exposure to cold in the winter and heat in the summer is reduced.
- With return air ducts, the concave interior provides a natural circulation that allows hot or cool air to circulate uniformly around the dome.
- Because the winds that lead to heat loss flow gently around the dome, extreme wind turbulence is reduced.
- It functions as a down-pointing headlight reflector, reflecting and concentrating inside heat. This aids in preventing radiative heat loss.
- According to the Oregon Dome Co., a dome owner can save up to 30% in energy per year compared to a rectilinear house. This contributes to the reduction of wasted energy in the environment (Buckminster Fuller Institute s.d.).

Laura Kurgan's arguments

However, Fuller omitted several shortcomings of this system. In her article *Threat Domes* published in 1997, Laura Kurgan argued that, if Fuller focused on the difference between inside and outside – snow and rain, light and heat, he neglected what happened inside the dome at street level. She questioned *"who is inside and who is outside? What of the mirrors on the dome's exterior? How and where do they situate, represent, and redraw the city?"*. In the same article, the author mentions the need of air-conditioning to regulate the temperature inside the structure (Kurgan 1997).

Pros and cons table

Table 4: Pros and Cons analysis of the Dome Over Manhattan (Author 2022)

Category	Advantages	Disadvantages, questions
Thermal comfort	Winter and mid-season: no need for extra heating as the greenhouse uses the passive solar technology.	Summer: the dome is prone to overheating, with its limitation of heat losses and direct sun exposure on all sides → need for air conditioning
Water supply	The dome provides rainwater collection to use in the city.	/
Solar gains	Winter and mid-season: solar gains provide an extended summer season.	During the summer, the solar gains make the dome prone to overheating.
Maintenance	/	The dome is so high and large that is difficult to clean, and with time a lot of dust, water stains and glass discoloration will occur.
Space, comfort, architecture	Good thermal performance even during the winter. Energy savings from the double skin. Uniform and higher ventilation due to its spheric shape	Since it is a city, the pollution levels might rise quickly if no sufficient ventilation is provided. The humidity levels might not be comfortable, especially in summer, as all living entities exhale water condensation from the inside of the greenhouse or dome. Fuller states that only lightbulbs will provide internal gains, but that is not true. He did not take into account the electronic devices, people, cars, and plants, which might thus cause overheating.

Overall, the Dome over Manhattan can be considered a visionary project. In fact, the nature houses that are being constructed now all use this idea as a starting point: the benefits of enclosing the living space in a glazed volume. However, like the other case studies, the DoM seems to have overheating problems, especially during sunny seasons. The choice to have a greenhouse around the core house severely adds to the amount and cost of materials, even if these are reduced by the particular geometry. This also leads to a larger embodied carbon footprint.

Goal of this case analysis: This case study is related to the biomimetic Research by Design developed in chapter 5. The goal here is to determine the pros and cons of replacing a traditionally shaped greenhouse by a geodesic dome, as well as the potential paths for improvement.

5. Summary of case study results

A parameter that is crucial is the localization of the HGH, as the pros and cons of the different cases differ depending on the climate zone. In particular, mean temperature and the quantity of daylight impact the solar and heating gains as well as the energy production and the level of humidity of the model.

The following key characteristics derived from the aforementioned case studies as well as the literature review will be used to design the HGH prototype developed in the next chapter:

- The construction materials will be glass for the greenhouse and steel or a material that does not swell with water for the inside house due to the high humidity levels
- The prototype will be oriented East-West in the longitudinal direction of the greenhouse using climatic design considerations, so that all bedrooms can easily face North (to avoid the effects of overheating in summer) and the living spaces South (to benefit from the maximum light)
- A thick layer of insulation will be incorporated in the façade of the inside house to reduce its thermal losses
- Technical equipment: a large technical space is needed to account for all supplementary energetical / water cycles systems

The analysis of the different case studies already highlighted some areas for further improvements:

- Avoid overheating of the system during the warm days
- Passive solar gains might not be sufficient to heat the whole house during cold/ cloudy days (especially in Sweden)
- Energy production shall be maximized to guarantee the autonomy of the prototype
- The glass house needs to be ventilated properly to reduce the humidity rate, the bad smells, and the inside pollution rate
- The cleaning and the maintenance of the glass house can be expensive
- The air circulation is more uniform in a spheric space like a dome than in a rectangular/ triangular greenhouse -therefore the ventilation is more efficient in a dome
- The quantity of material needed to build a dome is lower than to build a rectangular greenhouse with a sloped roof

3

CHAPTER 3

THE BUILD-UP OF V² - HGH PROTOTYPE

For the purpose of this thesis, a prototype of a house in a greenhouse (HGH) is designed, based on the case studies displayed in the previous chapter. This chapter includes descriptions of the architectural, structural, and technical aspects of the prototype, as well as illustrations. The goal is then to quantify the efficiency of the outer glass skin as an insulation layer through energy consumption simulations.
All mentioned dimensions are in meters (m).

III. CHAPTER 3 – THE BUILD-UP OF V² – HGH PROTOTYPE

Description of the HGH prototype

The HGH prototype that is designed for this thesis is original and based on the literature review and the case studies analyzed in the previous chapter. The project is called V², with a V from *vetro* (meaning *glass* in Italian) and the V from *verde* (meaning *green* in the same language, both in the sense of sustainable and the colors of nature).

The inside house accommodates a single family of 4 or 5, with someone working (partly) from home. All residents have access to the agricultural production of the greenhouse for their consumption. The project is situated in Brussels, Belgium. The design aims to provide both a comfortable and sustainable way of life for its inhabitants, amid nature (Figure 18 and Figure 19). One of the purposes of the house it to live more connected with nature as it is accepted that it has positive effects on health and wellbeing. This concept is named biophilia (Grinde and Patil 2009) (Superior Health Council 2021).

Layout

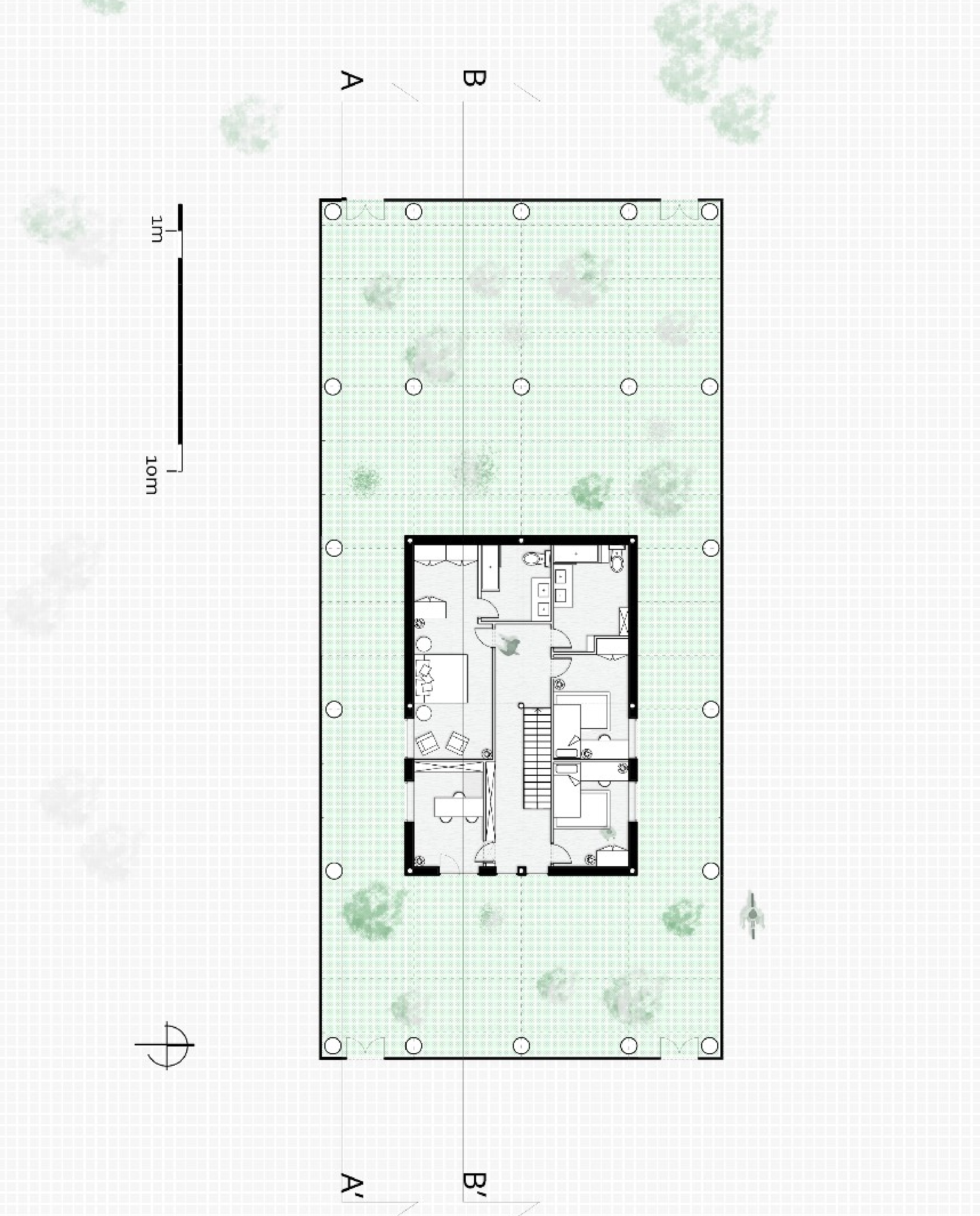
V² is composed of two parts: the core house and the greenhouse. The core house counts two floors of 96 m² each (12x8m), each 3m high. The roof is flat.

On the upper floor, there are three bedrooms, one office and two bathrooms. Most bedrooms are oriented towards North to avoid overheating during the summer and provide a constant, soft light throughout the day (Figure 17).

Downstairs, all living spaces are oriented South and open-up to a large wooden terrasse, to enjoy the sun as much as possible. The technical installations, as well as a laundry room and storing areas are located on the Northern side of the house (Figure 18).

The following pages contain plans and sections of the prototype. They were turned to have a better overview.

Figure 17: First floor of the house: 3 bedrooms, one office, 2 bathrooms (Author, 2022)



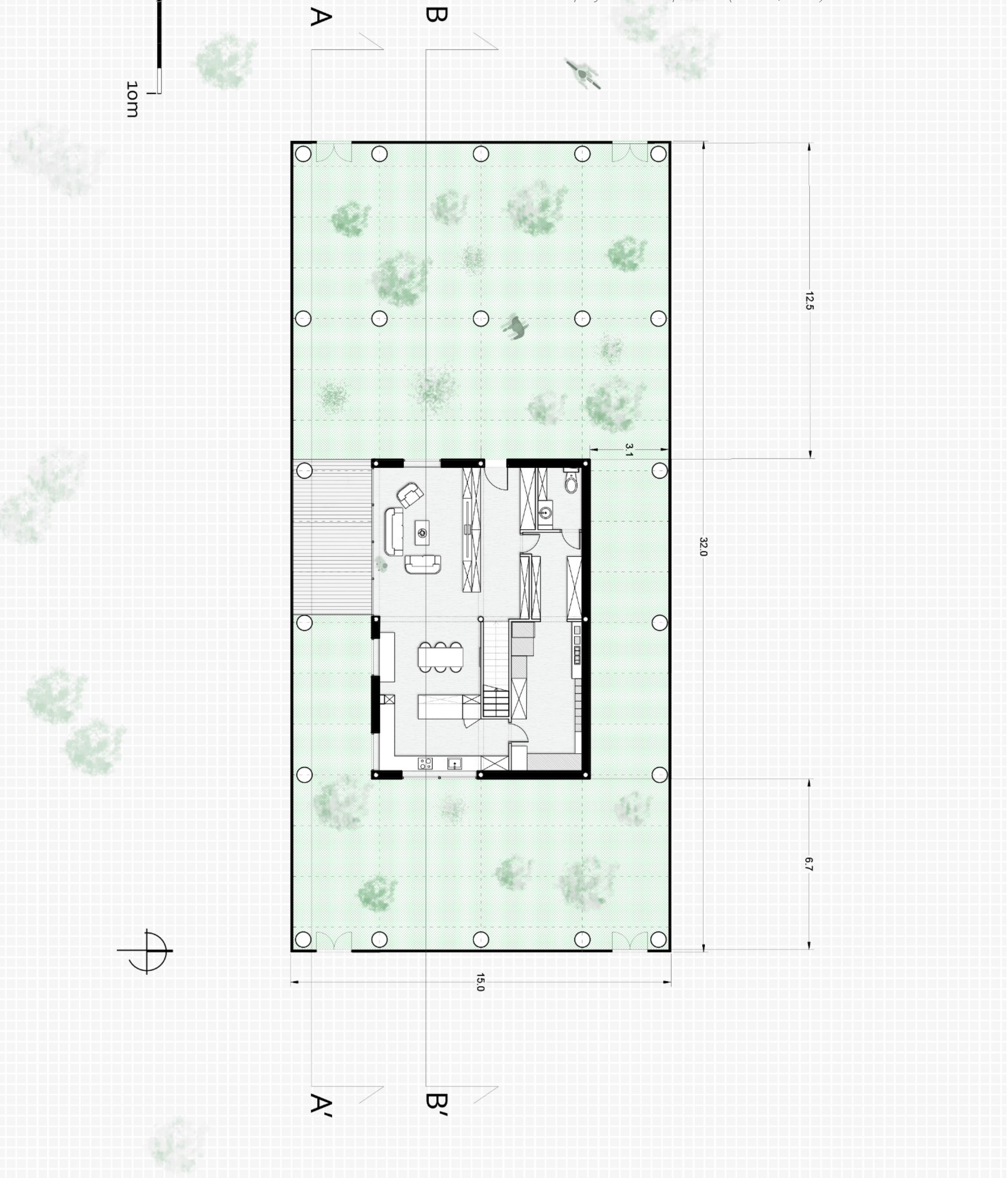


Figure 18: Groundfloor of the house: living room, kitchen, technical spaces, terrasse and the greenhouse. The dimensions of the different elements are displayed on this picture. (Author, 2022)

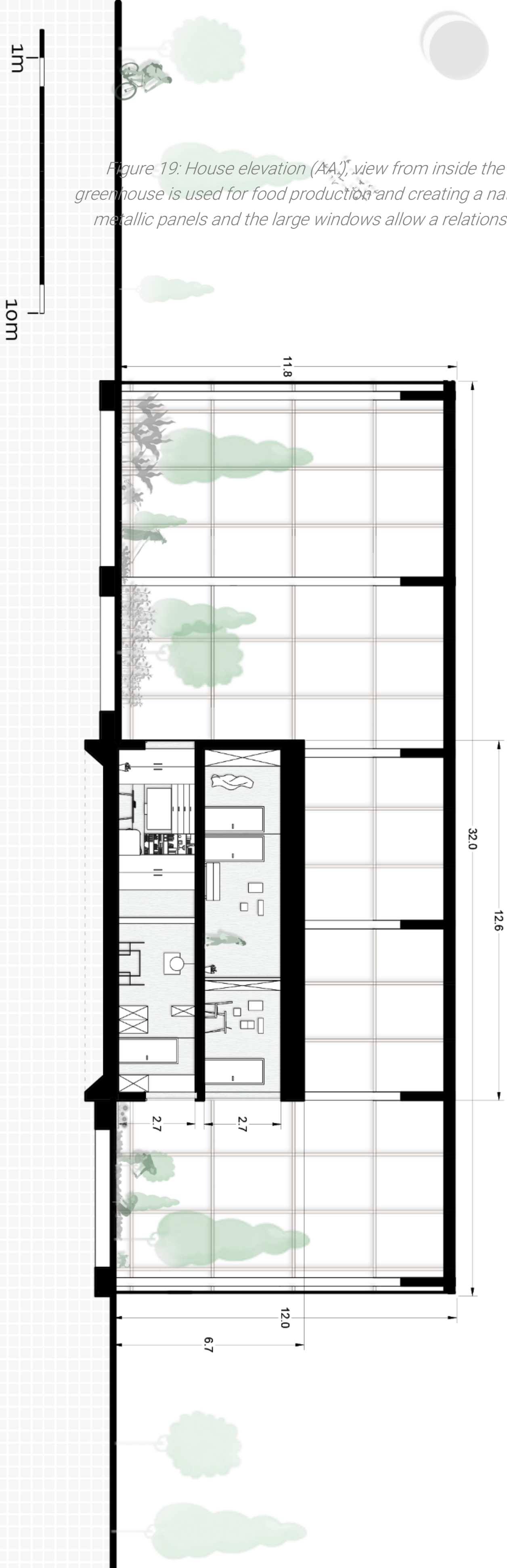


Figure 19: House elevation (AA'), view from inside the greenhouse and outside the house. The greenhouse is used for food production and creating a natural environment; the house is cladded with metallic panels and the large windows allow a relationship with the surroundings. (Author, 2022)

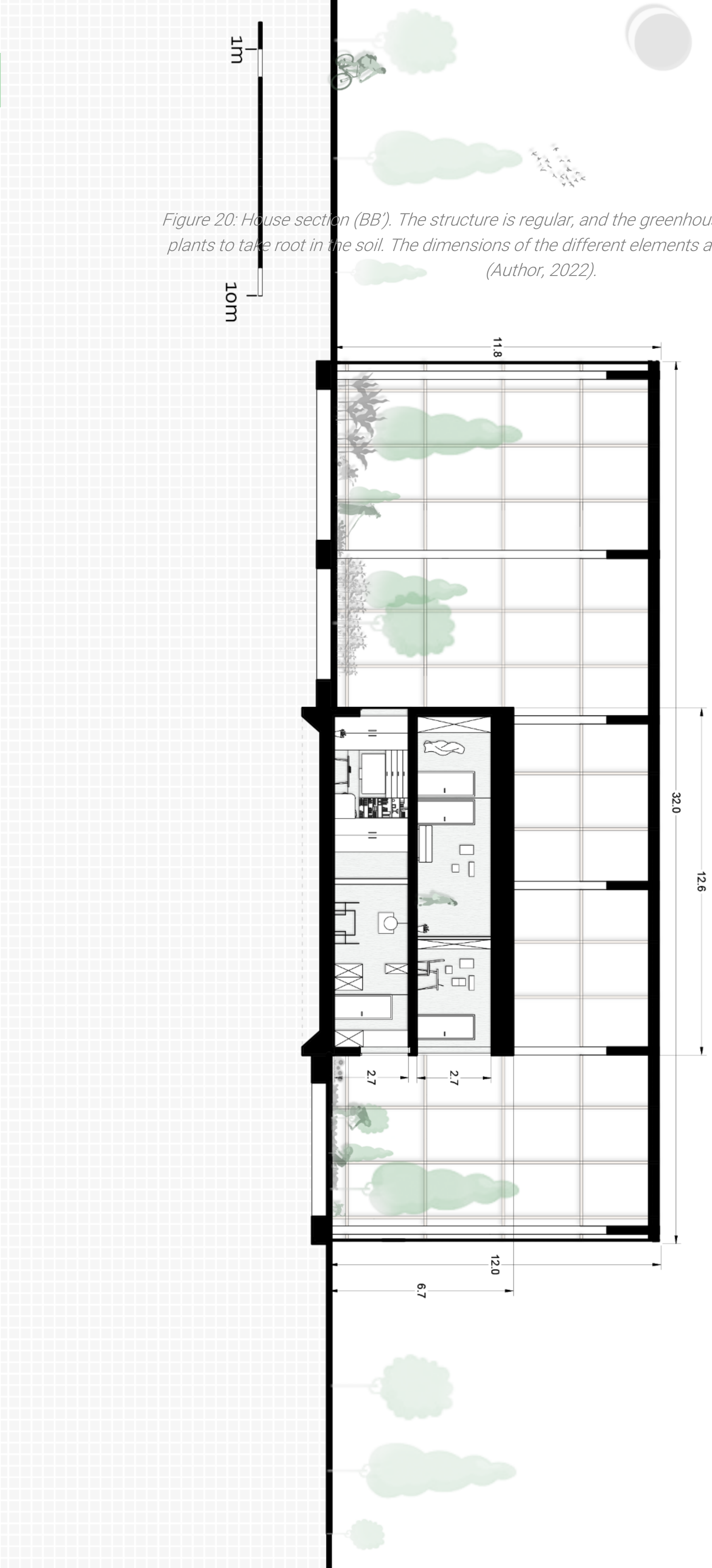


Figure 20: House section (BB'). The structure is regular, and the greenhouse foundations allow for the plants to take root in the soil. The dimensions of the different elements are displayed on this picture (Author, 2022).

Figure 20 shows that the windows of the house are in double glazing, with aluminum frames and a thermal break. They are placed very high and hidden in the slab above in order to open up the view to see the natural surroundings. The structure of the inside house is composed of steel columns and beams, concrete foundation slab and wooden floors. The walls are lightweight, made up of metallic panels for the outdoor cladding, and are insulated with a rockwool layer. The thickness of this insulation will be changed for the processing of the energy scenarios.

The cladding panels create patterns (Figure 19). Metal was chosen over, for example, a wood cladding because the interior of the greenhouse can get humid due to the vegetation– as noticed in Kaseco. Since wood absorbs water and inflates, cracks could appear on the façades or inside the home. This could lead to additional maintenance costs or other problems later on. Metal has the advantage of being waterproof if treated against rust.

The greenhouse's surface covers 480 m² (32x15m) with a 12m high double-sloped roof. Its structure is also composed of steel tubular sections for the columns, as well as I-beams. The foundations are made up of a concrete slab, where plants can grow without limitations in the holes, as shown on Figure 21. The windows of the greenhouse are in simple glazing (Figure 20).

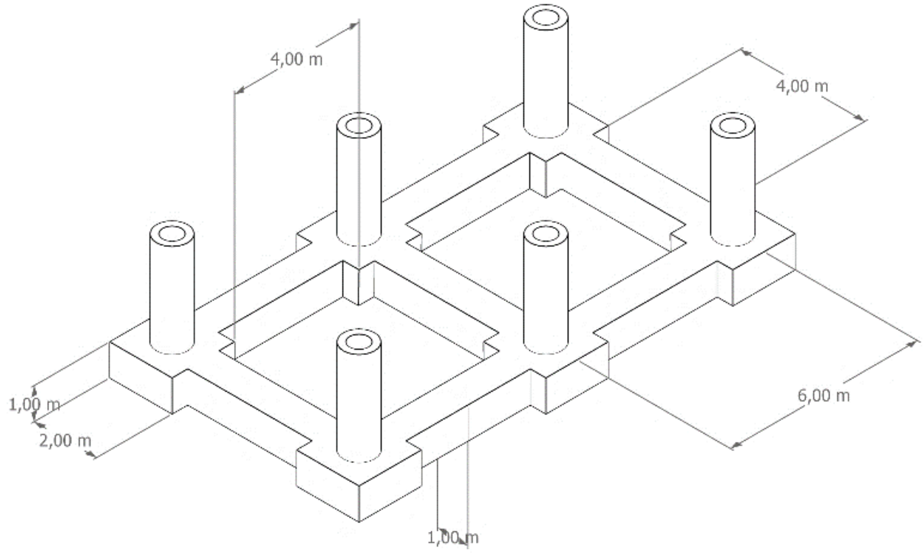


Figure 21: Greenhouse foundations scheme: holes are left open to plant crops and trees (Author, 2022)

Technical elements

First, V² uses solar energy collected via solar panels on the greenhouse roof, so that the house is autonomous both in hot water and electricity production.

Second, the rainwater that is collected on the roof of the greenhouse and covers both drinkable (filtered) and non-drinkable water needs. The grey wastewater of the house is also filtered several times before being used to nourish the plants of the greenhouse. This ensures a closed water loop system where V² is again autonomous.

All the aforementioned aspects of V² are illustrated on Figure 22 below.

This design, with alternations in terms of amount of insulation and/or greenhouse, is used in the following chapter for various energy simulations.

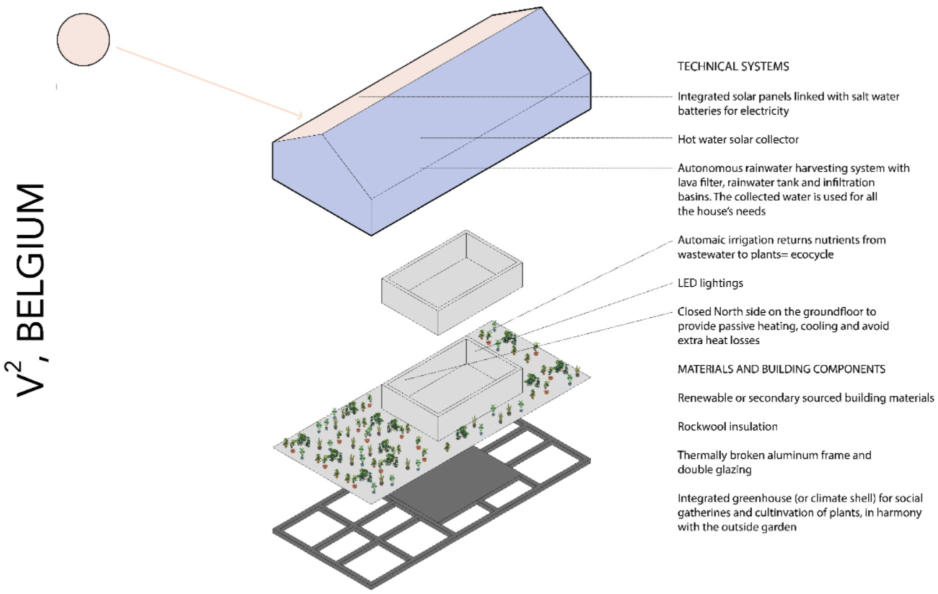


Figure 22: V² organization, built-up and systems (Author, 2022)

Further details on the prototype are available in Appendix 5 – Details of Prototype V² p.182.

4

CHAPTER 4

ENERGY SIMULATIONS

The aim of this chapter is to determine whether surrounding a house by a greenhouse provides sufficient thermal insulation. To that end, dynamic energy simulations of five insulation scenarios were conducted using the software Open Studio, an Energy Plus interface that was coupled with the 3D modeling program Sketchup. This chapter will first go over the different scenarios and provide some hypotheses on the results. Afterwards, all input data will be explained before diving into the actual simulations. The results are then compared, and a conclusion is drawn on the thermal impact of the greenhouse

IV. CHAPTER 4 – ENERGY SIMULATIONS

1. Introduction

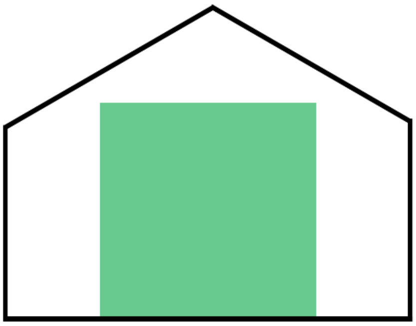
Scenarios

To understand how or how much influence the greenhouse has on the insulation of the core house, dynamic energy simulations[7] will be conducted.

Because of its scope and research question's specificity, this thesis will focus on five scenarios (Figure 23) to deliver concluding and quantifiable results:

SCENARIO 1

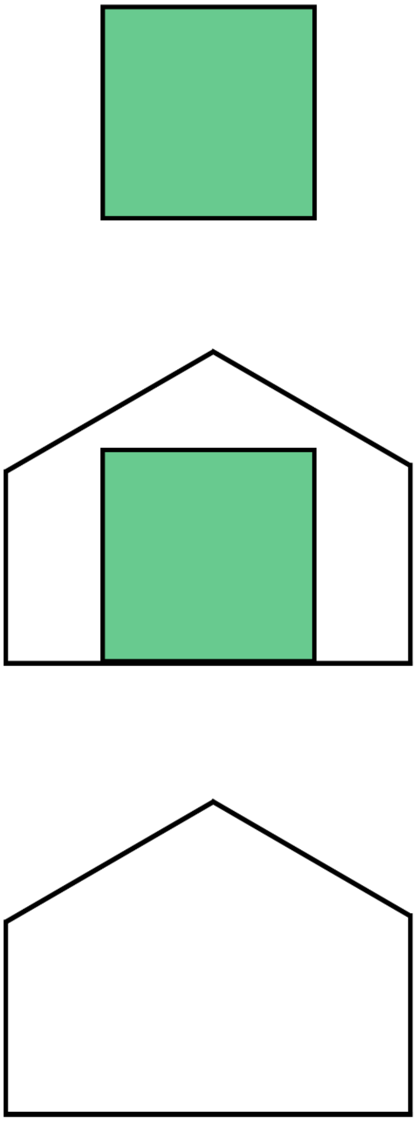
No greenhouse, just the core house, 0 cm of insulating materials on the envelope



SCENARIO 2

Greenhouse around the core house, 0 cm of insulating materials on the envelope

[7] Dynamic simulations are conducted over an extended period. Stationary (or static) simulations are carried out for one instant t.



SCENARIO 3

No greenhouse, just the core house with 33 cm of insulating materials on the envelope

SCENARIO 4

Greenhouse and core house with 33 cm of insulating materials on the envelope

SCENARIO 5

Greenhouse only

Figure 23: Energy simulation scenarios. From top to bottom: scenario 1 (house only, no insulation); scenario 2 (house and greenhouse, no insulation); scenario 3 (house only, insulation); scenario 4 (house and greenhouse, insulation); scenario 5 (greenhouse only) (Author, 2022)

Definitions

Three key results will then be analyzed: heating demand, cooling demand, and energy demand. These outcomes are expected to give insights about the validity of the HGH concept in Belgium.

Like any other building, V² presents:

- *Energy* (or heat) *gains,* which result from the heat caused by the sun (solar gains) and the heat generated inside (from people, equipment, and plants).
- *Energy* (or heat) *losses,* which result from transmission losses (through the walls and ceiling of the house; through the walls and ceiling of the greenhouse); and ventilation losses.

Given the energy gains and losses:

- *The heating demand* is the amount of heat that needs to be added to reach a comfortable temperature inside the house (here 20°C).
- *The cooling demand* is the amount of heat that needs to be removed to reach the comfort temperature inside.
- *The energy demand* is the difference between the losses and the gains, the latter multiplied by the gain utilization factor[8] which will be independently calculated. In short, it is the sum of demands for heating or cooling to keep the temperature inside comfortable. The energy demand is the heat that must be added or removed for the house to stay at a comfortable temperature (i.e., 20°C here). Analyzing the energy demand of the five scenarios will thus give an insight on the insulating properties of the greenhouse.

To properly define the inputs of these simulations, a few parameters must be detailed, namely the climate type, the number of residents and their activity levels (including presence duration in and out the house) the plants grown inside the greenhouse (quantity, type, heat production) and the equipment’s share of heat production.

[8] The gain utilization factor is automatically calculated by the software.

Assumptions

Intuitively, preliminary conclusions can be drawn before going into the simulations:

- Scenario 1 compared to scenario 2 shall demonstrate that adding a greenhouse will increase the core house's indoor temperature on average, reducing the heating demand. However, it could result in increased cooling demand. The air layer between both constructions will insulate the house.
- Scenarios 2 and 3 will allow to compare the general efficiency of both insulation techniques (greenhouse vs insulating layer). They should both insulate the core house. Per contra, the HGH concept is known to tend towards overheating, so the scenarios might have different shares of heating and cooling demands.
- Scenario 4 compared to scenario 2 should show that adding an insulating materials layer on the core house already surrounded by a greenhouse will decrease both cooling and heating needs, thanks to improved insulation. This fourth scenario should result in the best energy efficiency of all.

2. Input Data

Parameters' definition

People

A family of five lives in V[2]: the parents (Laura and Natasha), their two kids (Leo and Alexei) and Emily, Alexei's partner (Figure 24).

- The two moms (respectively 45 and 46 years old) live there full-time, and Laura works from home while Natasha is at her office every weekday from 8AM to 7PM.
- Leo (20) is a law student. He lives at home but is usually at university from 8AM to 7PM.
- Alexei (22) studies architectural engineering. They live with their girlfriend Emily in a campus dorm room and come home for the weekend.

All five usually have breakfast together in the city every weekend morning from 8AM to noon, leaving the house empty. Laura and Natasha then go to their weekly walk on Saturday and their pottery class from 1PM to 8PM.

It is assumed that each person produces 120W/sqm in the house (low to mixed activity levels) and 100W/sqm (low activity levels) in the greenhouse[9].

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[9] More details in appendix, p. 180

Figure 24: People definition: V² residents. All illustrations were drawn by the author (Author, 2022)

Schedules and affluences

Based on the assumptions above, it is possible to draw the affluence graphs of the house's use for one typical week, separating weekdays (Monday to Friday) and weekend days (Saturday and Sunday) (Graph 1).

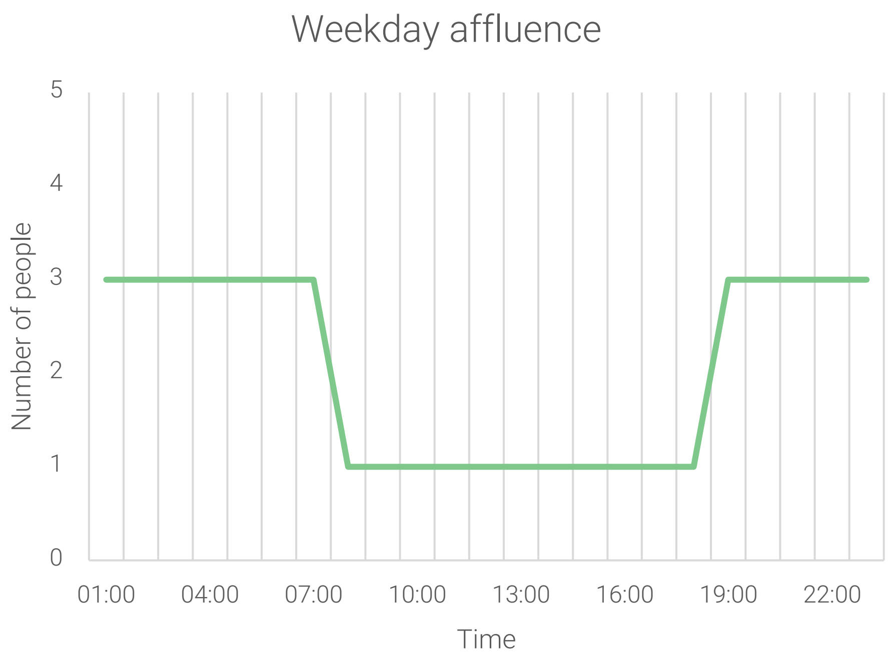
Climate and time period

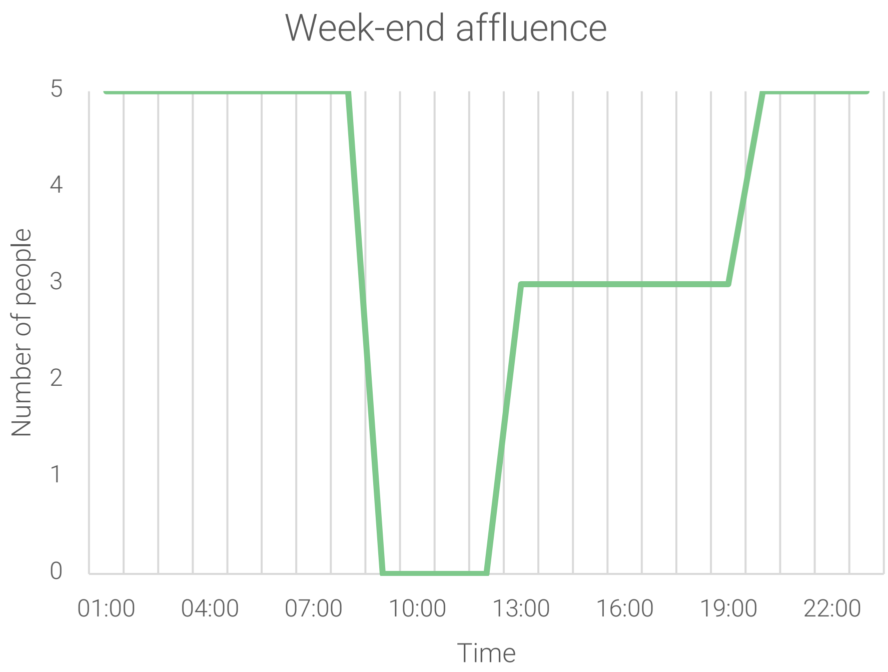
The software has been parameterized for a house in Brussels. It automatically considers the characteristics of the climate zone for the simulations over one full year.

The key assumption of the simulations is that the target temperature to reach inside the core house is 20°C every day of the year.

Equipment

It is assumed that lighting produces 7 W/m^2 in the house (Descamps 2021), 5W/m^2 in the greenhouse, and computer equipment 5W/m^2 in the house (Shesho, Tashevski and Filkoski 2020) when people are present. The presence of people is dictated by the affluence graphs on the next page.





Graph 1: Weekday (top) and weekend (bottom) affluence. The number of people present in the house changes the internal gains as people produce heat. (Author, 2022)

Plants

Carbon dioxide increases temperatures. Hence, photosynthesis reduces temperatures. Moreover, plants produce heat during their blossoming phase. The following paragraphs will quantify this heat production in order to add it to the simulations.

The US NOAA (National Oceanic and Atmospheric Administration) argues that with increased CO_2 concentrations comes an increase in temperatures (NOAA 2021). A reverse statement is also true: in the process of photosynthesis, plants absorb carbon dioxide, a greenhouse gas, and sunlight, lowering the temperature (Kurniawan 2004). Photosynthesis uses energy from light and is thus only possible during the daytime for most plants. Since it uses CO_2, the temperature will decrease during the day. However, at night, indoor temperatures inside the greenhouse will rise if the system is closed and no air exchange with the outside is possible (Kurniawan 2004).

Heat production only happens during the blossoming phase of plants. It depends on the rate of CO_2 emissions from plants, according to the calorific equivalent of $1\,{}^{\mu mol}/_{s} = 0{,}47\ W$ (Seymour 2010). It is a process that necessitates a lot of energy from plants, which they only use to enhance pollination during the flowering time. A study compared the heat production of plants with their mass (Seymour 2010). Given the scope of this thesis, an average value of the ratio power over mass was calculated at 0,013 W/g of plant per year (refer to Appendix 6 – Energy simulations p. 186).

Next, it was important to define which vegetables would grow inside the greenhouse to know when they would bloom, hence produce heat. Three commonly found vegetables were chosen: local trees, beans, carrots, and tomatoes. It is assumed that each type of crop will cover one fifth of the greenhouse's net open area, the rest being occupied by circulation paths and resting spaces.

Based on the average mass of one of each of these crops' production per square meter multiplied by 0,013 W/g, the power of each crop can be determined. Considering the area allowed for each entity multiplied by the share of blooming time (i.e.: when they produce heat); the final amount of power (or heat production) per plant is calculated[10].

Overall, it can be assumed that all plants and trees will, in the greenhouse, produce 486 kWh per year[11] and contribute to internal heat gains.

[10] These calculations are further detailed in Appendix 6 – Energy simulations, p.196

[11] This number was determined by summing each individual result.

Materials

The following Table 5 includes all materials that were used in the V² prototype. The materials and building techniques are simplified and typical for a new construction in Belgium with a metallic structure, façade cladding and decking, double glazing windows in the house and simple for the greenhouse, and the floors with concrete, screed, and a wooden covering. The green materials on Table 8 refer to the insulating layers that will change with the scenarios. Further information is available in Appendix 6 – Energy simulations, p.191

Table 5: V² materials table (Author, 2022)

	HOUSE	GREENHOUSE
Localization	Material	
EXTERIOR		
Roof	Metal roofing	
	Insulation mineral wool	
	Metal decking	
Walls	Metal finish	
	Insulation mineral wool	
	Dry wall	
Slab	Wooden parquet	
	Screed	
	Insulation mineral wool	
	Concrete foundation slab	
SUBSURFACES EXTERIOR		
Windows roof		Glass
Windows walls	Glass	Glass
	Air	
	Glass	
INTERIOR		
Wall	Dry wall	
	Air	
	Dry wall	
Floor	Wooden parquet	
	Screed	
	Plywood	

Model simplifications

- The house is considered as one thermal zone, not considering the different rooms inside as their own insulation value can be neglected compared to the outer walls.
- Table 6 summarizes the power produced by the different elements as per hypotheses on input data detailed hereabove.
- Due to limitations of the Openstudio program, the HGH model is designed having walls and roof composed of (from out to in): glazed surface – 3m or more of air – metal finish – (insulation) – dry wall complex. This ensured that the software would understand the actual repercussions of this double skin on the energy fluxes of the model (Figure 25).

Table 6: summary of the input data (Author, 2022)

	House	Greenhouse
Equipment	5 W/m²	0
Lighting	7 W/m²	5 W/m²
People	120 W/m²/p	100 W/m²/p
Plants	0	486 kW/yr

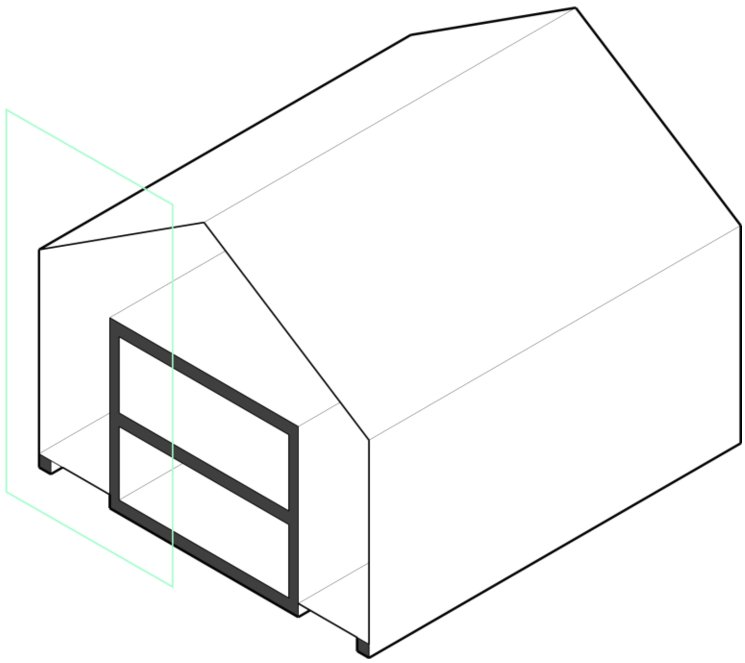


Figure 25: section of the model design assumptions in Openstudio. Assumption: each wall is a very thick complex which includes both layers (green). (Author, 2022)

3. Simulation results

The software studies the energy performance of the system during one entire year based on the climatic zone area. All seasons are considered. The output of the simulations is the total energy demand needed in order to have a constant 20°C temperature inside the core house.

The most relevant results of total energy, cooling, and heating demands per year for the core house only are displayed in the following table and graphs.

The 4 scenario summary tables of the OpenStudio simulation results are available in the Appendix 6 – Energy simulations (P. 193 - 194).

The sum of the heating and cooling demands equals the total energy demand.

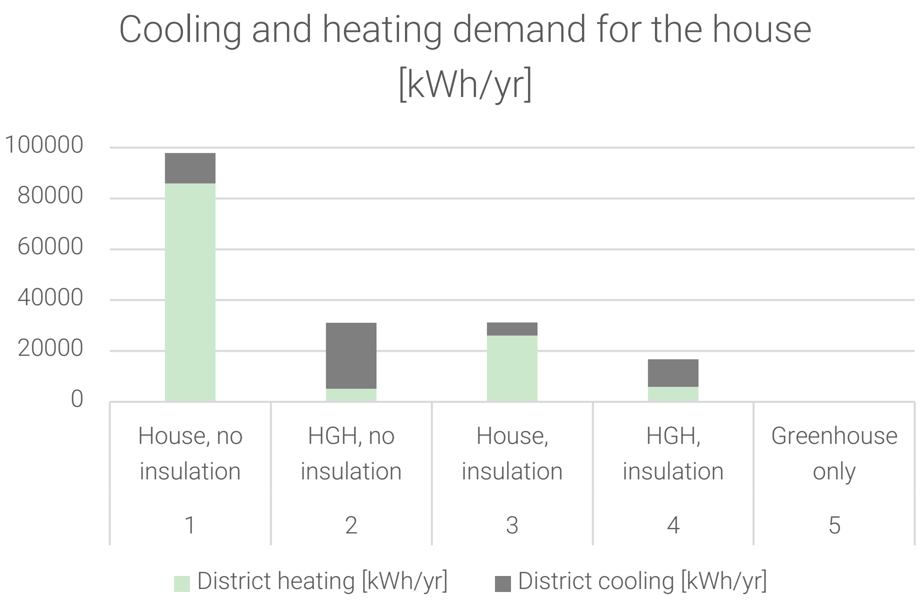
Table 7: heating and cooling demand for the house [kWh/yr] of each scenario (Author, 2022)

Scenario number	Scenario name	Heating demand [kWh/yr]	Cooling demand [kWh/yr]
1	House, no insulation	85914	11997
2	HGH, no insulation	5156	25955
3	House, insulation	25986	5172
4	HGH, insulation	5917	10755
5	Greenhouse only	0	0

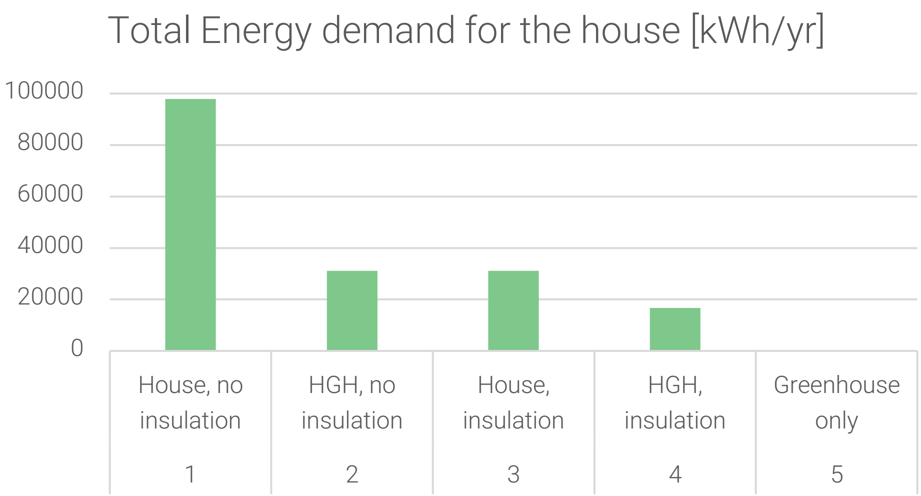
Table 8: total energy demand for the house [kWh/yr] of each scenario (Author, 2022)

Scenario number	Scenario name	Total Energy demand for the core house [kWh/yr]	Energy demand in % of scenario 1
1	House, no insulation	97911	100%
2	HGH, no insulation	31111	31,77%
3	House, insulation[12]	31158	31,82%
4	HGH, insulation	16672	17,03%
5	Greenhouse only	0	0,00%

[12] *Insulation* refers to the 33 cm of Rockwool insulating composite (with cavities) all around the envelope of the house (ceiling and walls).



Graph 2: Cooling and heating demand for the house [kWh/yr] (Author, 2022)



Graph 3: Total energy demand for the house [kWh/yr] (Author, 2022)

The following conclusions can be drawn from the simulation results.

- The house with no insulation and no greenhouse (scenario 1) has the highest energy demand, which makes sense as the systems must work harder to keep the house at a stable temperature, knowing that the heat gains and losses are important
- Scenarios 2 and 3 (insulating the house with Rockwool vs with a greenhouse) have similar total energy demand results. This proves that the greenhouse acts like a(n) (33cm) insulating layer, integrated in the roof and walls of a house. Furthermore, it is worth noting that the total yearly energy demand decreases by more than two thirds compared to scenario 1 without any insulation.
- However, scenarios 2 and 3 show contrary levels of heating and cooling demand. Indeed, the greenhouse will increase solar gains, hence reduce heating needs during the cold season but adding cooling needs during the warm season compared to a traditional insulation. Similarly, more heating is needed with a traditional insulating material than with a greenhouse during the cold season. This observation confirms the risk of overheating during warm days observed in the case studies if the house is insulated with just a greenhouse.
- Scenario 4 has the lowest energy demand of all. It shows that having a greenhouse as well as an insulated house (therefore two insulation layers) allows remarkably high energy savings. The total energy demand of this system is divided by two compared to scenarios 2 and 3 where there is only one insulation layer. It shows that the house will consume only 17,03% of the energy demand required in scenario 1 to maintain the same internal temperature. However, despite two insulation layers, the prototype is not fully autonomous in terms of heating and cooling since the total energy demand is still 16672 kWh/yr. This confirms a potential need for extra heating during frigid days.
- Scenario 4 has lower levels of energy demand than scenarios 2 and 3. It also has a lower heating demand, but a slightly higher level of cooling demand compared to scenario 3. Cooling needs are higher than heating needs. Once again, this observation suggests a risk of overheating during warm days.
- Scenario 5 shows of course no energy demand here, as this thesis looks at the energy demand of the house only.

Rationality of simulation results

According to the US Energy Information Administration, the typical energy consumption of a house reaches about 10000 kWh/year/US resident (U.S. Energy Information Administration 2021). Accounting for the fact that there are about three to five people in this prototype house, the theoretical consumption would reach circa 40000 kWh/year for the insulated house (scenarios 2 and 3). This calculation confirms the reasonableness of the prototype simulation results, giving a little bit more than 30000 kWh/year for scenarios 2 and 3.

Moreover, the French *Engie* group states that a typical 100m² well-insulated household consumes around 16975 kWh/year in total of which 10542 kWh/year of heating. Since V²'s core house covers almost 200m², this number can be multiplied by two, and reach 21284 kWh/year. This is in tune with the heating demand of 31158 KWh/year of the scenario 3 (taking into account the 20° target temperature for the prototype) [13].

[13] More details can be found in Appendix 6 – Energy simulations p.203

4. Conclusion and discussion

To conclude the simulation findings:

- The greenhouse around the house is as energy efficient as a typical 33 cm insulation layer integrated in the envelope of the house in terms of total energy demand of the system
- Combining two insulation layers (greenhouse and house with 33cm insulation as in scenario 4) reduces the energy demand of the system by six, or approximately 81.000 kwh/year, compared to a single non-insulated house
- Despite two insulation layers, the prototype is not autonomous in terms of heating and cooling throughout the full year. This demonstrates that some extra heating is still needed during cold/cloudy days.
- The energy demand for cooling is five times higher with a greenhouse than in a traditionally insulated house in Belgium. With two insulation techniques, it is still more than twice higher than with a single 33 cm traditional insulation layer. This proves that the greenhouse may cause some overheating during warmer days even when the core house is also insulated.

In conclusion, adding a greenhouse to an insulated house is a very smart way of improving its energy efficiency since it would further reduce its energy demand by 14486 kWh/year (approximately half). In addition, the greenhouse does not only provide insulation, contrary to a composite layer, it also provides an indoor farming station for local food production, semi-outdoor spaces that can be used at all hours of the day and year, and of course health qualities linked to biophilia (see chapter 3). It will however use more outdoor space around the house as well as additional resources and materials.

Yet, the greenhouse as-is shows flaws as observed in the case studies and demonstrated with the simulations. The system is not completely autonomous from an energy standpoint since there are additional cooling needs during warm days and still need for extra external heating during cold days. Other weaknesses observed in the case studies are overbrightness and risk of high humidity levels especially during these warm days.

The following chapter will analyze biomimetic design scenarios to address and/or mitigate these weaknesses as well as maximize the energy production with renewable systems.

5

CHAPTER 5

BIOMIMETIC RESEARCH BY DESIGN

Chapter 5 presents the results of the Research by Design conducted to address the weaknesses of the HGH identified during the case studies analyses and the energy simulations and maximize its energy production. Following the Challenge to Biology methodology described in Chapter 1, some biomimetic explorations will be conducted to optimize V²'s greenhouse: adding to the greenhouse (termite mounds, desert rhubarb's leaves, the flectofin system, the chameleon's hexagonal pattern); changing the shape of the greenhouse (sunflowers, geodesic dome); and lastly two scenarios which combine the options studied before. In the end, all scenarios will be compared and assessed in a critical way.

V. CHAPTER 5 – BIOMIMETIC RESEARCH BY DESIGN

1. Research Process – Challenge to Biology

The simulations and the case studies presented in the previous chapters demonstrated the insulating advantages of the greenhouse surrounding the house. However, several issues were also found for the HGH prototype. The five main weaknesses identified are the high humidity rate, the overheating during warm days, some residual heat needs during cold days, the high illuminance levels and the unoptimized renewable energy harvesting systems.

The aim of this chapter is to propose biomimetic solutions to optimize the HGH prototype by improving/ solving these issues using the top-down approach of the Research by Design process (RbD) as explained in Chapter 1.

The following steps of the *Challenge to Biology* RbD process were applied to find solutions to the weaknesses identified: (1) Identify; (2) Define; (3) Biologize; (4) Discover; (5) Abstract; (6) Emulate; (7) Evaluate (as defined in the literature review Research by Design and Biomimicry18).

(1) Identify the function

The goal(s) pursued with the modified design of the greenhouse are:

- Prevent overheating on warm days
- Reduce the humidity rate
- Reduce heat losses on cold days
- Reduce the illuminance levels in the greenhouse
- Optimize the energy harvesting systems

(2) Define the context

The modified design is to be applied on or replacing a greenhouse surrounding a core house in an oceanic temperate climate zone like Belgium. Scenario 4 – house with 33 cm of insulation surrounded by the greenhouse - is used as a base for the research of this chapter, as it is the scenario with the lowest total energy demand.

(3) Biologize the problem

The following (non-exhaustive) processes which aim at improving thermal and energy efficiency were identified in nature:

- Ventilating
- Covering
- Following the orientation of the sun
- Capturing humidity
- Changing skin color in reaction to the sunlight

(4) Discover natural models

The following biological organisms, behaviors and / or ecosystem allowing the natural processes above were analyzed in depth (Figure 26):

- Termite mounds
- Desert rhubarb leaves
- Chameleon skin
- Sunflower and Strelitzia Reginae flower behavior

Figure 26: From left to right and top to bottom: termite mound (@brewbooks on Flickr); desert rhubarb leaf (Karin Kloosterman); sunflower (Jon Sullivan); chameleon (Martin Van Lokven / Minden Pictures); Strelitzia Reginae flower (@ntdanai on iStock).

(5) Abstract the design principles

The table below shows a description of the key elements of the problems translated into the technical needs and proposes a biomimetic solution to address them.

Table 9: Biomimetic Research by Design: abstraction of the design principles: translation of the problem into a technical solution and search of an organism or mechanism to bio mimic to act like the technical element (Author, 2022)

Problem	Translation into technical solution	Biomimicry
Summer: Overheating	Natural ventilation Sun shading	Termite mounds ventilation Double face system (Desert Rhubarb) Kinetic façade (Strelitzia Reginae) Hexagonal parametric pattern (chameleons)
Winter: Non-sufficient natural passive heating	Limit heat losses	Kinetic façade (Strelitzia Reginae) Hexagonal parametric pattern (chameleons) Geodesic dome
High humidity levels	Natural ventilation	Termite mounds Kinetic façade (Strelitzia Reginae) Hexagonal parametric pattern (chameleons) Geodesic Dome
High illuminance	Sun shading	Double face system (Desert Rhubarb) Kinetic façade (Strelitzia Reginae) Hexagonal parametric pattern (chameleons)
Energy harvesting not optimized	Water collection Solar energy harvesting	Double face system (Desert Rhubarb) Hexagonal parametric pattern (chameleons) Geodesic dome Following the sun path (sunflowers)

A noticeable feature of this table is that one technical, architectural solution can solve more than one design problem, and it can be based on more than one natural approach.

(6) Emulate nature's strategies

To emulate the natural strategies described above, three categories of interventions on the V² prototype were considered, based on the type of bio-modification on the greenhouse: adding/subtracting, modifying and the combination of the two.

The following table enunciates all the interventions considered and therefore defines eight different scenarios in total: four additions, two modifications and two combinations. For each, the degree of Biomimicry described in the state of the art is also added.

Table 10: Biomimetic Research by Design scenarios divided into three categories: add, change, and the combination of the two (Author, 2022)

i - Addition	ii - Modification	iii - Combination
1.1 - Termite mounds (ecosystem)	2. 1 – Sunflower (ecosystem)	3.1 - Sunflower + termite + flectofin + desert rhubarb
1.2 - Desert Rhubarb (organism)	2.2 - Geodesic dome (ecosystem)	3.2 - Geodesic dome + chameleon
1.3 – Flectofin / Strelitzia Reginae (organism)		
1.4 – Chameleon (organism)		

Adding to the greenhouse

1.1. Natural ventilation: termite mounds

Solves/improves: humidity, overheating
Aggravates: heat losses
Does not change: energy harvesting, brightness

Scenario 1.1 uses the methods of termite mounds to ventilate the greenhouse in a natural manner. In the comprehensive conference report *What termites can tell us about realizing the living building* by Scott Turner and Rupert Soar, research about linking termite mounds to the ventilation of buildings was investigated. The authors concluded that termite mounds do not rely solely on air coming in and getting out but work with a mechanical drive like a human's lungs with the contraction of the diaphragm. This was also proven by the biomimetic approach used in the Eastgate Center by Mick Pearce and ARUP Engineering (1996, Zimbabwe) (Turner and Soar 2008).

However, the last 25 years have shown that the Eastgate Center (Figure 27) building relies a lot on mechanical fans to allow the air to turn, instead of solely the passive method of the termites (Turner and Soar 2008).

To summarize, the conclusions of the report show that lung ventilation is launched by the tidal movement of air, in turn put in motion by active respiratory muscles. Similarly, termite mounds collect energy from the chaotic transients that characterize turbulent winds (Figure 28) (Turner and Soar 2008).

The role of the mound is thus to use the winds to create a diaphragm effect and provide natural ventilation.

Therefore, scenario 1.1 will focus on creating a porous envelope where the high-frequency components of turbulent winds may cool its surface layers through evaporation. This will provide natural cooling for air driven through the walls by the lower-frequency components of the wind.

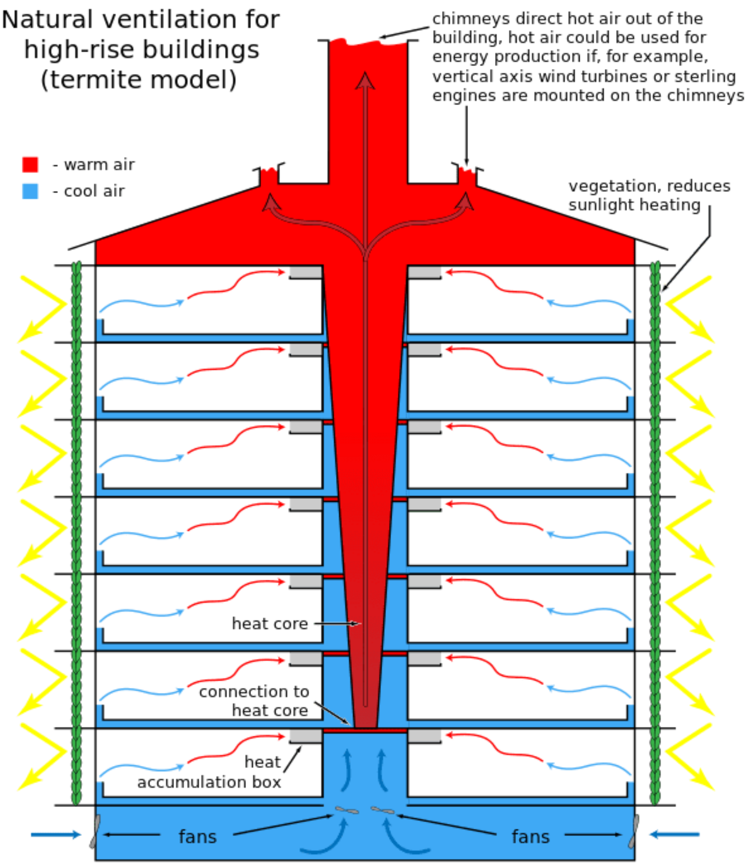


Figure 27: Eastgate Center by Mick Pearce (1996, Zimbabwe) (found on the asknature.org website (Biomimicry Institute 2006))

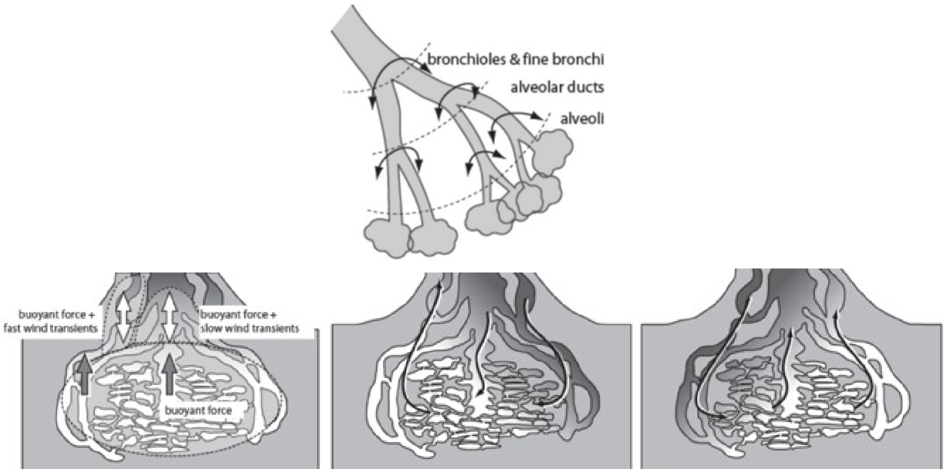
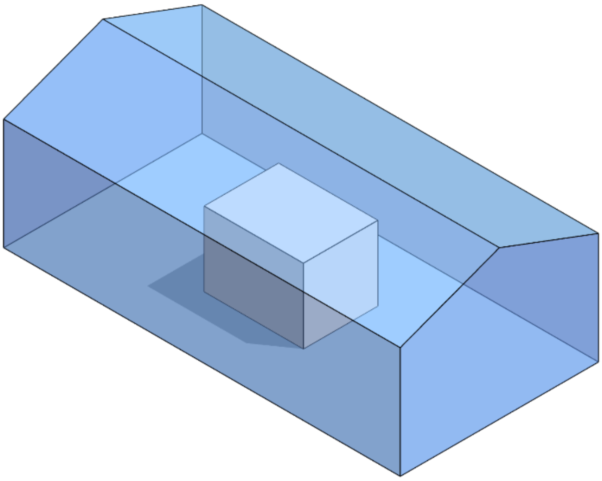


Figure 28: The working system of lungs (top) and termite mounds (bottom): both need a diaphragm for the air to move and ventilate (Turner and Soar 2008)

The steps are represented on Figure 29.

Steps:

1. Scenario 0 – V^2 as designed
2. Adding the chimney[14] – need something to work as a diaphragm
3. Changing of the façades from closed to porous, allowing for natural ventilation thanks to the natural forces and the stack effect



[14] The chimney includes a cover on top, comparable to a traditional chimney to avoid any water getting inside.

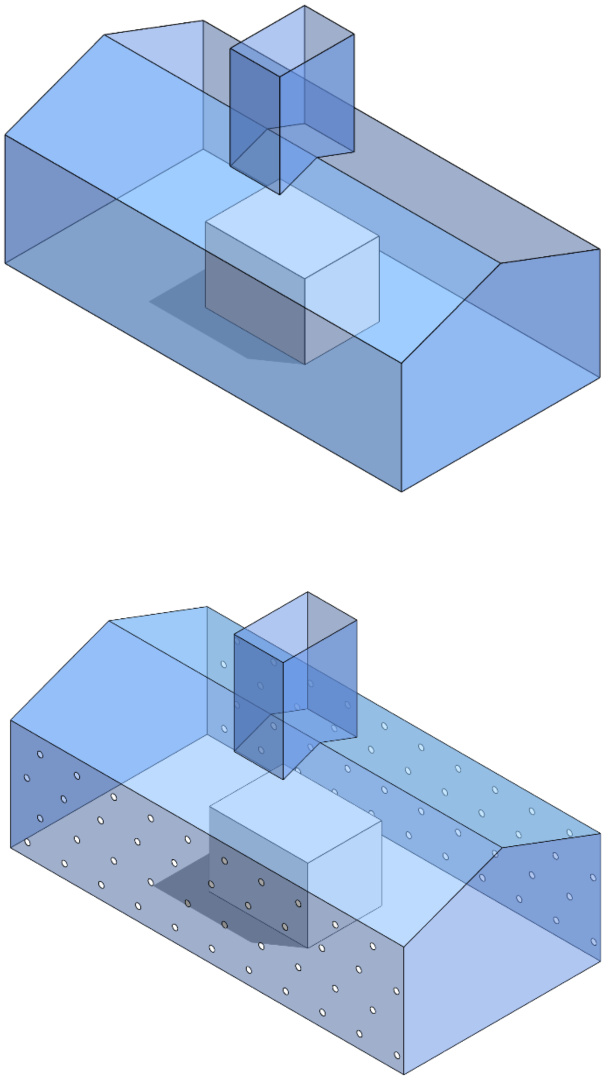


Figure 29: Termite mounds RbD steps: a) house in the greenhouse, scenario 0; b) addition of the chimney; c) modifying the walls to be porous and allow the wind's force to provoke the ventilation (Author, 2022)

1.2. Sun-shading and water collection: Desert Rhubarb

Solves/improves: overheating, energy harvesting, brightness
Does not change: humidity, heat losses

Scenario 1.2. is based on the *Rheum Palaestinum* (also called the Desert Rhubarb). This uncommon perennial plant is found in Jordan and Southern Israel, where it flourishes in locations with minimal annual rainfall. It has an underground woody stem and develops predominantly in shallow ravines on stony-sandy terrains during the winter and early spring in years with above-average precipitation. It has one to four spherical leaves with a wrinkled surface that are 20–60 cm in diameter (Figure 30) (Khammash 2016). Their distinct 3D form that resembles a scaled-down mountainous terrain with well-developed steep drainage networks, posed the issue of whether selection processes were involved in their development (Lev-Yadun and Katzir s.d.).

Several studies reveal that rainwater collection is connected to the horizontal catchment area of the leaf rather than the surface area maximized by the wrinkles. Because the rate of water absorption must be greater than the rate of transpiration, rhubarb leaf wrinkles increase the leaf surface area relative to the leaf footprint and may have a role in managing leaf temperature, which is directly related to condensation (Lev-Yadun and Katzir s.d.) (Khammash 2016).

Khammash's study concluded that the rhubarb's self-irrigation system, which is given by its large-sized leaves and leaf surface shape, boosts water absorption by a factor of sixteen when compared to other desert plants (Figure 31). Thus, the plant appears to have evolved a maximization of both the footprint and surface area of leaves, even at the price of transpiration rate, in order to achieve continuous sub-foliar condensation (Khammash 2016).

This wrinkled surface can be compared to a sun shading system, as the leaves in this scenario can be long enough to cover the façade. To keep the rainwater collection advantages, the lamellae must respect the primarily principle of the leave's particular wrinkles.

Figure 30: Desert Rhubarb leaf. The wrinkles optimize the water collection and flow on the leaf. (Photograph: Gidi Ne'eman, University of Haifa–Oranim)

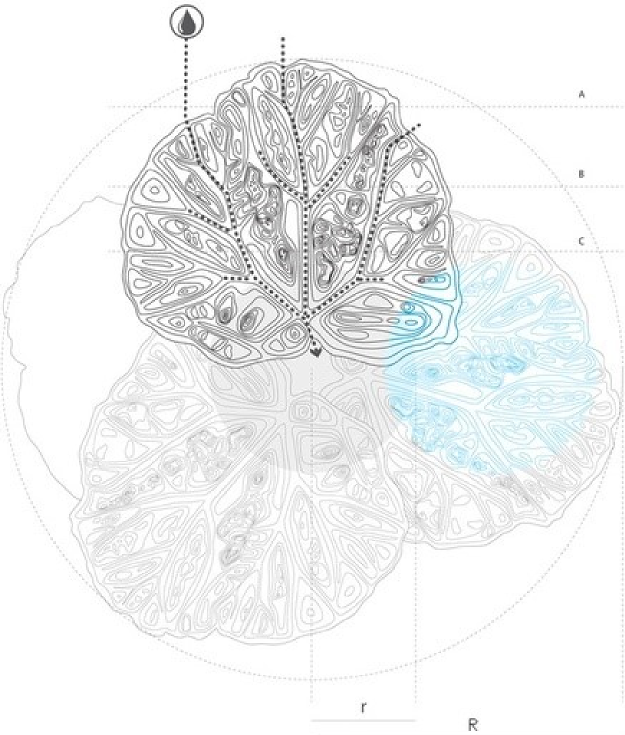
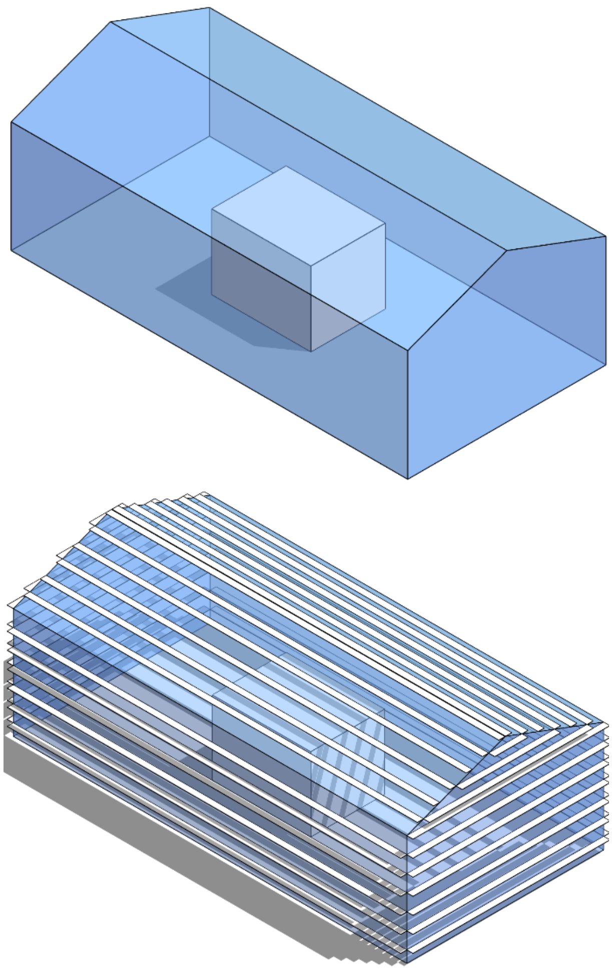


Figure 31: Desert Rhubarb leaf : water harvesting system and efficiency (Vivian Stasi)

The steps are represented on Figure 32.

Steps:

1. Scenario 0 – V^2 as designed
2. Using a sun shading system with a simple lattice everywhere – but that lowers the brightness levels too much. The lattice presents the geometry of the leaves, which allows not only to stop the sun rays, but also to collect rainwater in a more efficient manner at the same time (see detail).
3. The lattice placed only on the Southern and Eastern sides of the building, including the roof – but the roof is not optimized to catch the rainwater
4. The roof's sun shading devices placed by mimicking the geometry of the actual leaves, directing the water towards two main exit points on the roof. The water is then collected on the next lattice on the façade.



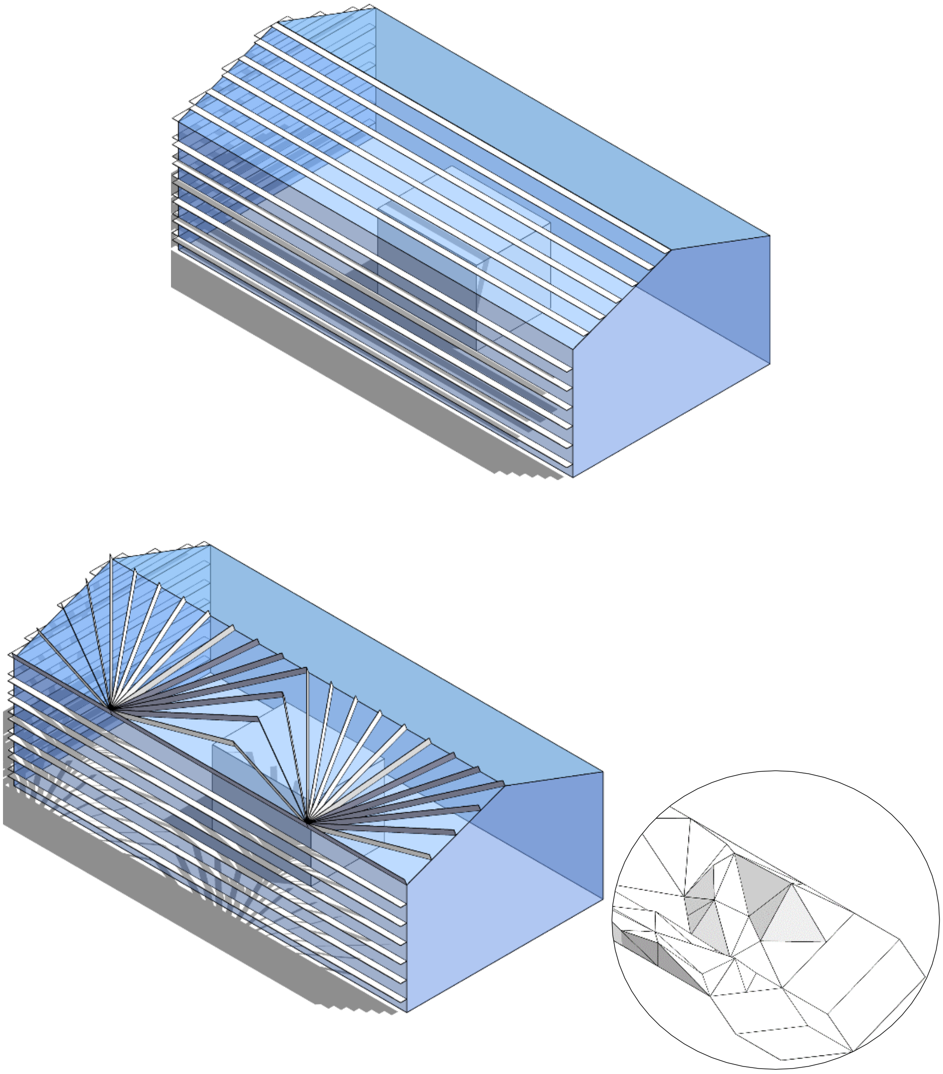


Figure 32: Desert Rhubarb RbD steps: a) house in the greenhouse, scenario 0; b) addition of sun shading lamellae (that display the leaf's geometry); c) removing the lamellae where not needed; d) modifying the roof lamellae to match the leaf's geometry on the roof and better collect rainwater; d') representation of the geometry of the leaf on a flat plate (Author, 2022)

1.3. Kinetic façade

The following paragraph will define kinetic façades systems. A lot of examples of this concept exist, and the work kinetic must be defined in order to understand the following designs.

Kinetic is defined by the Merriam-Webster dictionary as of or relating to the motion of material bodies and the forces and energy associated therewith (Merriam-Webster 2022). Kinetic façades are therefore composed of subsystems that can be deployed, moved, and adapted to a changing environment. The first automated subsystem was for daylight regulation. Mechanically or pneumatically operated blinds, sunshades, or apertures necessitate simple operating methods, with a photosensor serving as the light condition detector. These shading systems range from basic lamellar blinds spinning around their own axis, to folded shutters, to intricate geometrical multidimensional kinetic systems that, like paper origami toys, fold in or unfold in response to variations in daylight level (Sandak, et al. 2019).

Flectofin system - Strelitzia Reginae

Solves/improves: humidity, overheating, brightness, heat losses
Does not change: energy harvesting

In architecture, deployable systems require the use of technical hinges. These tend to need an elevated level of maintenance as they are exposed to important loads from their gliding and rotation. By contrast, deployability in nature relies on the flexibility and elasticity properties of animals or plants (e.g.: leaves or petals) (Lienhard, et al. 2011).

The *Flectofin system* is a biomimetic top-down process inspired by the natural deployment system found in the Bird-Of-Paradise flower (*Strelitzia reginae*). It is a kinematic principle (Figure 33). The flower of the Strelitzia has two petals that serve as a perch for pollination birds. When the animal lands on this platform to drink nectar, it bends down due to its weight. The petal's longitudinal direction bends, which causes its transversal part to spread out to the sides (Knippers and Speck 2012) (Figure 34). When the bird flies away, the system goes back to its initial position. It is therefore fully reversible and suitable for an adaptive façade application (Pelicaen 2018).

Lateral torsional buckling is the resulting movement of the uniaxial bending of a stiff beam member. It subsequently causes an out-of-plane bending due to built-up tension in a perpendicularly attached elastic fin. The elastic stress in the fin is released after a critical tension peak is met, producing a deflection into a less strained equilibrium state (Pelicaen 2018).

Though the up scaling is plainly confined to constructions of many meters in length, it much exceeds the proportions in which fold hinges are often utilized in technology. Furthermore, larger areas, such as the façades of big buildings, can be shaded by increasing the number of Flectofin panels used to cover the whole surface (Mosselter, et al. 2012).

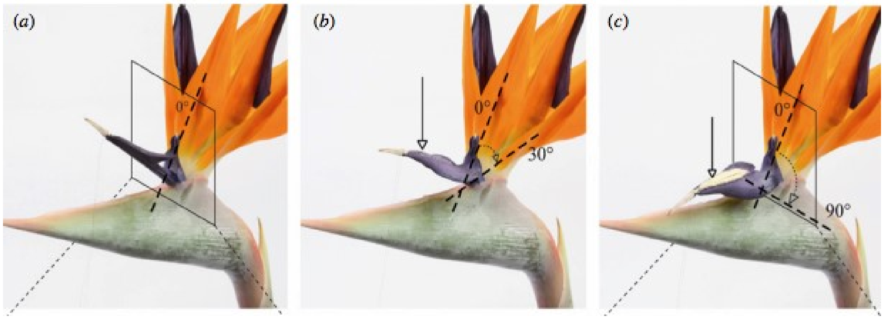


Figure 33: The kinetic system of the Strelitzia reginae flower undergoes elastic deformation. The sheath-like perch opens when mechanical force is applied (Knippers and Speck 2012).

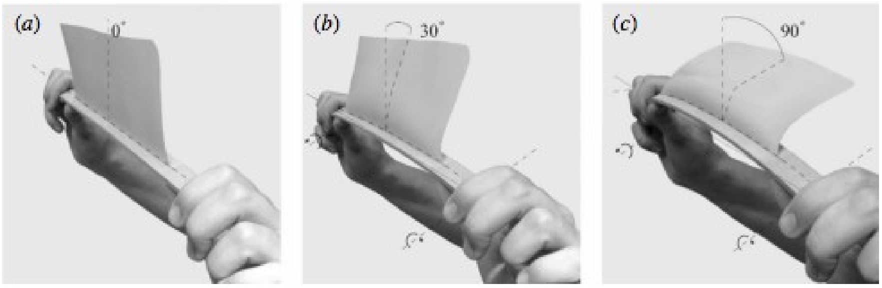


Figure 34: The deformation mechanism in the bloom of Strelitzia reginae abstracted and reproduced using a basic physical model. The connected lamina deflects up to 90° sideways when the backbone is bent (here by hand), which is beginning by lateral-torsional buckling (b) and continues as unsymmetrical bending (c) (Lienhard, et al. 2011)

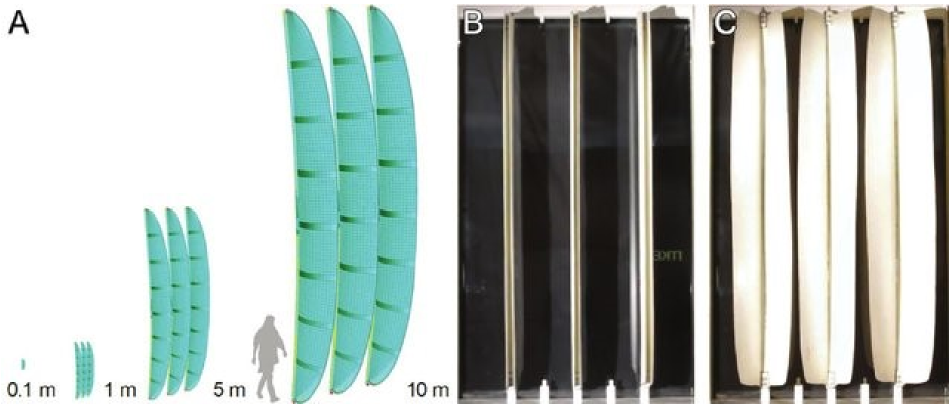
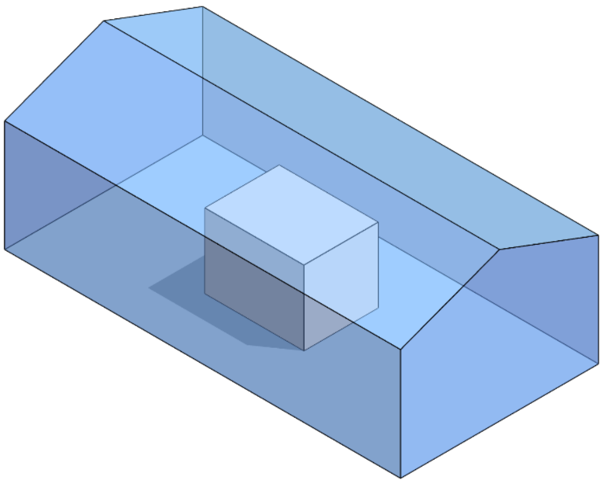


Figure 35: Flectofin ® (A) Scaling up of a Flectofin® with a single lamina from the size of the concept generator (perch of the flower of Strelitzia reginae) to varied sizes that can be used as window and façade shading systems. (B,C). Mockup of a double lamina Flectofin® demonstrator in opened and closed position. © ITKE Stuttgart (Mosselter, et al. 2012)

The steps are represented on Figure 36.

Steps:

- Scenario 0 – V^2 as designed
- Adding the flectofin system to the two largest façades, to provide natural ventilation and shading.



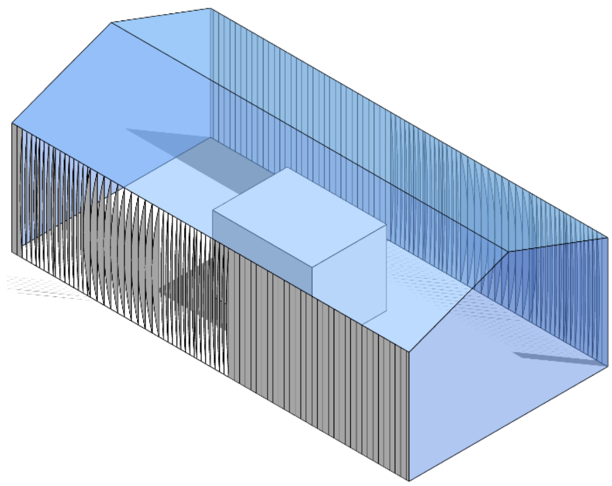


Figure 36: Flectofin RbD steps: a) house in the greenhouse, scenario 0; b) replacement of 2 glazed walls by flectofin lamellae; c) zoom-in on the system (Author, 2022)

Chameleon - hexagonal pattern

Solves/improves: humidity, overheating, brightness, energy harvesting, brightness, heat losses

In 2015, Wanders Werner Falasi Architects developed an adaptable façade with a hexagonal parametric pattern. Their design is based on cell structures and the chameleon's extremely changeable skin (Figure 37) (Urukia 2021).

Climate management and thermoregulation are achieved using smart adaptable façade units, such as hexagons. They automatically adjust to the sun's trajectory:

- When exposed to excessive heat, each component shuts to seal the structure, as shown by the responsive skin’s constructive detail on Figure 38.
- When it is too chilly or dark, they open.
- The workplace features fixed PV nano cells installed in areas of the outer walls that gather sunlight for power throughout the day (Urukia 2021).

Since this design was made for the United Emirates, the cells open to get cool air and close to avoid shield against hot air, which is not necessary in Belgium all year-round. A reverse mechanism can thus be thought about for the Belgian temperate climate.

The cells can also shelter extra illuminance, a problem that was found in Kaseco.

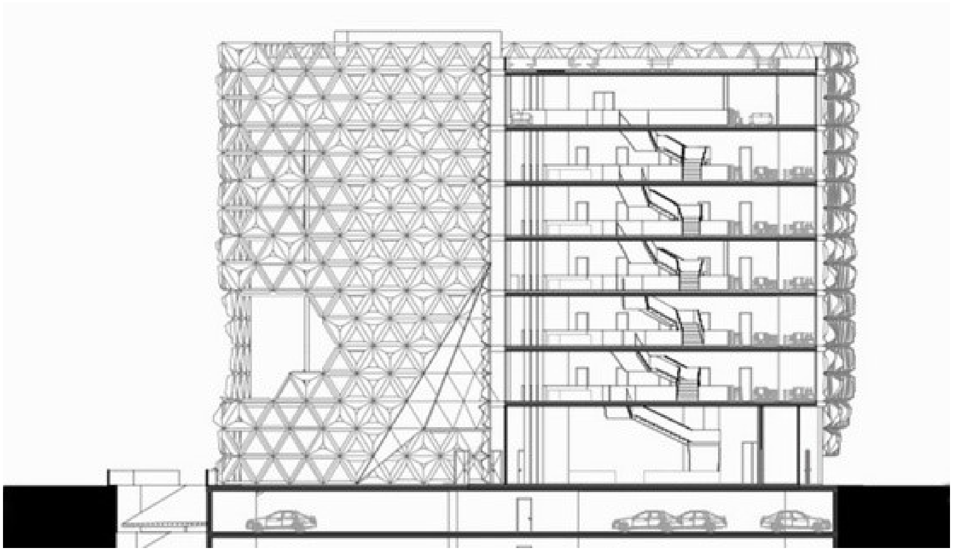


Figure 37: Wanders Werner Falasi Architects: development of adaptable façade with a hexagonal parametric pattern, based on cell structures and chameleons' changeable skin (2015) (Urukia 2021).

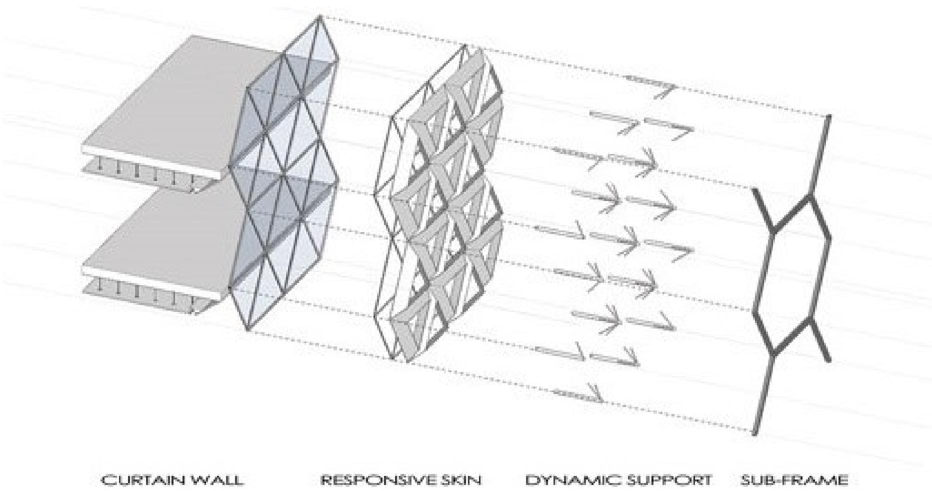
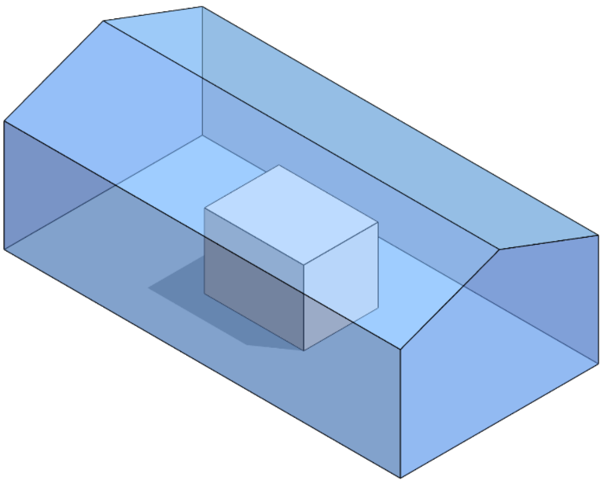


Figure 38: Hexagonal pattern façade construction (Urukia 2021)

The steps are represented on Figure 39.

Steps:

1. Scenario 0 – V^2 as designed
2. Adding the chameleon system on the two largest façades



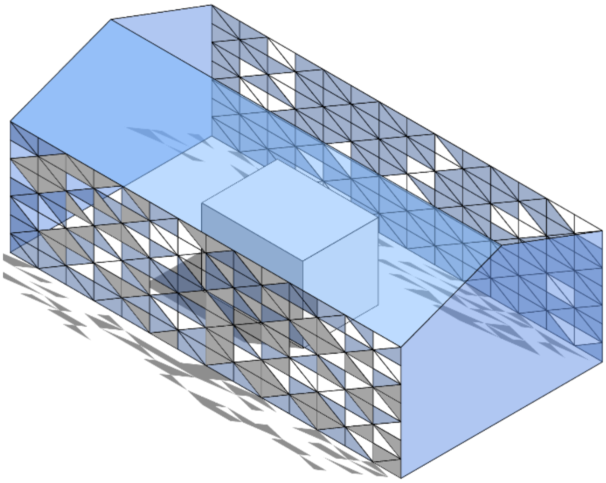


Figure 39: Chameleon RbD steps: a) house in the greenhouse, scenario 0; b) replacement of 2 glazed walls by the chameleon hexagonal system lamellae: some triangles are shaded/covered with photovoltaic cells, some open and some simply glazed (they are not fixed and can change according to needs) (Author, 2022)

Changing the greenhouse volumetry

1.4. South facing roof

Solves/improves: energy harvesting, heat losses, humidity
Aggravates: overheating, brightness

Roof orientation

A straightforward solution to harvesting more solar energy is having a single sloped roof instead of two panes. This allows more solar panels to be added on top of the structure while keeping their orientation ideal[15].

Further up, the slope of the roof could be made at the perfect angle to catch as much solar radiation as possible and provide the maximum possible power production. According to the website mpptsolar.com, solar panels are more productive when the sun's rays are perpendicular to their surfaces. However, in Belgium, the sun is at a different elevation angle in summer and winter. The most productive hours are around noon, all year round.

Solar panels

Considering these three conditions, a table can be raised to calculate the best orientation angle at noon at three critical dates. These values were taken from the Sun path diagram provided by Gaisma.com, available in Appendix 7 – Sun Path Diagram Brussels, p.193.

Table 11: Optimum PV tilt at noon according to the sun's elevation angle in Brussels throughout the year (Author 2022)

Date	Sun elevation angle (at noon)	Optimum PV tilt (=90° - elevation angle) (at noon)
June 21st	55°	90° - 55° = 35°
December 21st	15°	90° - 15° = 75°
Equinox (March 21st and September 21st)	38°	90° - 38° = 52°

To maximize even more PV panels production, the concept can be pushed forward. Indeed, three moments in time compared to the entire year is not a lot, even if the dates and time represent the most critical cases.

[15] For more information, see annex p.204.

Maximizing the solar panels production: the sunflower's heliotropic movement

The common sunflower (*Helianthus annuus*) is an annual plant with hairy stems and leaves, as well as large, terminal circular heads made of numerous little yellow buds. If the sunflower has been analyzed for its sunlight-dependent dry matter accumulation or blue-light-dependent organ development since the 1800s, there has been very little research about its heliotropic movements (solar tracking) (Kutschera and Briggs 2016). Yet, these attributes can be particularly interesting for photovoltaic panels placement and orientation.

In the article *Phototropic solar tracking in sunflower plants* (2016), scientists of the *Department of Plant Biology* from *Stanford* studied the sunflower and summarized the pertinent literature on solar tracking (Kutschera and Briggs 2016). These findings were concurred by another study, published in *Plan Science* the same year (Atamian, et al. 2016):

- Growing flowers follow the sun with their body and leaves, from East to West during the day. They then reposition themselves at night to face East for dawn.
- Mature flowers face East during a bright day, but wind and rain can bend the heads and change their orientation (Figure 40).
- The circadian rhythm (intrinsic rhythm of approx. 24h) has a role in the heliotropic movement during the day and the reorientation motion at night (Kutschera and Briggs 2016). Interactions between environmental response pathways and internal circadian function regulate sunflowers' development and reproduction by coordinating movement with anticipated environmental changes (Atamian, et al. 2016).

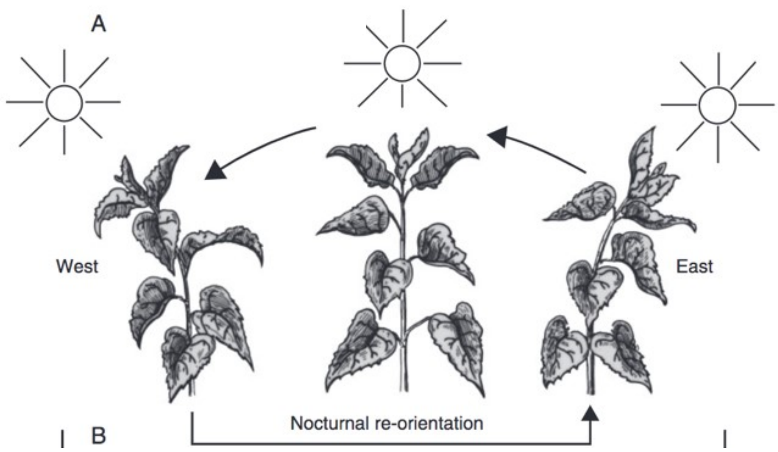
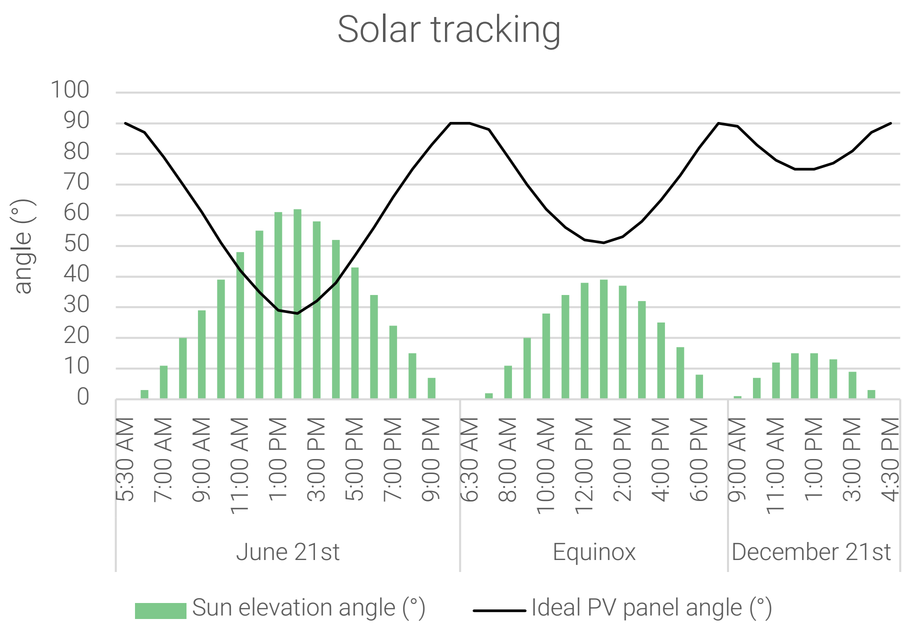


Figure 40: Growth-mediated solar tracking of the stem and upper leaves in a sunflower plant (Helianthus annuus, 'Sunspot'). The drawings were plotted from observations on a 10-week-old plant (Kutschera and Briggs 2016).

Conclusion

In conclusion, it is possible that solar panels efficiency could be improved if they were constructed in a way to turn towards the sun. That could be achieved through the placement of a photosensor and a motor (Figure 41).

Going back to the sun path diagram, it is possible to plot points for every hour. When the panel is at a 90° angle, it means it is vertical. When it is at a 0° angle, it is fully horizontal. Graph 4 on the next page provides the angles calculated based on the Belgian sun path.



Graph 4: plot of the sun elevation angle (°) and corresponding ideal PV panel angle (°) over three critical dates: summer and winter solstice, as well as the equinoxes - in Brussels, Belgium (Turkiainen 2022) (Author, 2022)

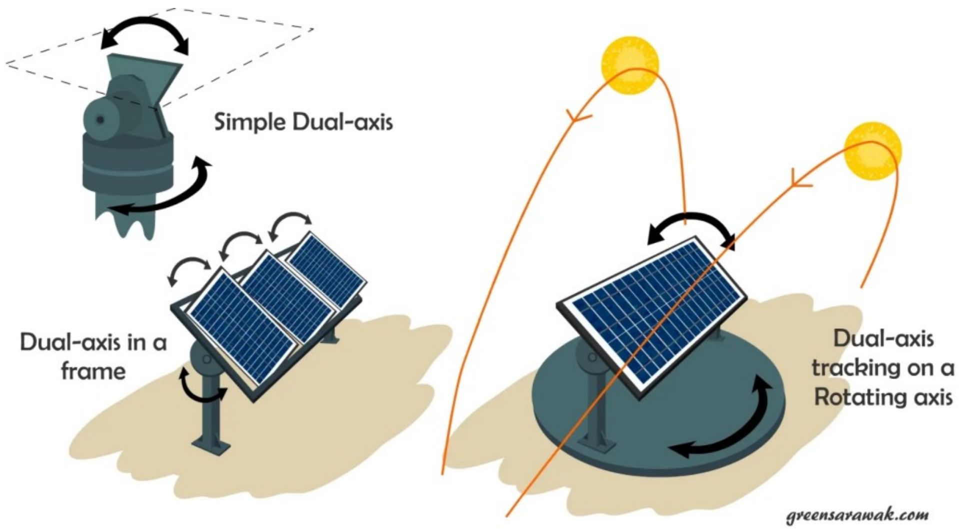
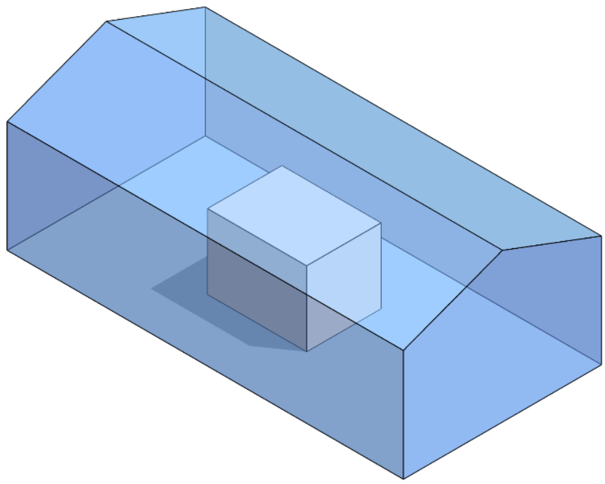


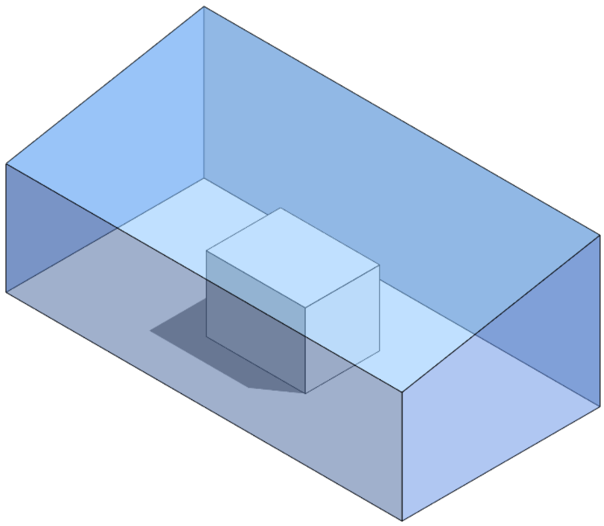
Figure 41: Dual-axis solar tracking motor for PV panels (Aurora Solar Energy)

The steps are represented on Figure 42.

Steps:

1. Scenario 0 – V^2 as designed
2. Modifying the slope of the roof to only face South
3. Adding solar panels on top
4. Providing a mechanical system to make the panels follow the sun like sunflowers





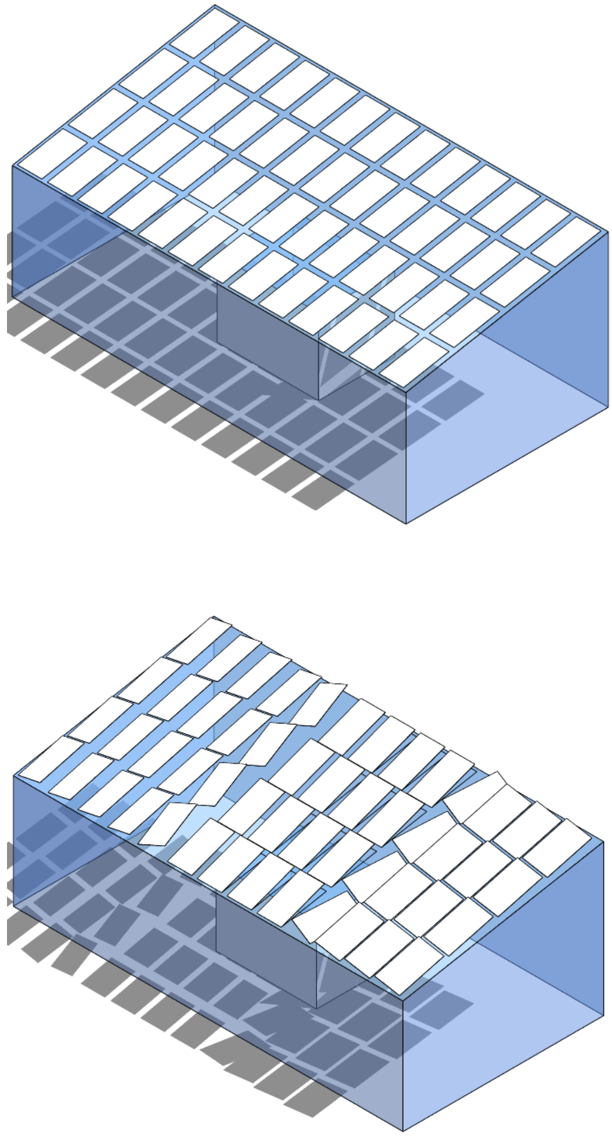


Figure 42: Sun RbD steps: a) house in the greenhouse, scenario 0; b) orienting the roof to only face South to have the best solar gains; c) layout of the solar panels; d) representation of the PV panels changing their orientation according to the sun's elevation angle (°). This ensures having the best solar energy gains throughout the day and the seasons (Author, 2022).

1.5. Geodesic dome

Solves/improves: energy harvesting, heat losses, humidity
Aggravates: overheating, illuminance

As mentioned in the Dome Over Manhattan case study in chapter 2, a geodesic dome is a spherical structure made of triangles (Buckminster Fuller Institute s.d.). This construction has some advantages, namely saving materials, better thermal performance, natural circulation of air, reduced wind turbulence and preventing radiative heat loss (refer to Geodesic Dome over Manhattan – USA, Nature City46). By changing the traditional shape of the greenhouse that has been considered up to this point, it is expected that the HGH model will benefit from these principles.

The sphere is an application of the *doing more with less* principle by enclosing the greatest volume of internal space with the smallest amount of surface area, hence conserving material, and money (Buckminster Fuller Institute s.d.).
This principle is also one of the two main ideas that underpin biomimetic design according by Gallo: the path of least resistance (Gallo 2018).

The steps are represented on Figure 43.

Steps:

1. Scenario 0 – V^2 as designed
2. Replacing the typical greenhouse by a geodesic dome

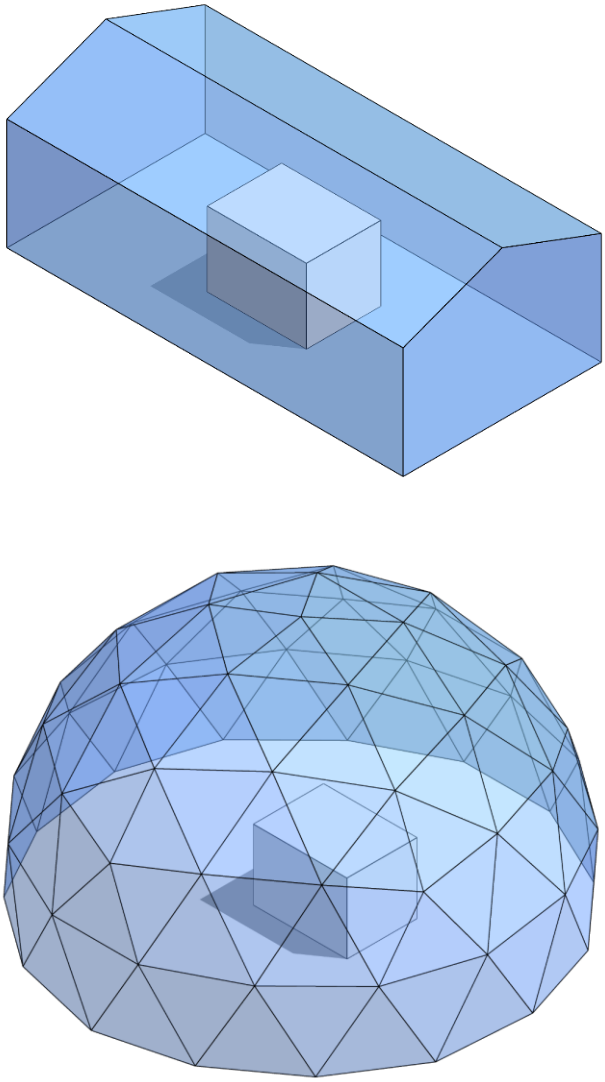


Figure 43: Geodesic dome RbD steps: a) house in the greenhouse, scenario 0; b) replacement of the traditional greenhouse by a geodesic dome (Author, 2022)

Combinations

This last part will go over two possible outcomes combining the scenarios developed before.

The application of these two super scenarios on real-life cases will be studied in the following chapter.

Table 12: summary of the super scenario's composition (Author 2022)

	Combination 1	Combination 2
Termite mounds	+	
Desert Rhubarb	+	
Flectofin	+	
Chameleon		+
Sunflower	+	
Geodesic dome		+

1.6. Combination 1

This first combination scenario uses the sunflower solution as a base for the greenhouse's shape, i.e., the modification of the slope of its roof and the motorized solar panels. Sun-shading with the desert rhubarb's scenario is the second addition on a small wall. The termite mounds natural ventilation system is then implemented, and lastly the flectofin geometry is applied on the 2 main walls, which can replace the porous membranes.

Since this combined solution is based on different scenarios which all solve one of the issues stated at the beginning of this chapter, scenario 3.1 can potentially solve every one of them. Additionally, combining several strategies allows the issues of one to be solved by the other (e.g., the termite mounds aggravate the heat losses but both the flectofin and sunflower enhance them).
The following table is a visual representation of the different scenarios, each with their pros and cons. The cells are left empty when a scenario does not address that particular issue.

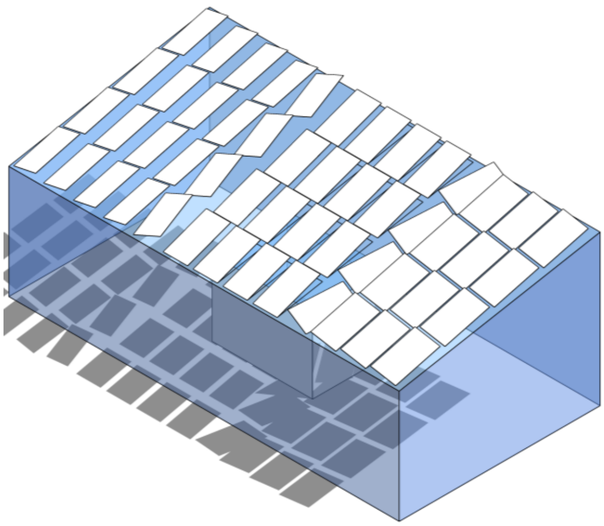
Table 13: the influence of combination 1 based on the several strategies it contains. Green = solved issue; Orange = aggravated issue; Empty = untouched issue. Combination 1 solves every issue in the end (flaws are countered) (Author, 2022)

Scenario	Overheating	Heat losses	Humidity	Illuminance	Energy
Termite mounds	+	-	+		
Desert Rhubarb	+			+	+
Flectofin	+	+	+	+	
Sunflower	-	+	+	-	+
Combination 1	**+**	**+**	**+**	**+**	**+**

The steps are represented on Figure 44.

Steps:

1. Sun-facing roof and mobile solar panels
2. Termite mound
3. Replacing the pores in the membrane by the flectofin system that provide the same diaphragm effect; implementing the sun shading based on the desert rhubarb scenario on one of the smaller sides of the greenhouse



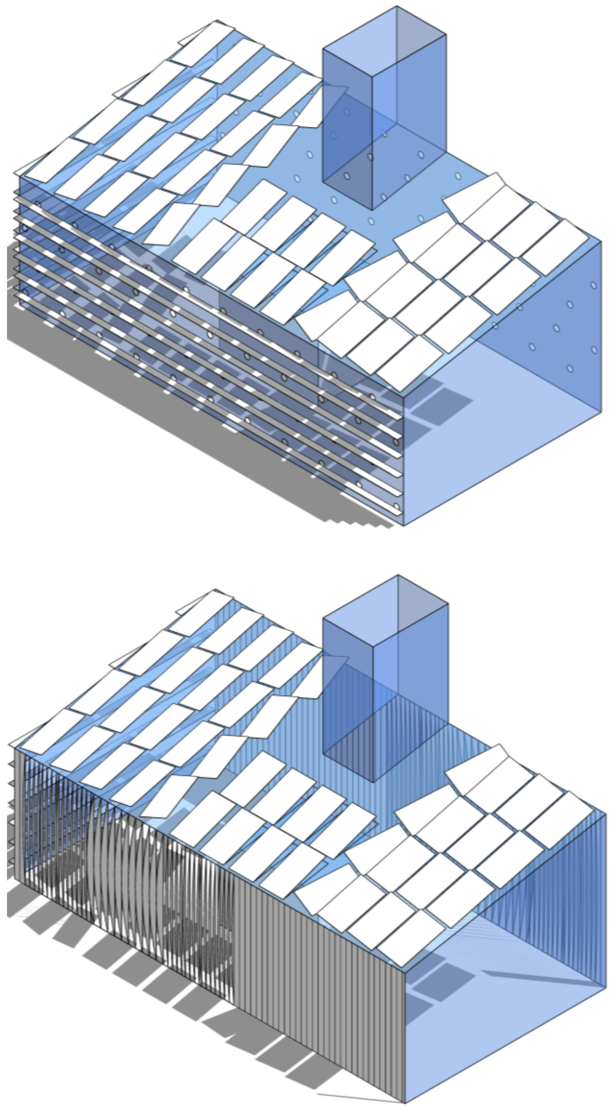


Figure 44: Combination 1 RbD steps: a) Sunflower and desert rhubarb's RbD results; b) implementation of the termite mound's RbD results; c) replacement of the pores in the envelope by the flectofin system (that will act as the diagram for the ventilation that is needed in b)) (Author, 2022)

1.7. Combination 2

This second combination scenario is more straightforward. Indeed, If the previous scenario was more about combining diverse strategies for their individual benefits, this one aims at providing the most optimized shape to implement the chameleon principle. It only uses two of the designs developed beforehand, and since the two solutions both use equilateral triangles as a base, the two are relatively easy to combine. It also allows for material, cost, and carbon savings.

This combination scenario uses the geodesic dome as a base for the greenhouse's shape. All the other issues are solved by the chameleon skin application. For the chameleon, each triangular cell can open, close, or simply be glazed based on the outdoor and indoor conditions.

The following table is a visual representation of the different scenarios, each with their pros and cons. The cells are left empty when a scenario does not address that particular issue.

Table 14: the influence of combination 2 based on the several strategies it contains. Green = solved issue; Orange = aggravated issue; Empty = untouched issue. Combination 2 solves every issue in the end by countering the flaws of the dome (Author 2022)

Scenario	Overheating	Heat losses	Humidity	Illuminance	Energy
Geodesic dome	-	+	+	-	+
Chameleon	+	+	+	+	+
Combination 2	**+**	**+**	**+**	**+**	**+**

The steps are represented on Figure 45.

Steps:

1. Geodesic dome
2. Addition of the chameleon system

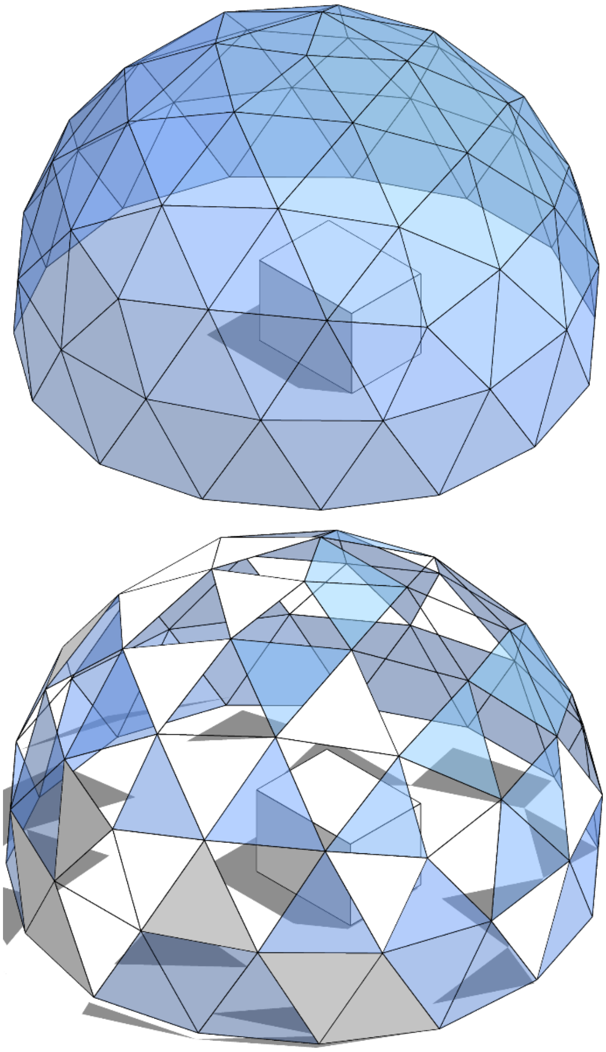


Figure 45: Combination 2 RbD steps: a) geodesic dome RbD result; b) replacement of the equilateral triangles of the dome by the chameleon principle (Author, 2022)

(7) Evaluate - Conclusions

The following table contains a critical reflection over each of the proposed scenarios.

Due to the scope of this Master Thesis, the cost of these constructions was not considered for this analysis. This report intends to open up the possibilities of insulating houses, not provide a market exploration. However, it should be noted that the architects Lacaton & Vassal, Pritzker prize winners of 2021, have been studying winter gardens and other double skin façade systems for a long time. In most of their projects, the plan is to use the money that would have been spent on incremental renovations and upkeep of the area over time for something else (Souza 2021). Their motto is *"never demolish, never remove or replace, always add, transform and revise!"* (Huber 2016). This thesis aims at bringing a scientific approach to this type of work.

Table 15: Pros and cons analysis and discussion of the Biomimetic RbD results (Author 2022)

Scenario	Pros	Cons
Termite mounds	Solves the overheating issue Low-tech solution Minimal maintenance Relatively easy to implement Material savings	Aggravates heat losses in the wintertime → might lead to lower comfort levels Only one studied example of buildings → lack of proof that it will function properly
Desert Rhubarb	Sun shading devices are known solutions and have been proven to work Solves more than one problem (brightness, overheating, energy harvesting)	Extra materials are needed → bigger embodied carbon footprint If low tech: not always at the right orientation If high tech: extra CO_2 Reduced transparency / heat gains of the greenhouse since the visible glazed surface is lowered
Strelitzia Reginae	The flectofin system has been thoroughly studied and optimized by experts in the past It solves more than one solution (ventilation, overheating, brightness, …)	High technology solution→ larger carbon footprint Extra materials are needed → bigger embodied carbon footprint The view from in to outside the greenhouse is negatively impacted Reduced transparency / heat gains of the greenhouse since the visible glazed surface is lowered

Chameleon skin	Has the potential to solve every highlighted problem (brightness, overheating, heat losses, energy harvesting)	High technology solution Has only been developed as a concept, there are no built constructions with the design → the results might be different than anticipated Reduced transparency / heat gains of the greenhouse since the visible glazed surface is lowered
Sunflowers / Sun facing roof	The solar panels also act as a sun-shading device Possibility to expand the idea with solar panels on the façades Better efficiency for both electricity and heating needs	High technology solution
Geodesic dome	Proven concept, many examples exist The shape is optimized for both energy harvesting (solar panels and water recuperation) and material usage	Relatively more complicated to build than a traditional greenhouse The brightness levels and overheating issues might be worsened Need more ground space than a rectangular greenhouse
Combination 1	Since some of the systems overlap, a good balance can be found between, on the one hand, the use of materials and high-technology and on the other hand the system efficiency and integrated solutions Relatively good balance between high tech and low tech	The heat losses might be worsened, as the flectofin panels need to be opened for the ventilation to work – which might not be ideal every day of the year Reduced transparency / heat gains of the greenhouse since the visible glazed surface is lowered
Combination 2	Optimization of all systems Only uses two scenarios, which reduces the needs of extra materials, and carbon footprint	High technology solution Reduced transparency/heat gains of the greenhouse since the visible glazed surface is lowered Needs more ground space than a rectangular greenhouse

6

CHAPTER 6

IN PRACTICE: INSULATING BRUSSELS VILLAS

This chapter will investigate the possibilities to use the outside optimized greenhouse solution and apply it to existing villas in Brussels City as an innovative insulation method since the energy efficiency of this solution has been proven. In addition, the improved HGH model also offers extra benefits such as providing a social space, the gains of biophilia on human's health, local food production and closed eco-cycles.

VI. CHAPTER 6 – IN PRACTICE: INSULATING BRUSSELS VILLAS

1. Introduction

In the Brussels Capital Region (BCR), the housing stock is significant, outdated and energy-intensive (Gobbo and Trachte 2015). To meet the goals of the European Green Deal, European governments have agreed on a new objective of 50 to 80% improvement in energy efficiency of the building stock by 2030 (European Commission 2022) (Carton 2009). Therefore, renovating and retrofitting the insulation of the current building stock are crucial steps to meet the objectives for 2030 (Carton 2009). It is noteworthy that the case study presented in Appendix 4 – Additional case studies p.177 could lead to further research on the subject of applying a greenhouse to a house, or a group of houses.

Insulation retrofit nowadays

Insulation possibilities are determined by the components used and how the houses are constructed (Gobbo and Trachte 2015). There are currently three main trends:

- Add an insulating layer on the **outside** walls of the house – currently the most efficient way of retrofitting (Biserni, et al. 2018). It also avoids thermal bridges and indoor moisture problems. The main problem is that it changes the appearance of the building drastically (Gobbo and Trachte 2015).
- Add an insulating layer on the **inside** of the house (on the inner side of the walls or below the roof) – this is less efficient, and the structure must allow for enough space to add these extra materials (Gobbo and Trachte 2015).
- Injecting an insulating material in the **cavity** of the two brick layers that form the external walls. This system involves drilling holes in the façades, more often uses petro-chemical composites, has limited insulating properties since it has a limited thickness and does not always reach everywhere in the cavity (Gobbo and Trachte 2015).

Detached houses

According to cadastral statistics, there are 5.821 villas (detached houses) in the Brussels Capital Region (BCR). 76% of these villas are located in the 4 following communes: Auderghem, Uccle, Watermael-Boistfort and Woluwé-Saint-Pierre. A brief study of the construction year of these villas reveals that close to 85% were built before 1981 at a period where the façade insulation techniques were less efficient[16]. This as well as its slow pace for renovation confirm the observation that the Brussels building stock is very energy intensive (Brussels Environnement 2022).

The objective of this chapter is to investigate (via Research by Design) different insulation possibilities by adding the 2 biomimetic greenhouse combinations described in the previous chapter over a typical single-family detached Brussels villa.

Types of houses selected

For this purpose, two types of detached residences shall be distinguished:

- *Type 1 house: The neighboring house:* is close to its neighbor(s) and has limited surrounding space to accommodate a greenhouse
- *Type 2 house: The isolated house:* isolated from the rest of the neighborhood, hence with a lot of space around it

[16] More details are available in Appendix 8 – Housing Statistics Brussels, p.206.

2. Research process – Biology to Design

In this case the research by design process will follow the approach *Biology to Design* (bottom up) since the aim is to apply a biomimetic solution found to another type of building (Brussels villas) as mentioned in the literature review (Chapter 1). The process therefore consists in the following five steps: (1) Discover; (2) Abstract; (3) Brainstorm; (4) Emulate; (5) Evaluate (as shown in the literature review Research by Design and Biomimicry18).

(1) Discover natural models

The optimized biomimetic greenhouses' (combinations 1 and 2 defined in chapter 5) main benefit is to offer a second glass layer acting as an insulating element to their inside core house as demonstrated in the dynamic simulations. This property is especially interesting in temperate to cold climates (Amoako-Attah and Bahadori-Jahromi 2016).

(2) Abstract design principles

Combinations 1 and 2 allow the core house to benefit from the heating gains (passive solar technology) while minimizing heat losses, ventilation and shading to prevent overheating and reduce the humidity levels, reasonable illuminance levels, and an optimized energy harvesting system.

(3) Brainstorm potential applications

Certainly, building a greenhouse such as combination 1 or 2 around an existing detached house is not always possible since it requires a significant ground surface available around the house and shape restrictions (e.g.: under 4 floors with a low-sloped roof).

Therefore, based on the type of the house to insulate and its immediate surroundings, three scenarios will be considered. For each scenario, there are two options for the greenhouse[17]: combination 1 or combination 2 (i.e.: the fully biomimetic optimized rectangular greenhouse or geodesic dome), the two super scenarios of chapter 5.

- A *full greenhouse:* to place around the house, like the typical HGH model. It is hardly implementable on neighboring houses, as the greenhouse need a minimum extra space of 3m on each side of the core house to be usable.
- A *semi-greenhouse:* attached to the house, on the ground. It also covers half the roof.
- A *rooftop greenhouse:* a greenhouse placed on the roof of the existing house. This solution only insulates the roof, not the walls.

[17] Thenceforth, the term *greenhouse* is used to refer to combination 1 and 2 defined in chapter 5.

2022: Tour Montparnasse's retrofit in Paris, France

An example of a similar practical application can be found today in Paris (Figure 46). Indeed, the iconic Tour Montparnasse is under a bioclimatic retrofit of its envelope which shares some key characteristics with this thesis's final proposal (Jardonnet 2017). The project foresees the addition of an outer glass skin around the building as well as the construction of an 18-m-high greenhouse on its top.

The objectives are, inter alia, to drastically reduce the external energy and water consumption of the Tour (planned reduction of 90% of energy needs (Olivier 2017)) mainly thanks to a better insulation because of the double skin and a recyclable circuit for the rainwater. The project is due to be completed by 2024 before the Paris Olympic Games.

Figure 46: New bioclimatic HGH retrofit of the Tour Montparnasse, Paris. (NOUVELLE AOM) (Jardonnet 2017)

(4) Emulate Nature's Strategies

Base volumetry – rectangular greenhouse vs dome

As mentioned before, 2 types of detached houses are considered: one with neighbors and limited space, and the other with unlimited space around it (Figure 47). Hence, an added greenhouse will likely be smaller for the type 1 houses than for the type 2.

Subsequently, the shape of combination 1 and 2 shall be compared (Figure 48). Based on the same constraint of providing at least 3m of space around the house on all sides, it will demonstrate below that the geodesic dome (combination 2) necessitates much more ground surface than the rectangular greenhouse (combination 1). Indeed, the ground surface needed for a dome follows the formula $\pi * r^2$, while the rectangular greenhouse only covers a surface of $L * W$, with

- r: the radius of the dome;
- L: the length of the rectangular greenhouse;
- and W: the width of the rectangular greenhouse.

For a house of 10 by 10m, with three levels of 3m each and a sloped roof that is 2m higher than the ceiling slab of the third floor (i.e.: the roof is between 9 and 11m high); the dome (combination 2) covers a surface of $\pi * (11 + 3)^2 = 616m^2$ while the rectangular greenhouse (combination 1) requires only $(10 + (3 * 2)) * (10 + (3 * 2)) = 256\ m^2$.

For a house with a floor surface of 100 m², the geodesic dome would occupy a ground surface 360 m² (2,4 times) greater than a rectangular greenhouse.

Besides, most dwelling plots in Brussels are either square or rectangular. This means that, provided that the greenhouse cannot go over the property lines, the geodesic dome would leave uncovered angles on the corners of the plot, which would be hardly accessible. A dome, due to its geometry, also prevents high trees or other plants to be planted near the edges, as its curvature does not allow for their full height to be reached and might be detrimental to the structure.

The same reasoning can be developed for half greenhouses, which would thus cover 308 m² and 128 m², respectively.

On rooftops, the construction of a dome compared to a rectangular greenhouse would imply that the angles of the roof are not covered by a glass outer skin. This implies lost space and a lower insulation level in the four corners of the roof. It might also cause some thermal bridges with the house roof.

To conclude, the rectangular greenhouse (combination 1) seems to be the most practical and the easiest solution to implement in most cases, especially in urban environments like Brussels.

Shading

Another constraint to take into account is the shade on the plot. Indeed, some existing houses are located near high trees or other tall houses which generate shadow. This might reduce the solar gain and other greenhouse's intrinsic benefits including food production, a sufficient social space, and efficient energy-collecting strategies (like sun's power).

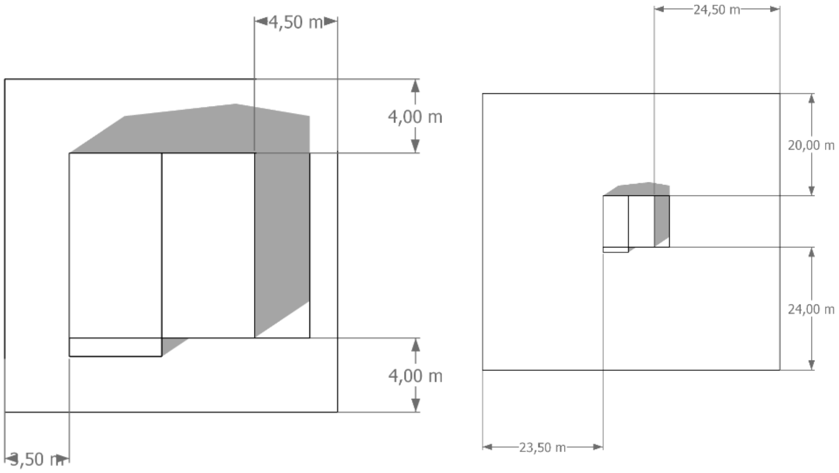


Figure 47: Typical dimensions available for each type of detached house[18] considered in this analysis: from left to right: a) Type 1: neighboring house (less than 5m that can be constructed on each side); b) Type 2: isolated house, with sufficient space around it for the greenhouse. The two houses have the same size. (Author, 2022)

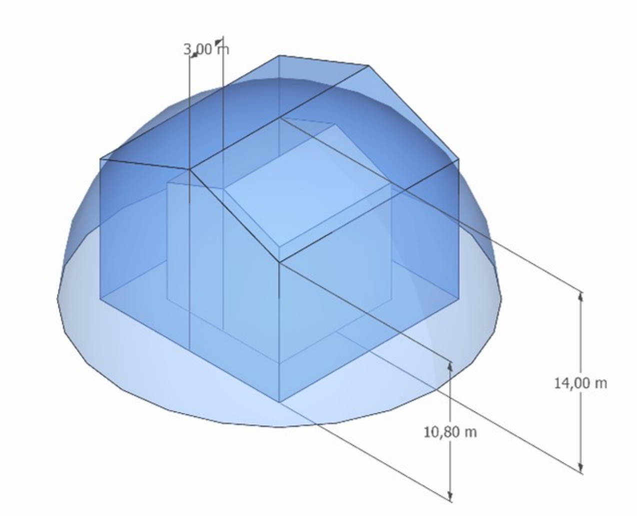


Figure 48: The geodesic dome has a larger footprint on the ground compared to the rectangular greenhouse, which makes it more difficult to implement in neighboring houses. (Author, 2022)

[18] These dimensions were taken from examples in Uccle via Google Maps.

Adding a full greenhouse around the house

Type of greenhouse: Combination 1 or 2 for type 2 houses; Combination 1 only for type 1 houses.

This scenario is the most straightforward of all. It consists of two simple steps: choosing the house and adding the full greenhouse over it. Of course, due to its size, the construction is not applicable everywhere.

To illustrate, this solution is not possible to add on the neighboring house, as there is not enough space around it to construct it within the cadastral limitations. This scenario is thus only possible to implement on the isolated house (type 2).

There, the benefits are full: the house will gain insulation, a comfortable space, local food production and all the other benefits mentioned before in this thesis.
This scenario is relatively easy to build since the greenhouse is not directly attached to the house: a limited amount of foundation work is needed, and the materials can be mounted quickly if prefabricated.

The final designs are represented on Figure 49.

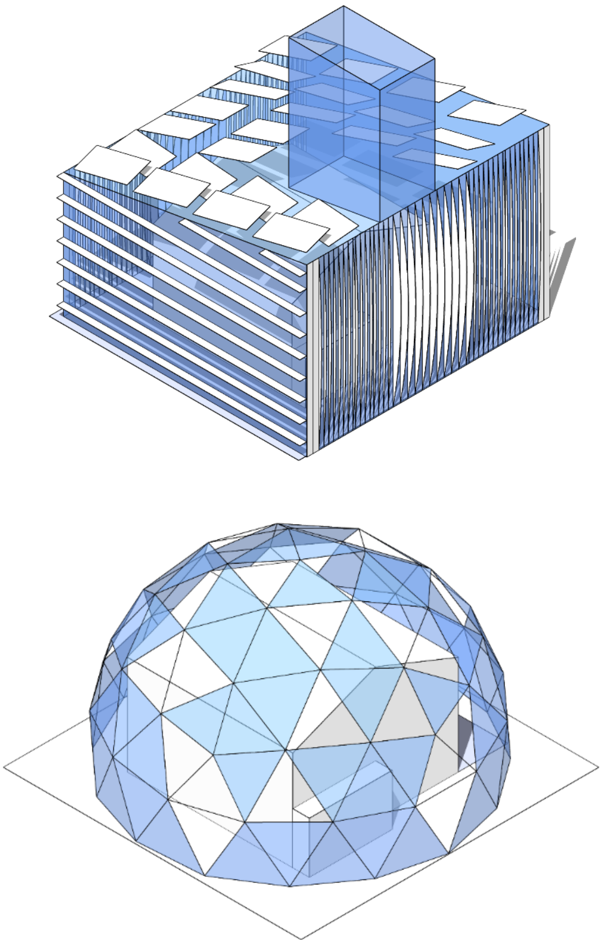


Figure 49: Full greenhouse RbD: a) combination 1; b) combination 2 (Author, 2022)

Attaching a semi-greenhouse around the house

Type of greenhouse: Combination 1 will be easier to implement on type 2 houses compared to type 1. Combination 2 seems to be difficult to apply in this situation.

This scenario can be considered for the two house-types. It is more technically difficult to implement than the full greenhouse, as it involves some structural or volumetric restructuration since the structure would be attached to the walls and the roof of the existing house.

In this scenario, the orientation of the greenhouse is important. Passive solar design techniques recommend a Southern exposure to maximize its solar contribution. This will not always be possible since it depends on the orientation of the existing house; in which case the glazed face shall ideally be within 30° of true South to benefit from about 90% of the optimal winter solar heat gain (US Department of Energy 2000)

- Oriented North-South: insulates half of the coldest side (North) and enjoys half of the benefits of passive solar heating (South). Either the Western or the Eastern sides are fully covered.
- Oriented East-West: the Southern side is fully covered, and thus the full solar gains can be enjoyed.

To simplify the simulations and avoid redundancy, the semi-greenhouse will be assumed to be implemented on the Southern side of the house.

The final designs are represented on Figure 50.

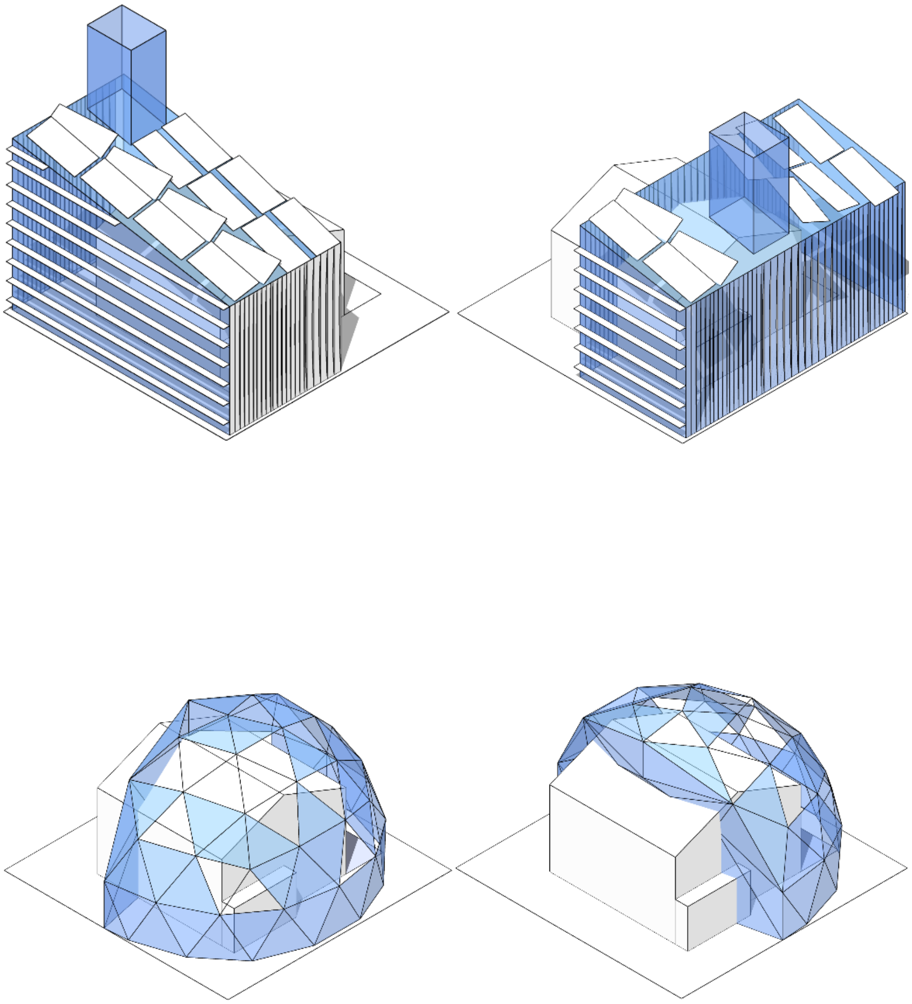


Figure 50: Semi-greenhouse RbD: from left to right and top to bottom: a) combination 1 oriented N-S; b) combination 1 oriented E-W; c) combination 2 oriented N-S; d) combination 2 oriented E-W (Author, 2022)

Adding a greenhouse on the roof of the house

Type of greenhouse: Combination 1 is better fitted for both house types

It is important to note that houses lose most heat through the roof (Webb, Aye and Green 2018). This solution might thus provide a way to enhance the thermal performance of a house without touching the walls.
Adding a rooftop greenhouse over an existing construction involves a set of constraints (Zurko 2016):

- Structure: The structural conditions of the house and more specifically the roof must be assessed, re-calculated and probably renovated. The extra weight of the materials and plants is significant.
- Access: The roof needs to be accessible.
- Technics: It is necessary to install electricity, and water on top of the roof. This would involve extra costs.
- Construction: A crane (or helicopters) is needed requiring coordination, experts, and extra costs.
- Water evacuation: Most buildings have roof drains to avoid water pounding on the roof. Since the greenhouse will be added in that place, these downspout locations and roof drain connections require restructuring.
- Light pollution: Some communes have light-pollution restrictions, and a lit-up greenhouse on a rooftop might produce a lot of light at night.
- Permits: Some additional permits are required to build over a pre-existing construction.

In spite of these restrictions, this solution can be implemented for both house types. Moreover, the greenhouse is perfectly oriented like in the optimized V² proposition. Its location gives it more privacy and a better view on the surroundings. However, this scenario has a limited cultivable space and increased difficulty of access (especially for elders or people with limited mobility) since it is situated on the roof.

As explained in the volumetrics considerations, the geodesic dome would not cover the angles of the roof causing lost spaces as well as possible thermal bridges on the roof of the house. The dome is therefore less recommended than the rectangular greenhouse in this scenario.

A further step for this scenario could be to prolong the greenhouse on the Southern wall of the house, mid-way between scenarios 'half greenhouse' and 'roof greenhouse'. That way, all rooms could have a balcony opening-up to the glass construction, and heat gains would be maximized thanks to the orientation.

The final designs are represented on Figure 51.

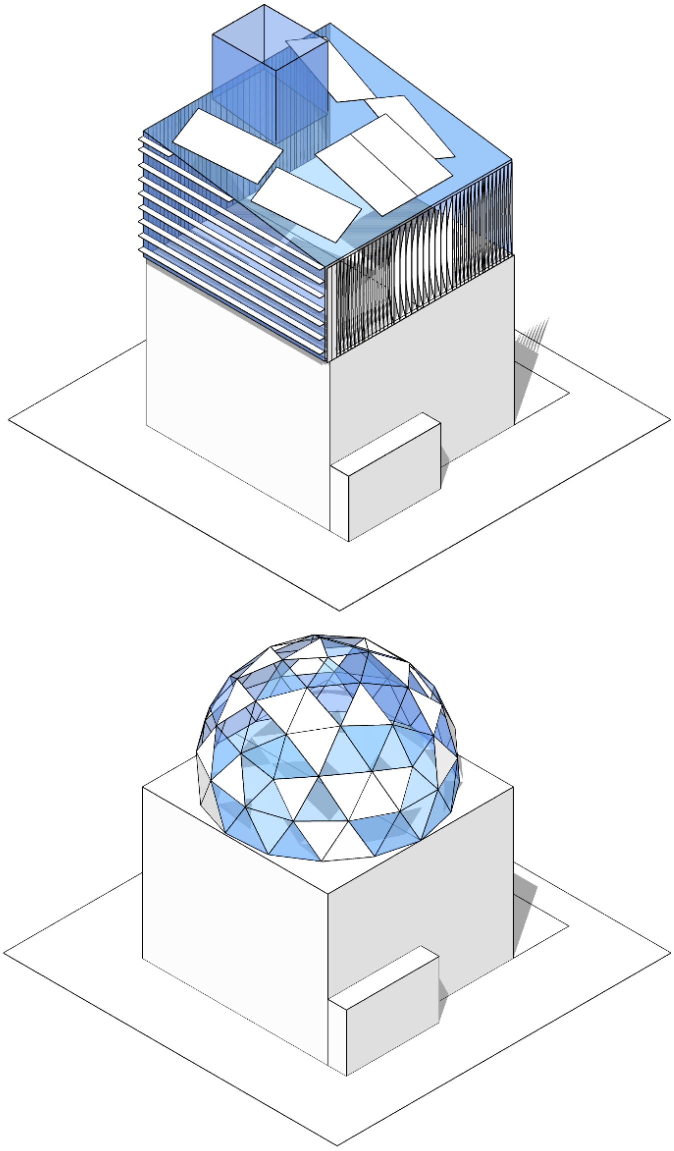


Figure 51: Roof-greenhouse RbD: a) combination 1; b) combination 2 (Author, 2022)

(5) Evaluate – Conclusions

Feasibility

The following table sheds light on the feasibility of each scenario for each house and greenhouse type based on the basic spatial and volumetric requirements explained above in the RbD process.

As a reminder, combination 1 is the optimized rectangular greenhouse; combination 2 the optimized geodesic dome; type 1 is the neighboring detached house; and type 2 the isolated detached house.

Table 16: Feasibility analysis of the different scenarios (Author 2022)

	Type 1		Type 2	
	Combination 1	Combination 2	Combination 1	Combination 2
Full greenhouse	+	-	++	+
Semi greenhouse	+	-	++	+
Rooftop greenhouse	++	-	++	-

All in all, it appears that the rectangular greenhouse (combination 1) is easier to apply to existing villas compared to the geodesic dome as it requires much less space around the house.

It is noteworthy that the solutions above will mainly depend on the size and shape of the existing house.

- A neighboring house is more difficult to insulate with that HGH model compared to an isolated house. Moreover, the geodesic dome option is never applicable to a type 1 house.
- An isolated house could accommodate all three solutions depending on the owner's needs and willingness. Of course, the benefits will differ according to the selected scenario (Table 17).
- The rooftop greenhouse solution, which occupies the least additional space, could be a solution for both house types. However, it counts many prerequisites, and is less easily applicable from a technical and structural point of view.

Comparison

The following table contains a critical reflection of the proposed scenarios based on the observations explained during the RbD process.

Due to the scope of this Master Thesis, the cost and legal / urbanistic obligations (permits needed in all cases) of these constructions were not taken into account for this analysis. This report intends to illustrate possibilities of insulating houses, not provide a market exploration.

Some conclusions about the size of the greenhouse (GH) can already be mentioned:

Table 17: Pros and cons analysis and discussion of the Villas RbD results (Author 2022)

Scenario	Pros	Cons	Conditions / prerequisites
Full greenhouse	Full heating gains (roof and walls are covered) Best energy-efficiency of the model Full energy collection benefits Straightforward to implement No volumetric changes Insulates the most (walls and roof) Perfect orientation Better security	Cannot be implemented in neighboring houses Food production only around the house (limited space) Reduced social benefits (limited space)	Sufficient ground space around the house House not too high (practical reasons and GH height) If flat roof: possible food production / social space on roof (but requires additional structural work)
Semi-greenhouse	Requires less space than a full GH Lower structural and volumetric changes compared to rooftop GH Half the energy production benefits compared to full GH	Reduced heating gains compared to full GH Insulates less than the full GH Lowest social and food production benefits because of reduced space Reduced energy-efficiency of the model	Deep feasibility investigation (windows, structure, walls, roof, …) needed to attach the GH to the house Sufficient space around the house (but less than for the full GH) The orientation of the existing house must be favorable

Rooftop greenhouse	Perfect orientation Requires no space around the house Full food production benefits	Reduced social benefits (less accessible than on the ground floor – especially for reduced mobility or elders) Reduced energy collection benefits Only insulates the roof Reduced heating gains (walls not covered) Reduced energy-efficiency of the model	Flat roof needed Structural, volumetric, and technical modifications or conditions will be needed to build it on the roof Roof access Extra security measures (security glass in the lower parts of the GH to avoid falling from the roof)

Overall, all scenarios are workable for at least one of the house types. However, they come with many conditions or prerequisites, especially on existing houses in an urban area.
In particular, the full greenhouse solution is the easiest to build and the most energy-efficient (thermal improvement, insulation, solar gains). Yet, it requires a lot of space around the house for it to be worthwhile. Ergo, it may not be easy to apply to most villas.

The two other scenarios require much less or no space on the ground but induce lower energy-efficiency levels (as they insulate only part of the house, and their reduced size limits the solar gains). Since they are leaning on or build over existing houses, deep feasibility studies as well as structural and/or volumetric changes are required to bear the additional weight of the greenhouse.

3. Conclusion

This study demonstrates that combinations 1 & 2 could be used to further insulate existing villas in Brussels but unfortunately will not be applicable in many cases because of the numerous prerequisites and the urban character of the area.

In particular, the full greenhouse solution is the easiest to build and the most energy-efficient (thermal improvement, insulation, solar gains). However, it requires a lot of space around the house for it to be worthwhile. The semi or rooftop greenhouse scenarios require much less or no space on the ground but induce lower energy-efficiency levels (as they insulate only part of the house, and their reduced size limits the solar gains) and entail detailed feasibility studies as well as structural and/or volumetric changes to bear the additional weight of the greenhouse. The rectangular greenhouse is easier to apply to existing villas compared to the geodesic dome as it requires much less space around the house. Overall, there is a preferred theoretical scenario for each house type.

Of course, including these combinations during the design phase of a new house is much easier and less expensive since the spatial and structural conditions could be taken into account in the building process from the start.

Another possibility is to apply derivatives or smaller features of the HGH concept using passive solar design techniques to existing villas such as verandas[19] or sun spaces[20]. They allow to improve the energy efficiency of the houses with much lower additional spatial or structural requirements. This latest recommendation is in line with the conclusion of an article on the energetical impact of conservatory on UK dwellings (climate zone similar to Belgium). They indicate that judicious implementation of passive solar design strategies in conservatories, with increasing conservatory size in elongated South-facing orientation with an aspect ratio of at least 1,67; could reduce energy consumption (by 5 kWh/m²), building emission rate (by 2 kgCO²/m²), and annual gas consumption (by 7 kWh/m²) of a typical UK house (Amoako-Attah and Bahadori-Jahromi 2016).

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[19] A veranda is a roofed open glass gallery or portico attached to the exterior of a building

[20] A sunspace is an isolated-gain passive solar home design that is closed off from the house (with doors or windows) and has three main functions: provide auxiliary heat, a sunny space to grow plants (in pots), and a pleasant living area (Energy saver 2022).

7

CONCLUSION

In this last chapter, a general overview of the Master Thesis first concludes the different analysis and development conducted. Afterwards, the main objectives and research questions are confronted with the answers provided in this research. Eventually, the contribution, limitations and potential further research on this subject are described.

VII. CONCLUSION

1. General overview

The energy demand of a building is determined by its energy performance, and building envelopes are responsible for 40% of a building's energy losses. As a result, enhancing the energy efficiency of building skins is critical to meeting the emission reduction objective to address climate change. In other words, it is essential to insulate the envelope of both new and existing structures, particularly in Belgium, where the current building stock is inadequately insulated.

In order to solve these critical issues, the following actions were taken in this thesis. First, the most recent advances in biomimicry, building envelopes, and bioclimatic design from the scientific literature were summarized. Second, numerous relevant case studies of buildings with a glass skin, a biomimetic façade, or a house encased in a greenhouse were thoroughly examined to assess their benefits while also identifying their shortcomings. Third, V², a House in a GreenHouse (HGH) prototype was created, and simulations were conducted to quantify its energetical behavior. Simulation results indicate that the prototype has insulation properties similar to an insulation layer on the façade of a house. However, the HGH concept is more interesting for temperate to cold climate zones because of its different heating and cooling behaviors compared to a traditional insulation method. As a result, this thesis established that HGHs are viable and valuable in Belgium.

Nonetheless, a few weaknesses of the HGH concept were observed. Consequently, a first biomimicry Research by Design process was followed to mitigate the concept’s flaws and improve its properties. Natural solutions based on the functioning of the termite mounds, desert rhubarb leaves, strelitzia reginae flowers, sunflowers, chameleon skins, and geodesic domes were applied to the initial prototype. In the end, two final optimal combinations that combine more than one answer are proposed for practical applications.

Ergo, a second Research by Design process was conducted to evaluate the practical use of the two optimized combinations to improve the insulation of Brussels villas. To that end, an evaluation process was conducted to determine the feasibility and the pros and cons of adding the two types of optimized greenhouses to either isolated or neighboring houses. Three alternatives were considered for the greenhouses: a full greenhouse around the house, half a greenhouse around the house, or a greenhouse only on the rooftop of the house. Each style of villa has a recommended solution based on its spatial and volumetric qualities. The study's findings indicate that the biomimetic design idea created to increase a house's energy performance is theoretically relevant to Brussels Villas.

In conclusion, this thesis has demonstrated that double skin façades, biomimetic enhancements, and passive solar design are all key techniques to improve the thermal behavior of a building.

2. Discussion of the main objectives

The main research question stated in this thesis is:

Is the House in a GreenHouse concept valuable for Belgium? How can we improve its energy performance through biomimetic design and apply this solution to the retrofit of Brussels Villas?

First, the energy simulations carried out on the V² prototype proved that adding a greenhouse over a non-insulated house is as efficient as using traditional insulating materials for the energy performance of the house in the Belgian climate zone. Theoretically, the HGH concept is therefore worthwhile, especially considering all the extra benefits it brings to the users.

Second, the greenhouse can further be improved by addressing its shortcomings through a biomimetic approach. Two optimized biomimetic combinations solutioning the disadvantages of the prototype are proposed to improve the energy performance of a house.

Third, this system was proven to be applicable to insulate the Brussels villas under some conditions. The energy losses of Brussels' villas can be mitigated through insulation, and the biomimetic greenhouse can be used to such a purpose.

The different sub-questions are:

What are double-skin façades? (How) do they improve a building's energy performance?

Double-skin façades consist of two layers, wherein air flows through the intermediate cavity. They have many advantages, including acoustic and thermal insulation, passive heating and cooling depending on the climate, and are overall energy efficient. Their thermal insulating properties were proved during the energy simulations, where the house without insulation but a greenhouse and the house with insulation and no greenhouse displayed the same energy demand values in the end. Yes, double-skin façades improve a building's energy performance.

Which types of biomimetic envelopes already exist? (How) do they improve a building's energy performance?

Biomimicry is a vast realm. The possibilities are endless. Some examples of biomimetic envelopes were highlighted in the literature review, as well as the One Ocean Building case study in the case studies. Several natural processes providing shading, ventilating, and energy harvesting systems applicable to building skins and contributing to a better energy performance were identified and analyzed in this thesis.

What is the impact of an outer glass skin on the efficiency of a house? How could it be improved by copying some natural bioprocesses?

The simulations with OpenStudio have proven than an outer skin glass improves the thermal performance of a house. Then solutions based on the properties of the termite mounds, the desert rhubarb, the strelitzia reginae flower, the sunflowers, the chameleon skin and the geodesic dome were found to further improve the benefits of a greenhouse by providing shade, ventilation, and optimized energy harvesting systems.

How could the thermal efficiency of Brussels Villas be improved through the addition of a biomimetic outer glass skin such as a greenhouse?

The improved biomimetic combinations proposed can be implemented on Brussels villas, given many conditions (flat roof, stability, room, permits, etc.). A theoretical preferred solution is recommended for each type of villa. The combinations prove to be an original solution to improve the thermal behavior of these villas.

3. Contribution

Following in-depth analyses, this research developed two aspects of the HGH model. First, its biomimetic optimization; and second, its applications. Specific literature on the subject is scarce, which is in inadequacy with the current climate and insulation crises.

Biomimetic façades and envelopes are still rarely realized. This Master Thesis introduces innovative developments and applications for biomimetic design emphasizing the extensive range of possibilities it offers. In this research, several biological role models countering the different issues noticed in traditional HGHs allowed a coherent and step-by-step optimization of a greenhouse.

Up until now, the building stock could be insulated in two manners: by adding a layer of insulation either outside or inside the construction. These two solutions, albeit being efficient, require deep volumetric or aesthetic changes to the core house. This thesis brings a new solution on the table for existing villas fulfilling the conditions: a greenhouse surrounding the house. Not only does it insulate as much as traditional insulation, but it also comes with new benefits: local food production, enhanced energy use and collection, social space, biophilia, and so on.

This illustration aims at projecting what a street with several HGH systems could look like.

Figure 52: illustration of the HGH model on several houses in the future (Author, 2022)

4. Limitations and further research

Of course, these findings should be regarded with caution, and a number of limitations should be acknowledged. First, the effect predictions in the model in the first part of the thesis are partly based on observatory studies. They are therefore subject to biases. However, they were completed with the energy simulations results and the literature review. Second, the unbuilt state of the HGH concept and the V² prototype also result in some limitations. The very nature of the OpenStudio software requires model assumptions and simplifications. These can slightly alter the results. Moreover, simulations are never as precise as studying and evaluating a built example at scale. Some built examples exist, but they have not been studied in a comparative energy way, and to our knowledge, biomimetic optimization have not been implemented.

To better understand the implications of these results, future studies could work with a built HGH example and research its energy consumption over time, for different biomimetic envelopes. This could be coupled with the energetic simulations of the biomimetic RbD results, as well as the villas retrofit scenarios.

A natural progression of this work is to analyze both the life cycle cost and carbon assessments of the different variations of the concept. First, as mentioned in this thesis, the objective of this study was to bring a scientific approach to the HGH model, not conduct a market study. The latter would thus be a complement to this research. Second, the carbon impact study could bring more depth to this thesis.

Following this, a future study could assess the long-term effects of potential for glass harvesting from commercial and office buildings for this purpose. This research would further link the HGH concept to the C2C and Carbon cycles principles. For example, the impact of the new fit of the Tour Montparnasse on its energy demand could be the topic of a future research since the project is due before 2024. A complementary carbon cycle study of this renovation project could be interesting as well.

Lastly, future research should be undertaken to explore how the other benefits (food, water, mental health, etc.) could profit the users of the model as well as, more broadly, the BCR.

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8

APPENDICES

This part of the thesis aims at providing more information on some of the topics mentioned in the main text. The structure of these follows the structure of the thesis, and each part is referenced to in the main text.

APPENDICES

1. Appendix 1 – Climate

A. Greenhouse effect

According to NASA, Life on Earth is reliant on energy from the Sun. Approximately half of the light that reaches the Earth's atmosphere travels through the air and clouds to the surface, where it is absorbed and subsequently reflected upward as infrared heat. The greenhouse gases absorb around 90% of this heat, which is then reflected back to the surface.

This results in the *greenhouse effect'*, the warming that occurs when the atmosphere traps heat emanating from Earth toward space. It has been expanding due to human growth since the mid-twentieth century, according to scientists. In fact, the presence of some gases in the atmosphere prevents heat from escaping. Long-lived gases that remain in the atmosphere semi-permanently and do not respond physically or chemically to temperature changes are referred to as *forcing* climate change. Human actions (most notably the combustion of fossil fuels) have significantly increased the concentration of greenhouse gases in the Earth's atmosphere, resulting in global warming.

Without human involvement, natural forces would push our world into a cooling phase (Nasa 2021). Therefore, building energy efficiency and operational energy use are becoming increasingly important as concerns about greenhouse gas (GHG) emissions and global warming grow (Webb, Aye and Green 2018).

B. Climate change

Figure 53 illustrates that heat waves are rising, while frost days are declining. According to the most severe predictions, temperatures might rise up to 7.2°C by 2100 compared to 1950–1970 levels (Pepermans and Maeseele 2017).

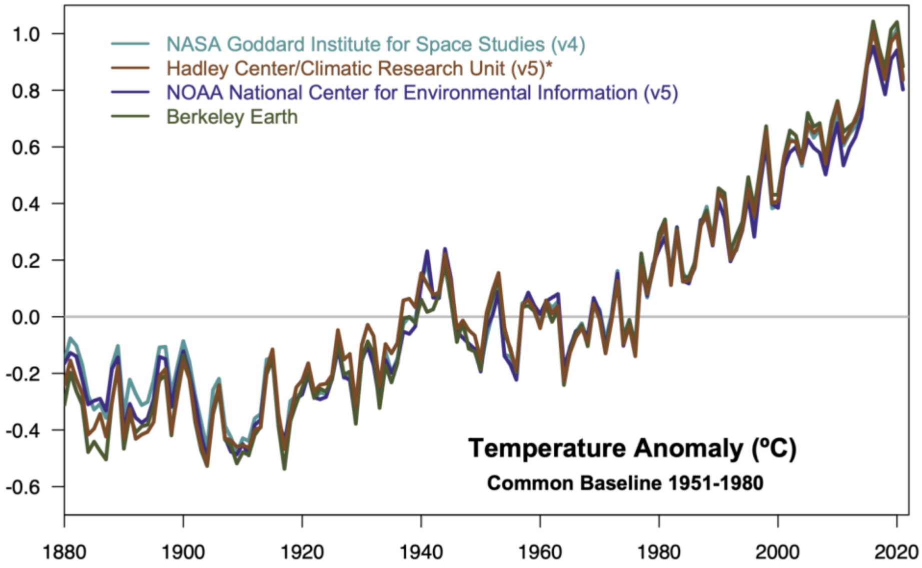


Figure 53: Global average temperatures are increasing since the 1880s, especially in the last 40 years (Nasa 2021).

C. Köppen's climate classification

The Köppen's classification was written one century ago by Wladimir Köppen (1846–1940) and has been verified since then by many successors in the field. This system classifies climate into five main types and 30 sub-types, based on average monthly temperatures and precipitations.

The article written by John Arnfield in *Encyclopedia Britannica* as well as the article *Present and Future Köppen-Geiger Climate Classification Maps at 1-km Resolution* in *Scientific data* by H. Beck et.al. both explain this classification in the same way:

- The five primary types of climates are indicated by letters A through E. These primary types are: (A) tropical or equatorial, (B) arid or dry, (C) warm/mild mid-latitude, (D) continental, and (E) polar.
- The secondary letters are there to refine those definitions. These types and their subgroups are represented in Figure 55 (Beck, et al. 2018) (Arnfield 2020).

Belgium

Belgium is situated in a *Cfb* climate region: temperate oceanic climate (Figure 55). These are found in the higher middle latitudes on the western faces of continents between 40° and 60° latitudes and are frequently found immediately North of Mediterranean climates. Because of the cold ocean currents, the summers are moderate. Winters are milder than in other regions at similar latitudes, although they are typically gloomy and damp (Beck, et al. 2018) (Arnfield 2020).

Belgium has substantial precipitation throughout the year. Its twenty warmest years occurred in the past 21 years. The annual average temperature in Brussels was 2.4°C higher in 2015 than in the pre-industrial period and continues to climb (Pepermans and Maeseele 2017).

Belgium is situated in the orange zone of the map of Figure 54, where there has been a climb of +1 to +2°C on average since the 1980s. Temperature data over the last few decades show significant warming, with the most recent data extending up to 2020. 2016 and 2020 are tied for the warmest year since 1880, maintaining a long-term pattern of rising global temperatures. Since 2005, the ten hottest years recorded since the 1860s have occurred, the seven most recent years being the warmest (Nasa 2021).

Sweden

Sweden is situated in the *Dfb* area: warm-summer humid continental climate (Figure 55). The average temperature for the year in Stockholm is 6.1°C, and the warmest month is usually July with an average temperature of 17.2°C (Weatherbase 2022).

Sweden is situated in the orange/red zone on the map (Figure 54). This means that is underwent an increase of +2 to +4°C in the last 40 years.

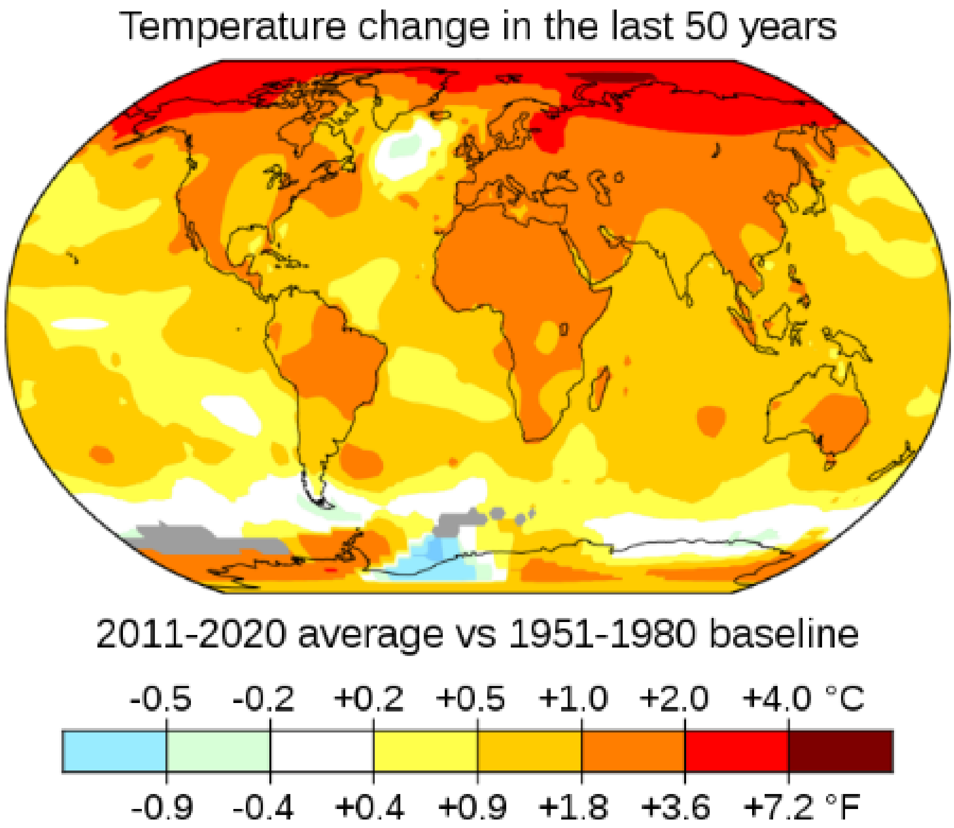


Figure 54: Temperature change in the last 50 years: Global average temperatures for the period 2011-2020 are between 1°C and 4°C higher compared to the 1951-1980 baseline temperatures. The Northern regions are the most affected by global warming (Nasa 2021).

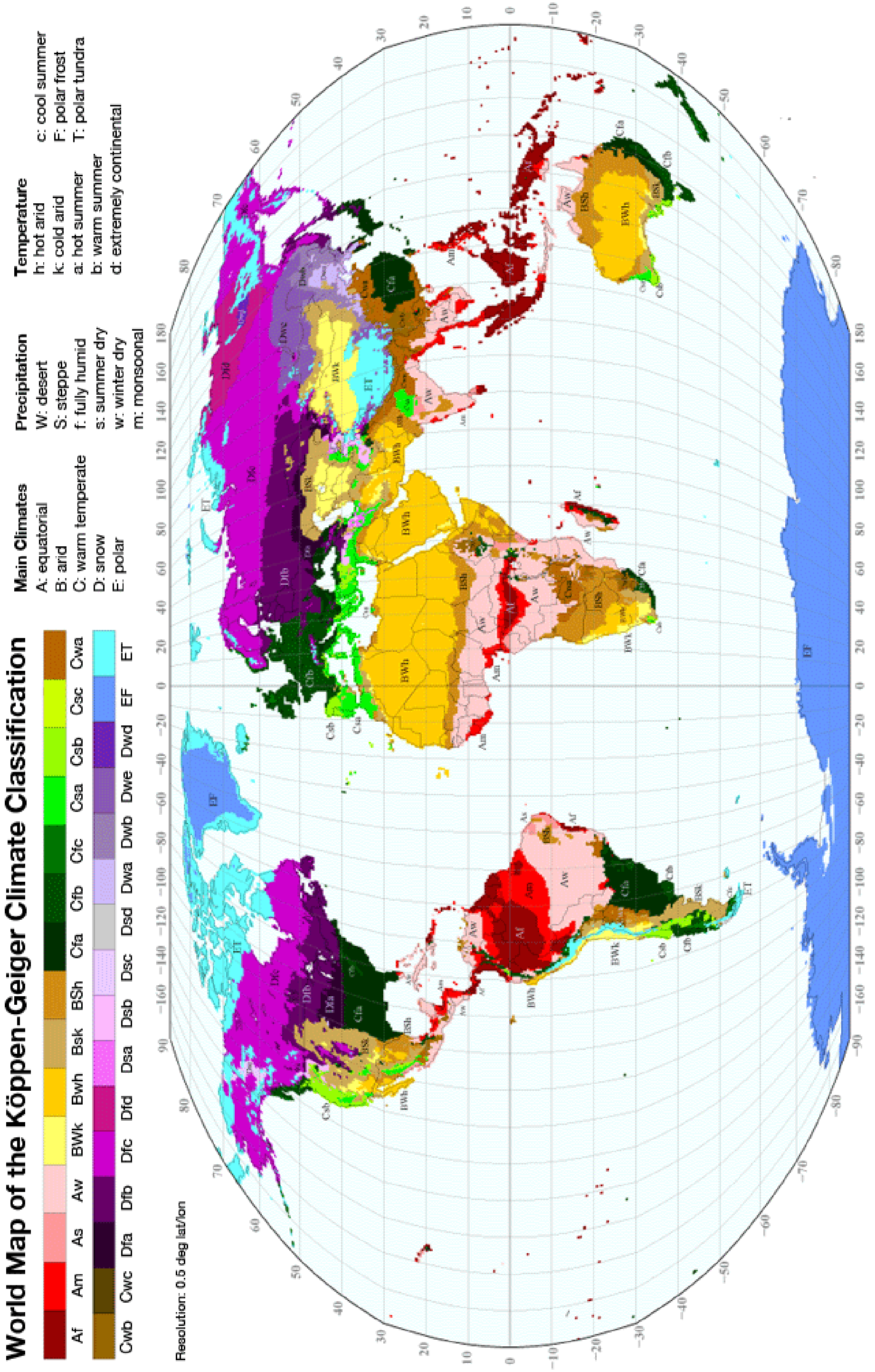


Figure 55: Köppen-Greiger world map Climate Classification. Belgium is in the Cfb region (dark green), and Sweden in Dfb (purple) - (Kottek M 2006)

2. Appendix 2 – Biomimicry

The detailed table below presents different morphologies or processes found in nature and their applications on elements to control in a building: heat (and cool), air, water, and light (Badarnah 2017).

Morphology	Processes (🔴🔵🟢🟡) *	Mechanism	Applications
Wrinkles	Evaporation 🔴🟢 Reflection 🔴🟡 Convection 🔴🔵	Wrinkles on the surface of the skin provide sufficient surface area for holding moisture and promote evaporation [100]. Additionally, these wrinkles create self-shaded areas for reduced heat loads and generate convective currents for enhanced heat loss.	Cooling external cladding
Hexagons	Flow 🟢 Condensation 🟢 Interception 🟡	Hexagonal micro-structuring of surfaces decreases contact angle significantly and results in a super-hydrophilic surface [89], and creates an optimal pattern of capillary water flow [101,102]. Hexagonal array of facets on a spherical plane enhances light interception [103].	Moisture and light harvesting
Spikes	Condensation 🟢	Spiky leaves create a thin boundary layer that improves water collection from fog [35].	Moisture harvesting
Knobs	Condensation 🟢	Knobs on silk fibers attract water from humid air [90].	
Grooves	Transport 🟢 Convection 🔴🔵 Irradiation reduction 🔴🟡	The presence of grooves on plants surfaces provides a guided water collection and transportation [104]. Termite mounds with macro grooves enhance heat dissipation and ventilation via convection [68], and create self-shaded regions.	Water distribution, ventilation, and heat dissipation
Capillaries	Transport 🟢 Diffusion 🟢	Special arrangement of integument's scales create micro-channels, a semi-tubular capillary system, over body surface to transport water via capillary forces [105]	Water transportation
Fractal	Flow 🔵🟢 Transport 🔵🟢 Diffusion 🔵🟢 Interception 🟡 Reflection 🟡	Fractal arrangement of flow systems is energy efficient [106,107]. The fractal network of nested loops in leaves provide an optimal transportation of fluids even at events of damage [80,108]. The fractal arrangement of Fibonacci sequence of seeds results in an efficient and compact packing for maximized light interception [85]. The fractal nanostructure of scales in butterfly wings is highly reflective [109].	Light harnessing, light shielding, and efficient transporting systems
Lamellae	Reflection 🟡 Absorption 🟡	Closely packed ridges with horizontal lamellae and micro-ribs, highly reflects certain wavelengths [109]. Variations in film thicknesses can result in 96% absorption of the incident solar radiation [110].	Light control and energy generation
Pores	Evaporation 🔴🟢 Diffusion 🔵🟢	Little pores on the skin surface allow direct diffusion of condensed water [75], and moisture loss in response to thermoregulatory demands.	Humidification and cooling
Trichomes	Reflection 🔴🟡 Scattering 🔴🟡 Condensation 🟢	Trichomes, microscopic fibers, enhance hydrophobicity and scatter light for reduced incident light at the interface [81].	Reducing heat loads and harvesting moisture
Mounds and Funnels	Flow 🔵 Velocity gradient 🔵	Mounds and funnels generate velocity gradients on the surface of ground and result in pressure gradient for wind-induced ventilation of burrows [73].	Ventilation

*Table 18: Distinct morphologies, corresponding processes, their underlying mechanisms, and potential applications for environmental adaptation. * The relevant environmental aspects involved in a process:*

Heat (🔴), Air (🔵), Water (🟢), and/or Light (🟡) (Badarnah 2017).

3. Appendix 3 – Double Skin Facades

Façades are one of the most important components in a building, not only aesthetically or functionally but also from an energy consumption point-of-view. They address functions such as view, illumination, ventilation, and user comfort (Ulrich, et al. 2014).

The double skin facade system was characterized by Harrison and Meyer-Boak as "*basically a pair of glass skin separated by an air corridor. Typically, the primary layer of glass is insulating. The air gap between the layers of glass acts as insulation against severe temperatures, winds, and sound. Sun-shading devices are frequently placed between the two skins*." (Poirazis 2004).

Figure 56 on the next page lists the advantages and disadvantages of double skin facades according to Poizaris' research.

Advantages mentioned by author	Oesterle et al., (2001)	Compagno, (2002)	Claessens et al.	Lee et al., (2002)	B.B.R.I., (2002)	Arons, (2000)	Faist, (1998)	Kragh, (2000)	Jager, (2003)
Lower construction cost (comparing to electrochromic, thermochromic photo-chromic panes)	√								
Acoustic insulation	√			√		√	√	√	√
Thermal insulation during the winter	√	√		√	√		√	√	
Thermal insulation during the summer	√	√		√			√	√	
Night time ventilation	√	√	√	√		√			
Energy savings and reduced environmental impacts						√			
Better protection of the shading or lighting devices	√	√		√					√
Reduction of the wind pressure effects	√	√	√						√
Transparency – Architectural design				√	√	√		√	
Natural ventilation	√	√		√		√	√		√
Thermal comfort – temperatures of the internal wall	√	√		√	√	√	√	√	
Fire escape	√								
Low U-Value and g-value		√				√		√	

Disadvantages mentioned by author	Oesterle et al. (2001)	Compagno (2002)	Claessens et al.	Lee et al. (2002)	B.B.R.I. (2002)	Arons (2000)	Faist (1998)	Kragh, (2000)	Jager (2003)
Higher construction costs	√				√	√			√
Fire protection	√				√				√
Reduction of rentable office space	√								√
Additional maintenance and operational costs	√		√		√				√
Overheating problem	√	√			√		√		√
Increased air flow speed					√				
Increased weight of the structure			√						√
Daylight	√								
Acoustic insulation	√				√				√

Figure 56: Pros and cons of double skin façades (Poirazis 2004)

4. Appendix 4– Additional case studies

A. The danger of high humidity levels

According to the article published in Environmental Health Perspectives in 1986, high humidity levels can cause a few health problems to humans, but also buildings (Arundel, et al. 1986).

When high humidity levels are paired with high temperatures, relative humidity has a significant negative direct influence on health. This combination lowers the rate of evaporative cooling of the body, which can produce significant pain or lead to heat stroke, exhaustion, and death (Arundel, et al. 1986).

High relative humidity exceeding 60% can create allergic mites and fungus, as well as change the quantity of formaldehyde, acid sand salts of sulfur, and nitrogen dioxides in the air. Buildings can potentially sustain structural damage as a result of it (Arundel, et al. 1986).

B. Climatron

The *Climatron*, created for the Missouri Botanical Gardens in St. Louis, was the first known greenhouse use of the geodesic dome (Figure 56). It was first open to the public in 1960. The Climatron greenhouse was developed by St. Louis architects Murphy and Mackey using Buckminster Fuller's concepts. The word *Climatron* was invented to underline the greenhouse dome's climate-control technology. The Climatron has no interior support and no columns from floor to ceiling, giving plants more light and area per square meter than traditional designs (Tingley 2020). A sophisticated temperature management system keeps the thick, green tropical rainforest environment in place.

The temperature inside fluctuates from 18° C at night to 29° C during the day. The average humidity level is 85%. From 1988 to 1990, the greenhouse was restored. Its new features included new glass panes and a redesigned interior. The degraded Plexiglas panes were replaced with heat-strengthened glass with a Bayer Company Saflex plastic interlayer. A low-emissivity layer is applied to the inside surface of this glass-and-plastic sandwich. This coating aids in the reduction of heating expenses by storing solar energy gathered during the day for use at night. The new glass support system is rigid and has internal gutters to transport condensation (Missouri Botanical Garden n.d.).

Figure 57: Climatron Geodesic Dome Greenhouse (Tingley 2020)

C. Greenhouse living concept

There is a third concept defined by the Greenhouse Living group: Eco-cycle cities. This part is in appendix as it is not as relevant as the others to this thesis – but it is insightful nonetheless, especially for potential future growth of the HGH concept.

Eco-Cycle Cities (urbanism) consist of a reflection towards building future cities. The cycle of water, nutrition and energy will be closed at a very local level. Such cities will provide good, nutritious food while reducing the need for transportation and creating human environments. Designs can go as far as to including a data center in the building that in turn heats up the greenhouse (Greenhouse Living 2021). This concept is illustrated on Figure 58.

Figure 58: Eco-cycle cities, that can provide infrastructure to a whole community within the same HGH principle. Munkaskog Naturvillor (Greenhouse Living 2021)

ReGen Villages concept

In 2016, the European businesses B.V. and EFFEKT presented ReGen Villages (Figure 59), an innovative new housing type. These are self-sufficient, off-the-grid community villages. They are made up of energy-positive buildings, renewable energy, power storage, high-yield organic food production on your doorstep, vertical farming aquaponics/aeroponics, water management, and waste-to-resource solutions. Every house is surrounded by a greenhouse as shown on Figure 60 (Crockett 2016).

While cities currently house more than half of the world's population, the efficiency of ReGen systems may reduce a household's dependency on high-frequency urban living. This would open the way for a new wave of peri-urbanism and rural expansion, allowing for more evenly distributed population density throughout the globe's surface. This allotment would also lighten the stress on municipal and national governments, which are already under strain due to overpopulation (Crockett 2016).

According to the architects, this density redistribution promotes a paradigm that provides not only environmental and financial benefit, but also social value by establishing a framework for empowering families and developing a meaningful sense of community, reconnecting people with nature and consumption with production. In addition to the environmental and social benefits, it restores a sense of achievement, making it a more realistic long-term plan (Crockett 2016).

The neighborhood is round, with nature houses encircling it. The other functions are shown in a circular pattern, from the edge to the center, as social areas, followed by food production. It has a lot of green areas. This circular layout provides for rapid access to various locations with gentle mobility, avoiding the demand for cars or other motorized vehicles.

The nature houses are adapted to the country in which the village is placed and provide numerous energy advantages compared to *normal* houses.

Figure 59: ReGen Village overview (Crockett 2016)

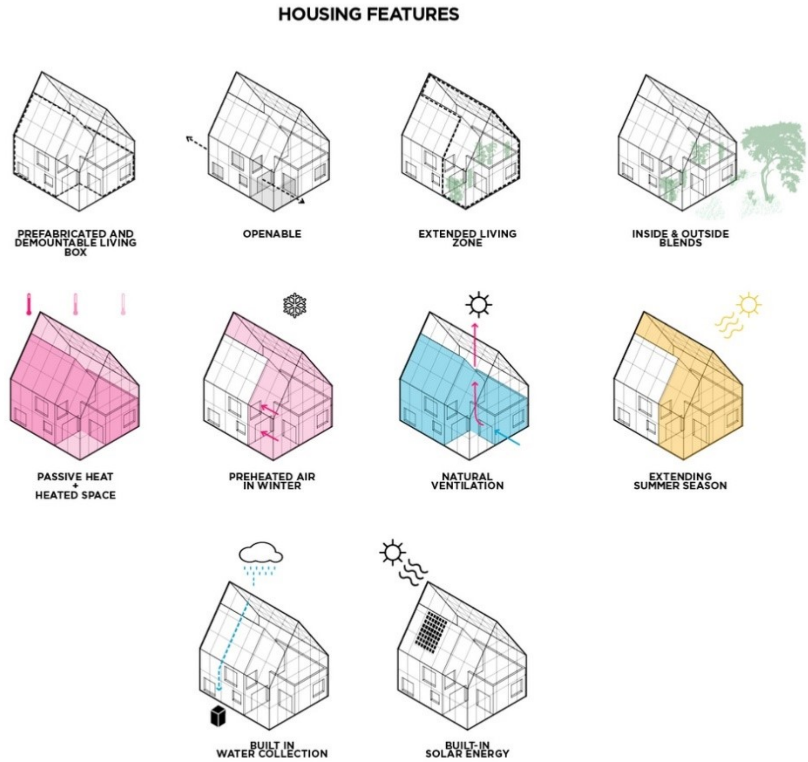


Figure 60: ReGen Village, the pros of Nature Houses (Crockett 2016)

D. Dome of visions – Scandinavia, Nature House

Concept: building in a greenhouse
Functions: flexible public space, study
Localization: Denmark
Builder and idea: DoV team, K. Tejlgaard

HGH do not need to have a sloped roof greenhouse (Figure 61). In fact, an experiment in Scandinavia designed a series of projects called *Dome of Visions* or *DoV* inspired by the geodesic dome of Buckminster Fuller. DoV is a study to learn more about how constructing within a greenhouse influences architecture and the well-being of its habitants. For this purpose, it uses a passive and solar heated space as a building envelope, which creates a third climate for the bulk of the usable space. According to Kristoffer Tejlgaard, a space that is neither inside nor outside and hence provides a better environment for man and nature to interact (Tejlgaard 2017).

The most insightful aspect of this case is of course the greenhouse. According to the architects, the dome, which serves as the inner house's structural envelope, protects the inside from rain and winds, but not only. Because it is a greenhouse and is solely heated by radiant heat from the sun, the dome heats up even during the winter, resulting in lower mechanical heating demands (Tejlgaard 2017). In the summer, the inside is cooled off by opening the top of the roof. Therefore, the most temperate regions are found around the central home, which offers shade in the summer and may maintain heat in the winter. The structure is mostly powered by the sun's energy, and the latter is optimized by the dome's shape.

The team analyzed the temperature indoors and outdoors, as well as humidity, acoustics, and CO_2 concentration in order to learn more about a more seasonal and energy efficient interior climate. They also tracked their own energy usage, which includes solar panels and a wood-burning stove. This offers a general idea of the dome's potential to serve as a residential and living room that is in tune with the seasons and the sun's intensity (Dome of Visions (DK) 2021).

The designers attempt to answer the two following questions: How can we design buildings that are both sustainable in the broadest sense and energy efficient at the same time? How can cities be developed while balancing everyday living and climate goals? (Dome of Visions (DK) 2021).

The Dome of Visions is a multi-purpose arena that caters to a wide range of interests. The Dome will host concerts, readings, architectural debates, business seminars, exhibits, and even camps where students and the city's creative elite congregate for days to immerse themselves in architecture's new problems (Dome of Visions (DK) 2021).

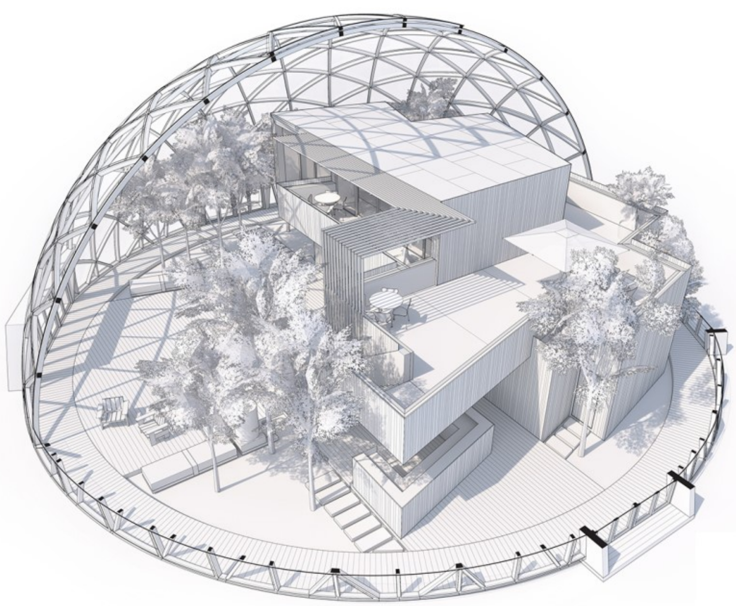


Figure 61: Dome of Visions 3 - overview (Tejlgaard 2017)

5. Appendix 5 – Details of Prototype V²

A. Architecture

The house's lay-out is separated into two floors spanning 8 x 12m each with a structural grid of 8 x 6m. The ground floor hosts the living spaces and the kitchen, as well as a large technical area next to the washing room. The first floor is composed of four bedrooms and two bathrooms. One of the bedrooms is used as an office for this example and enjoys a floor-to-ceiling window on the East side. The bedrooms are placed primarily on the North side of the building, to avoid overheating during the summer. Indeed, since this house is situated in Belgium rather than Scandinavia, the average temperatures are higher. To evermore increase the feeling of being lost in nature, the windows go remarkably high up and the frame is hidden in the slab. That way, residents have a thorough view of the nature around, daylight abundance and enjoy a comfortable environment all year long.

The roof-terrasse can be enjoyed as an extra semi-outdoors space by the residents. It is the hottest – and one of the most comfortable – parts of the house in the winter, thanks to the buoyancy effect.

This core house is situated in a large greenhouse of 32 x 15m with a 12 m-high double-sloped roof. The home entry is situated on the West site of the greenhouse, where most of the vegetation is present. Since the greenhouse serves as a tropical garden, the plants are not only local but from hotter parts of the world as well. This allows a local production of a variety of different foods, all available at kilometer-zero. The living spaces are in the South part of the building and enjoy a terrasse nearby.

B. Structure

The house is composed of a regular steel structure, formed with porticos. The structural elements are circular sections, fixed with bolts and entirely demountable. That way, if a piece of it must be changed later on or if there is a need to replace the plot's occupation, the house can be dismounted rather than destroyed. The grid is 4m x 6m to optimize the use of material whilst still being able to carry the weight of the house and ease the transport on the site. The floor slab is composed of wood, a material that associates well with steel and allows good spans for a limited slab thickness.

For the greenhouse, the structure is also composed of steel tubular sections for the columns, as well as I-beams.

The house rests on a concrete foundation slab. The greenhouse, however, is maintained by a shallow foundation grid that follows the structure. The plants can therefore take root into the soil.

C. Technical elements

V^2 counts several pieces of equipment and technical systems that were inspired by the work of Anders Solvarm and Koen Vanderwalle, respectively in the projects *Naturhus* and *Kaseco*. They are indicated in blue hatches on the ground floor plan.

V^2 first of all uses solar energy. With the help of solar panels, the house is autonomous both in hot water and electricity production. The heating and cooling of the house use electricity from the same renewable source, but the demand is limited as the greenhouse allows for extra insulation.

Second, the house is composed of two water systems. On the one hand, it takes advantage of its environment and captures the Belgian rainwater. After going through several filters, the water is clean and can be used in the house for the family's needs. On the other hand, the grey water is not wasted. Instead, it goes again through some filters (different than the rainwater of course) and can then be used for the plants. This water is richer in nutrients and ensures the well-being and natural growth of the plants, without the need of any chemicals (HOME, episode 1: Sweden 2020).

D. Materials

As explained before, the structure is composed of steel columns and beams, concrete foundation slab and wooden floors.

The walls are lightweight and are composed of rock wool insulation, proven to be natural, fire resistant and having a small embodied carbon footprint. It is also low maintenance and works both as thermal and acoustic insulation (Rockwool n.d.). The thickness of this insulation will be adapted for the several energy scenarios in this Thesis.

The façades of the house count several metallic panels, with three different patterns. Metal was chosen over, for example, a wood cladding because the interior of the greenhouse can get humid due to the vegetation– as noticed in Kaseco. Since wood absorbs water and inflates, some cracks could appear on the façades or inside the home. This could lead to additional maintenance costs or other problems later on. Metal has the advantage of being waterproof if treated well against rust.

The windows of the greenhouse are in simple glazing. Additionally, they are laminated for its roof so that someone can walk on it if needed. The windows of the house are in double glazing. All window frames are in aluminum, first because aluminum is 95% recyclable, and then for maintenance reasons as it needs less replacements compared to wood in the long run.

6. Appendix 6 – Energy simulations

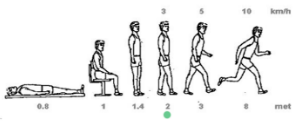
A. Assumptions

Target temperature of the simulations

The target temperature in the core house was set to 20°C .

This value was determined thanks to average activity levels and clothing resistance for the people in the house following the analyses below. The following graphs were retrieved from the *Energy Performance of Buildings* class from 2020-2021, by Filip Descamps (Descamps 2021).

Table 19: Metabolic rates for various activities (Descamps 2021)



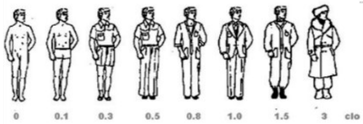
Metabolism

Table 11. Metabolic Rates for Various Activities

Activity	Activity Level W/Person EnergyPlus Schedule Value	Activity Level W/m²	met*
Resting			
Sleeping	72	40	0.7
Reclining	81	45	0.8
Seated, quiet	108	60	1
Standing, relaxed	126	70	1.2
Walking (on level surface)			
3.2 km/h (0.9 m/s)	207	115	2
4.3 km/h (1.2 m/s)	270	150	2.6
6.4 km/h (1.8 m/s)	396	220	3.8
Office Activities			
Reading, seated	99	55	1
Writing	108	60	1
Typing	117	65	1.1
Filing, seated	126	70	1.2
Filing, standing	144	80	1.4
Walking about	180	100	1.7
Lifting/packing	216	120	2.1
Miscellaneous Occupational Activities			
Cooking	171 to 207	95 to 115	1.6 to 2.0

Table 20: clothing resistance table (Descamps 2021)

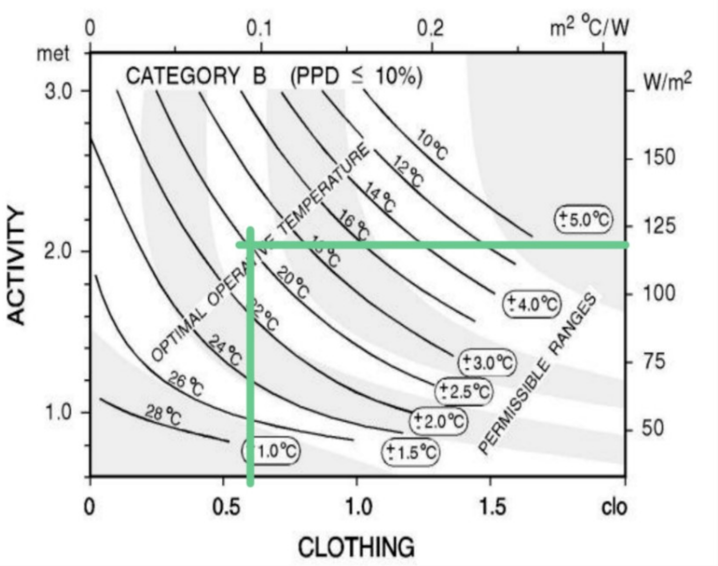
Clothing resistance I_{clo}



kledingcombinatie	Warmteweerstand [clo]
naakt	0,0
korte broek	0,1
standaard tropenpak: slip, korte broek, hemd met open boord en korte mouwen, dunne sokken en sandalen	0,3
dameskleding erg warme dagen: ondergoed, lichte zomerjurk en schoenen	0,3
zomerkleding dames: panty, ondergoed, rok, blouse of lichte sweater met korte mouw en schoenen	0,4
licht zomerpak: slip, lichte lange broek, hemd met open boord en korte mouwen, dunne sokken en schoenen	0,5
winterkleding dames: panty, ondergoed, rok en sweater met lange mouw of zware jurk, schoenen	0,6
licht werkpak: ondergoed, katoenen werkhemd met lange mouwen, lange werkbroek, wollen sokken en schoenen	0,7
winterpak: ondergoed. hemd met lange mouwen, lange broek, trui met korte mouwen. dikke sokken en schoenen	0,9
winterpak voor binnen: ondergoed, hemd met lange mouwen, lange broek, trui met lange mouwen, dikke sokken en schoenen	1,0
winterpak voor buiten: katoenen ondergoed met lange mouwen en broekspijpen, hemd, kostuum met lange broek, jas en vest, wollen sokken en zware schoenen	1,5

Warmteweerstand van enkele kledingcombinaties.

Design values



Graph 5: Temperature design values from activity levels and clothing resistance (Descamps 2021)

Plants

1.1. The correlation between CO2 concentration and temperature variations

As mentioned by the NOAA of the United States of America (National Oceanic and Atmospheric Administration) in their report *End of the African Humid Period*, there is a tight correlation between temperature and carbon dioxide content in the atmosphere. Basically, with increased concentrations of carbon dioxide comes an increase in temperatures (NOAA 2021). A reverse statement is also true: in the process of photosynthesis, plants absorb carbon dioxide, a greenhouse gas, and sunlight, lowering the temperature (Kurniawan 2004).

1.2. Photosynthesis

Most photosynthetic organisms are photoautotrophs, meaning they can make food directly from carbon dioxide and water with the use of light energy (Bryant and Frigaard 2006). In more simple words, most plants use carbon dioxide, water and light to make glucose, oxygen and water vapor in the process of photosynthesis.

The net equation of photosynthesis can be written as (Govindjee 1999, pg. 13):

$$6CO_2 + 12\ H_2O + Light\ Energy \rightarrow\ C_6H_{12}O_6 + 6O_2 + 6\ H_2O$$

Where:

- CO_2 is carbon dioxide (which, within a closed system, will cause temperature rises if not ventilated)
- H_2O is water (vapor, which causes condensation in the greenhouse)
- $C_6H_{12}O_6$ is glucose
- O_2 is oxygen

This means that for each mole of glucose produced, 6 moles of CO_2 are needed.

It can be noted that the first member of this equation includes the use of energy from light. That is a crucial condition in order for photosynthesis to happen. This means that, during the night, when there is no light, photosynthesis is not possible (for most plants). Carbon dioxide is thus not transformed into glucose, water nor oxygen and subsequently gets trapped into the greenhouse.

To simplify and summarize, it can be concluded that the temperatures will rise at night inside the greenhouse if the system is closed and no air ventilation is possible with the outside.

1.3. How much will plants contribute to heat gains?

To quantify the heat gains from plants, several intermediate steps are necessary (Seymour 2010):

- Rates of respiration to know how much CO_2 is produced from plants (Seymour 2010)
- The respiratory quotient (RQ), assumed to be 1 as carbohydrates are usually metabolized to convert O_2 consumption into CO_2 production (Seymour 2010)
- Heat production, obtained from the rate of CO_2 production according to the calorific equivalent of $1\ \mu mol/_S = 0{,}47\ W$ (Seymour 2010)
    - This uses Newton's Law of Cooling: $\phi = C \times (T_f - T_a)$ where:
        - ϕ is the heat production of a body
        - C is the thermal conductance
        - Tf is the floral temperature
        - Ta is the ambient temperature

- Because plants breathe continually during the day and night, heat production may be assumed to be constant. Photosynthesis, on the other hand, occurs exclusively during the day (need for light). This process, on the other hand, occurs only in flowers during the blossoming phase, hence it is time limited. There is thus no heat created when the plants are not in blossom. Heat generation, in reality, is a process that necessitates a lot of energy from plants, which they only utilize to enhance pollination during the flowering time (the heat will attract insects and disperse the olfactory molecules that attract insects more easily).

It is important to note that Figure 62 refers to particular plants, and results do not represent the entire realm of plants. However, the outputs will be simplified given the scope of this thesis by calculating an average value (Table 21).

Based on the figure hereabove, three different species were considered in order to make an assumption about the power produced by any plant, calculated at 0,013 W/g.

Species	Part	Mass	Maximum respiration rate Φ			Temperatures T_f	T_a	T_f-T_a	Conductance	Reference
		g	nmol s^{-1} g^{-1}	µmol s^{-1}	Watts	°C	°C	°C	mW $°C^{-1}$	
Symplocarpus foetidus	Spadix	3.76	286	1.07	0.50	18.2	−7.4	25.6	19.4	1
Symplocarpus renifolius	Spadix	3.61	287	1.04	0.49	15.0	5.0	10.0	48.7	2
Arum italicum	Spadix	1.84	733	1.35	0.63	31.4	20.6	10.9	58.4	3
Philodendron melinonii	Spadix	25.6	200	1.88	0.88	39.5	27.2	12.3	71.8	4
Philodendron imbe	Spadix	25.9	72.1	1.87	0.88	21.9	12.9	9.0	97.5	5
Philodendron appendiculatum	Spadix	9.64	93.9	0.91	0.43	27.1	22.9	4.3	103	6
Philodendron solimoesense	Spadix	95.1	52.8	5.02	2.36	41.1	27.5	13.6	174	3
Philodendron selloum[a]	Spadix	137	78.2	10.46	4.91	40.3	18.5	21.8	232	7
Philodendron grandifolium	Spadix	97.2	49.0	4.76	2.24	22.6	16.3	6.4	350	5
Amorphophallus konjac	Appendix	213	25.4	5.41	2.54	28.5	26.9	1.6	1570	8
Helicodiceros muscivorus	Appendix	3.20	450	1.40	0.66	29.8	15.2	14.6	45.1	9
Arum concinnatum	Appendix	14.5	169	2.29	1.08	33.2	22.1	11.1	97.1	10
Sauromatum guttatum	Appendix	10.2	213	2.17	1.02	28.0	26.0	2.0	510	11
Dracunculus vulgaris	Appendix	47.2	72.0	3.62	1.70	26.6	24.1	2.5	681	12
Amorphophallus titanum	Appendix	488	122	73.46	34.53	31.0	24.3	6.5	5168	13
Dracunculus vulgaris	Male florets	1.89	113	0.21	0.10	18.6	10.3	8.3	12.1	12
Helicodiceros muscivorus	Male florets	0.65	820	0.55	0.26	24.3	12.8	11.5	22.5	9
Arum concinnatum	Male florets	0.40	846	0.33	0.16	26.2	21.4	4.8	32.7	10
Nelumbo nucifera	Flower	42.2	49.7	2.10	0.99	30.0	10.0	20.0	49.4	14
Magnolia ovata	Flower	55.6	30.4	1.69	0.79	29.7	24.3	5.4	147	6
Victoria cruziana × amazonica[b]	Flower	282	8.5	2.39	1.12	30.7	25.1	5.6	201	15
Victoria amazonica[c]	Flower	271	9.7	2.63	1.24	32.6	26.5	6.1	203	16
Macrozamia machinii	Male cone	167	46.0	7.70	3.62	36.5	30.1	6.4	565	17
Cycas revoluta	Male cone	600	23.1	13.86	6.51	34.4	29.0	5.4	1206	15
Hydnora africana	Osmophore	8.45	8.3	0.07	0.03	25.0	24.5	0.5	65.4	18
Hydnora abyssinica	Osmophore	11.4	27.5	0.31	0.14	31.9	30.8	1.1	131	18

Sources of the data are: [1]Knutson 1974, Seymour & Blaylock 1999, Seymour 2004; [2]Seymour & Ito unpublished; [3]Seymour & Gibernau unpublished; [4]Seymour & Gibernau 2008; [5]Seymour & Schultze-Motel unpublished; [6]Seymour, Silberbauer-Gottsberger & Gottsberger 2010b; [7]Nagy *et al.* 1972, Seymour *et al.* 1983, Seymour 1999; [8]Lamprecht & Seymour in press; [9]Seymour *et al.* 2003a; [10]Seymour *et al.* 2009a; [11]Lamprecht *et al.* 1991; [12]Seymour & Schultze-Motel 1999; [13]Lamprecht & Seymour 2010; Baumann *et al.* 1998; [14]Seymour & Schultze-Motel 1998; [15]Seymour unpublished; [16]Seymour & Matthews 2006; [17]Seymour *et al.* 2004; [18]Seymour *et al.* 2009.

Notes: [a]*Philodendron selloum* is called *P. bipinnatifidum* by Mayo (1991), but differs in many characteristics (Gottsberger & Amaral 1984). [b]Hybrid from the Adelaide Botanic Garden. [c]The original publication erroneously listed mass-specific respiration rate in pmol s^{-1} g^{-1}; it should have been nmol s^{-1} g^{-1}.

Figure 62: Maximum rates of respiration and heat generation (ϕ) of intact thermogenic flowers, inflorescences, and cones, in proportion to floral component mass and temperature differential (Tf) between flowers and ambient air (Ta). The rate of heat generation and the temperature difference are used to compute thermal conductance (Seymour 2010).

Table 21: power of plants per mass ratio calculated based on the table above (Author 2022)

Species	Power (W)	Mass (g)	Power over mass ratio (W/g)
Cycas revoluta	6,51	600	0,011
Symplocarpus renifolius	0,49	3,61	0,136
Philidendron solimoensense	2,36	95,1	0,025
Average	3,12	232,90	0,013

Next, it was important to define which vegetables would grow inside the greenhouse in order to know when they would bloom, hence produce heat.

Three commonly found vegetables and local tree types were chosen: typical trees, beans, carrots, and tomatoes.

Figure 62 and Table 22 highlight the blossoming period of each chosen crop (i.e., when they will emit heat) (Urban Farmer 2022).

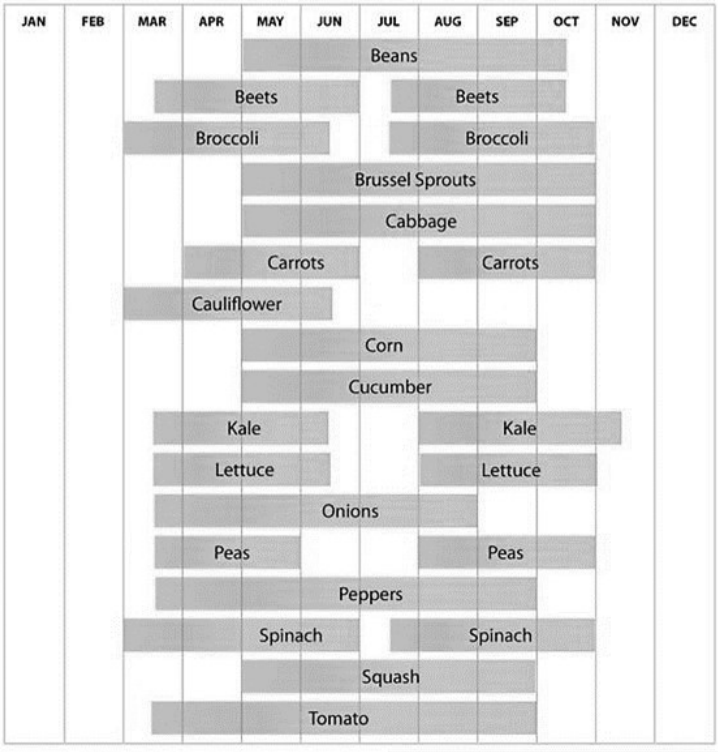


Figure 63: planting schedule. From this were taken the values for carrots, beans, and tomatoes that are displayed in the table under (Urban Farmer 2022)

Table 22: blossoming time calculation based on heat production schedules for greenhouse plants (Author, 2022)

	Beans	Carrots	Tomatoes	Trees
January	0%	0%	0%	0%
February	0%	0%	0%	0%
March	0%	0%	50%	0%
April	0%	100%	100%	100%
May	100%	100%	100%	100%
June	100%	100%	100%	100%
July	100%	0%	100%	100%
August	100%	100%	100%	100%
September	100%	100%	100%	100%
October	50%	100%	0%	0%
November	0%	0%	0%	0%
December	0%	0%	0%	0%
% time of heat production/yr	**45,8%**	**50,0%**	**54,2%**	**50%**

Each of these crops will cover one fifth of the allowed greenhouse space, or 76,8 m². The remaining 76,8 m² will be used for circulation and sitting spaces.

This will contribute to internal heat gains.

Table 23: plant heat production per year for V² (Author, 2022)

	Mass (g/sqm)	Power (W/sqm)	Surface (sqm)	Power_tot (W)	% blossoming time per year	Power tot (W/y)
	(Moestuin Weetjes 2022)	=0,013 x Mass		= Power * surface	(Urban Farmer 2022)	= Power tot * % time
Bean	2000	27	77	2058	45,83%	**943**
Carrot	7500	100	77	7716	50,00%	**3858**
Tomato	26667	357	77	27435	54,17%	**14861**
Tree	907000	12150	77	933141	50,00%	**466571**
					kWh/year	486

Materials

This table includes all materials that were used in the V² model definition in OpenStudio. For each material, the thickness and resulting thermal transmittance value were defined. These show how much heat can go through the material (Table 25 and Table 24).

Table 24: House materials table for V² that was inputted in Openstudio (Author 2022)

HOUSE				
	Material	d [m]	λUi [W/m.K]	d/λUi [m^2.K/W]
EXTERIOR				
Roof	Metal roofing	0,015	45,006	0,00
	Insulation mineral wool	0,33	0,032	10,31
	Metal decking	0,015	45,006	0,00
Walls	Metal finish	0,008	45,28	0,00
	Insulation mineral wool	0,33	0,032	10,31
	Dry wall	0,127	0,16	0,79
Slab	Wooden parquet	0,025	0,15	0,17
	Screed	0,15	0,41	0,37
	Insulation mineral wool	0,25	0,032	7,81
	Concrete foundation slab	0,3	2,4	0,13
Windows	Glass	0,003	0,008	0,38
	air			0,15
	glass	0,003	0,008	0,38
INTERIOR				
Wall	Dry wall	0,127	0,16	0,79
	Air			0,15
	Dry wall	0,127	0,16	0,79
Floor	Wooden parquet	0,025	0,15	0,17
	Screed	0,15	0,41	0,37
	Plywood	0,025	0,15	0,17

Table 25: Greenhouse materials table for V² that was inputted in Openstudio (Author 2022)

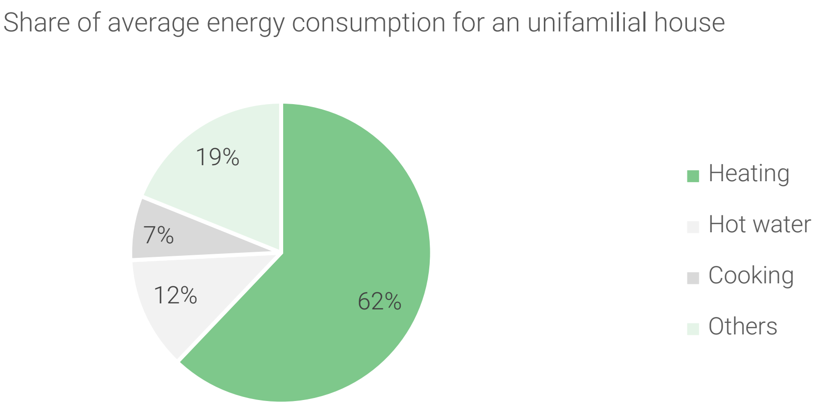
GREENHOUSE				
	Material	d [m]	λUi [W/m.K]	d/λUi [m^2.K/W]
Windows roof	Glass	0,003	0,008	0,375
Windows walls	Glass	0,003	0,008	0,375

France's average household energy consumption

The following data directly come from Engie's official website (Engie 2021).

Table 26: Average French household energy consumption per year, link with V²'s energy simulations results (Author 2022)

Electrical consumption post	Annual average consumption house of 100m²) (kWh/year)
Heating	10.542
Hot water	2.054
Cooking	1.171
Others	3.208
Total (house of 100m²)	16.975



Graph 6: Share of energy consumption for a French unifamilial house, on average (Engie 2021) (Author, 2022)

B. Energy simulation results

These figures were directly taken from the OpenStudio output file. Please note that these results are expressed in GJ and thus have to be converted to kWh, the unit used in this thesis. Moreover, the plant's share of internal gains has to be added to the cooling demand, since it was not taken into account in Openstudio.

Scenario 1

End Uses

	Electricity [GJ]	Natural Gas [GJ]	Gasoline [GJ]	Diesel [GJ]	Coal [GJ]	Fuel Oil No 1 [GJ]	Fuel Oil No 2 [GJ]	Propane [GJ]	Other Fuel 1 [GJ]	Other Fuel 2 [GJ]	District Cooling [GJ]	District Heating [GJ]	Water [m3]
Heating	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	309.29	0.00
Cooling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	41.44	0.00	0.00
Interior Lighting	19.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fans	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pumps	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	19.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	41.44	309.29	0.00

Note: District heat appears to be the principal heating source based on energy usage.

Figure 64: simulations scenario 1 output (OpenStudio 2022)

Scenario 2

End Uses

	Electricity [GJ]	Natural Gas [GJ]	Gasoline [GJ]	Diesel [GJ]	Coal [GJ]	Fuel Oil No 1 [GJ]	Fuel Oil No 2 [GJ]	Propane [GJ]	Other Fuel 1 [GJ]	Other Fuel 2 [GJ]	District Cooling [GJ]	District Heating [GJ]	Water [m3]
Heating	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.56	0.00
Cooling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	91.69	0.00	0.00
Interior Lighting	19.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fans	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pumps	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	19.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	91.69	18.56	0.00

Note: District heat appears to be the principal heating source based on energy usage.

Figure 65: simulations scenario 2 output (OpenStudio 2022)

Scenario 3

End Uses

	Electricity [GJ]	Natural Gas [GJ]	Gasoline [GJ]	Diesel [GJ]	Coal [GJ]	Fuel Oil No 1 [GJ]	Fuel Oil No 2 [GJ]	Propane [GJ]	Other Fuel 1 [GJ]	Other Fuel 2 [GJ]	District Cooling [GJ]	District Heating [GJ]	Water [m3]
Heating	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	93.55	0.00
Cooling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.87	0.00	0.00
Interior Lighting	19.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fans	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pumps	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	19.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.87	93.55	0.00

Note: District heat appears to be the principal heating source based on energy usage.

Figure 66: simulations scenario 3 output(OpenStudio 2022)

Scenario 4

End Uses

	Electricity [GJ]	Natural Gas [GJ]	Gasoline [GJ]	Diesel [GJ]	Coal [GJ]	Fuel Oil No 1 [GJ]	Fuel Oil No 2 [GJ]	Propane [GJ]	Other Fuel 1 [GJ]	Other Fuel 2 [GJ]	District Cooling [GJ]	District Heating [GJ]	Water [m3]
Heating	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	21.3	0.00
Cooling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	36.97	0.00	0.00
Interior Lighting	19.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fans	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pumps	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	19.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	36.97	21.3	0.00

Note: District heat appears to be the principal heating source based on energy usage.

Figure 67: simulations scenario 4 output (OpenStudio 2022)

The following table shows the conversion from GJ to kWh.

Table 27: Openstudio results: conversion to show how/what (the) end results were used in this thesis (Author, 2022)

	Openstudio		Conversion			In Thesis		
Scenario name	District Heating (GJ)	District Cooling (GJ)	District Heating (kWh/y)	District Cooling (kWh/y)	Heating gains from plants (kWh/y)	Heating demand (kWh/yr)	Cooling demand (kWh/yr)	Total Energy demand (kWh/yr)
House, no insulation	309,29	41,44	85914	11511	486	85914	11997	**97911**
HGH, no insulation	18,56	91,69	5156	25469	486	5156	25955	**31111**
House, insulation	93,55	16,87	25986	4686	486	25986	5172	**31158**
HGH, insulation	21,30	36,97	5917	10269	486	5917	10755	**16672**

As mentioned previously, scenario 5 results in 0 kWh/yr for each of these parameters (i.e., district heating and cooling, and energy demand). This is because only the energy performance of the core house is evaluated.

7. Appendix 7– Sun Path Diagram Brussels

Table 28 was defined following the sun path on the figure below (Turkiainen 2022). It was inputted in excel and resulted in the graph present in the main text. The ideal PV panel angle was calculated as 90° minus the sun elevation angle.

The graph was retrieved on March 21st, which explains why the “today” path is not visible.

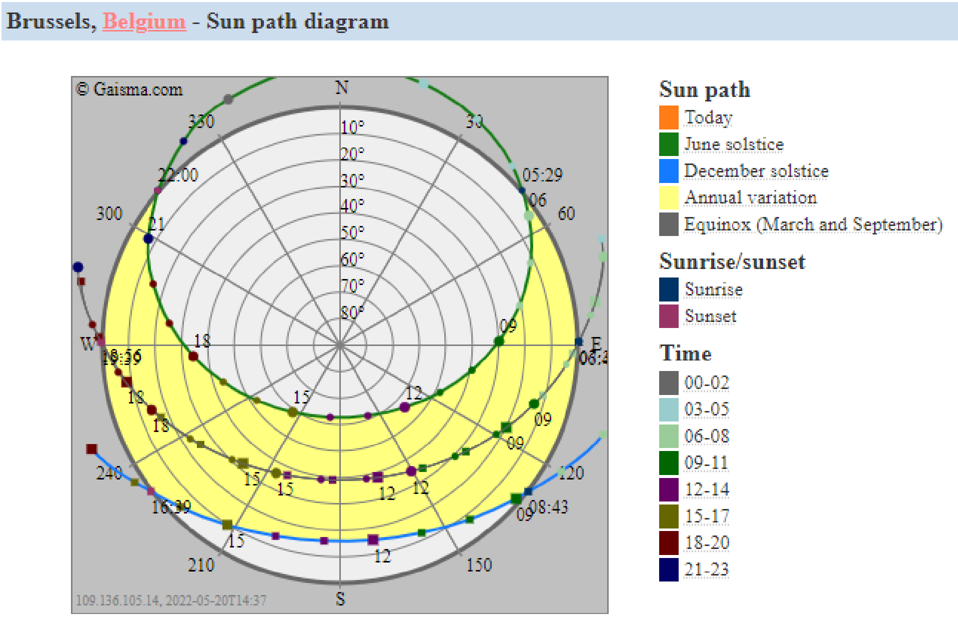


Figure 68: Brussels Sun path diagram (Gaisma.com 2022) (Turkiainen 2022)

Table 28: sun path diagram, resulting sun elevation and ideal PV panel angles for V² (Author 2022)

Date	Time (h:m)	Sun elevation angle (°)	Ideal PV panel angle (°)
June 21st	5:30 AM	0	90
	6:00 AM	3	87
	7:00 AM	11	79
	8:00 AM	20	70
	9:00 AM	29	61
	10:00 AM	39	51
	11:00 AM	48	42
	12:00 PM	55	35
	1:00 PM	61	29
	2:00 PM	62	28
	3:00 PM	58	32
	4:00 PM	52	38
	5:00 PM	43	47
	6:00 PM	34	56
	7:00 PM	24	66
	8:00 PM	15	75
	9:00 PM	7	83
	10:00 PM	0	90
Equinox (September) – March very close	6:30 AM	0	90
	7:00 AM	2	88
	8:00 AM	11	79
	9:00 AM	20	70
	10:00 AM	28	62
	11:00 AM	34	56
	12:00 PM	38	52
	1:00 PM	39	51
	2:00 PM	37	53
	3:00 PM	32	58
	4:00 PM	25	65
	5:00 PM	17	73
	6:00 PM	8	82
	7:00 PM	0	90
December 21st	9:00 AM	1	89
	10:00 AM	7	83
	11:00 AM	12	78
	12:00 PM	15	75
	1:00 PM	15	75
	2:00 PM	13	77
	3:00 PM	9	81
	4:00 PM	0	90

8. Appendix 8 – Housing Statistics Brussels

The following tables and graphs were prepared based on a file downloaded from the STATBel website, which displays all Belgian cadastral 1995-2021 statistics (see extracts at the end of this appendix).

To quantify the 2021 building stock of detached houses in the Brussels Capital Region (BCR) that is considered in this thesis, several statistics were considered, namely the date of construction, and house type (Direction générale Statistique - Statistics Belgium 2022).

The table below presents a summary of houses and buildings per commune in 2021 in the Brussels Capital Region (BCR).

Table 29: Number of individual houses by commune in 2021 in the BCR (Direction générale Statistique - Statistics Belgium 2022)

	Number of detached houses	Number of individual houses	Number of buildings	% detached houses/ ind houses
ANDERLECHT	287	12.921	18.784	2,2%
AUDERGHEM	425	6.377	7.931	6,7%
BERCHEM-SAINTE-AGATHE	104	3.393	4.813	3,1%
BRUXELLES	442	14.788	27.410	3,0%
ETTERBEEK	6	4.709	7.876	0,1%
EVERE	11	3.871	5.665	0,3%
FOREST	55	4.996	8.492	1,1%
GANSHOREN	15	2.197	3.540	0,7%
IXELLES	44	7.946	14.467	0,6%
JETTE	106	5.118	7.510	2,1%
KOEKELBERG	2	1.404	2.548	0,1%
MOLENBEEK-SAINT-JEAN	49	5.644	10.672	0,9%
SAINT-GILLES	1	4.165	7.501	0,0%
SAINT-JOSSE-TEN-NOODE	6	2.185	3.536	0,3%
SCHAERBEEK	40	12.726	19.254	0,3%
UCCLE	2.182	13.452	18.612	16,2%
WATERMAEL-BOITSFORT	446	5.831	6.935	7,6%
WOLUWE-SAINT-LAMBERT	174	6.937	9.464	2,5%
WOLUWE-SAINT-PIERRE	1.426	8.004	9.860	17,8%
TOTAL BCR	5.821	126.664	194.870	4,6%

In the region, detached houses accounted for 4.6% of all houses and 3% of all buildings in 2021. The table above allows to identify the communes counting the highest rate of detached houses in the BCR: Woluwé Saint Pierre, Uccle, Watermael Boitsfort, and Auderghem.

The following table displays the categories of buildings in the communes selected in 2021.

Legend:

- R1 = Closed type houses
- R2 = Semi-enclosed houses
- R3 = Open type houses, farms, castles (detached houses)
- R4 = Buildings and flat blocks
- R5 = Commercial houses
- R6 = All other buildings

Table 30: Number of buildings in the selected communes of the BCR by type in 2021 (Direction générale Statistique - Statistics Belgium 2022)

Commune	R1	R2	R3	R4	R5	R6	Total
AUDERGHEM	4.625	1.327	425	945	247	362	7.931
WSP	3.982	2.596	1.426	1.245	221	390	9.860
UCCLE	8.158	3.112	2.182	3.202	778	1.180	18.612
WB	3.694	1.691	446	629	147	328	6.935
Total	20.459	8.726	4.479	6.021	1.393	2.260	43.338
% of all buildings	47,21%	20,13%	10,34%	13,89%	3,21%	5,21%	100%

The share of detached houses in these communes was 13.3% on all houses and 10.3% on all buildings in 2021 as shown in the table above.

As per the cadastral statistics, the year of construction of the detached houses in these 4 communes is as follows:

Table 31: Number of detached houses per construction period in the BCR in 2021 (Direction générale Statistique - Statistics Belgium 2022)

Date of construction	Detached houses (R3)
Before 1962	60,1%
1962-1970	16,8%
1971-1981	7,7%
After 1981	15,4%

In conclusion, there are 5.821 villas or detached houses in the BCR. They represent 4,6% of all individual houses and 3% of all buildings.

The 4 communes selected (Auderghem, Uccle, Watermael Boistfort and Woluwé Saint Pierre) count 4.479 detached houses or 76% of all detached houses in the BCR which is a representative sample. The table above show that more than 75% of these were built before 1971 and close to 85% before 1981, during periods where the façade insulation techniques were not very developed and used. Indeed, the Brussels building stock is one of the most energy-intensive in Europe and the current pace for renovation is far from sufficient (Brussels Environnement 2022).

The following tables are 2021 extracts from the source file "*Statistique cadastrale du nombre de bâtiments 1995-2021*" available on the STATBel website (Direction générale Statistique - Statistics Belgium 2022).

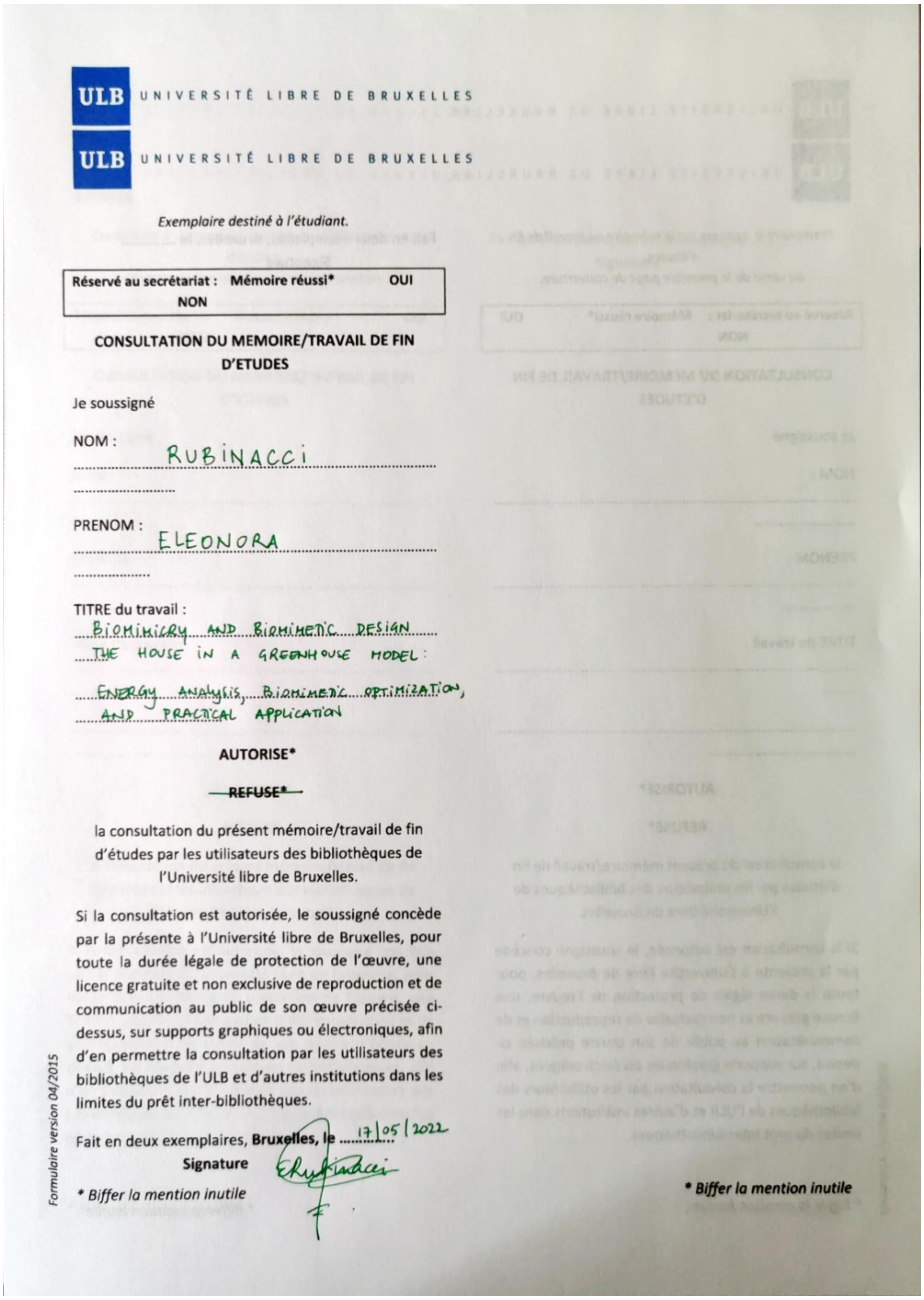
Table 32: Cadastral statistics per commune and for BCR (year 2021) (Direction générale Statistique - Statistics Belgium 2022)

Statistique cadastrale du fichier des bâtiments			2021									
refnis	localité	compteur détail	Maisons de type fermé (R1)	Maisons de type demi-fermé (R2)	Maisons de type ouvert, fermes, chateaux (R3)	Buildings et immeubles à appartements (R4)	Maisons de commerce (R5)	Tous les autres bâtiments (R6)	Total (R7)	Total Maisons (R1+R2+R3)	% R3 sur Maisons	%R3 sur tous batiments
21001	ANDERLECHT	Nombre de bâtiments	11.177	1.457	287	2.526	1.583	1.754	18.784	12.921	2,2%	1,5%
21002	AUDERGHEM	Nombre de bâtiments	4.625	1.327	425	945	247	362	7.931	6.377	6,7%	5,4%
21003	BERCHEM-SAINTE-AGATHE	Nombre de bâtiments	2.782	507	104	976	156	288	4.813	3.393	3,1%	2,2%
21004	BRUXELLES	Nombre de bâtiments	13.398	948	442	5.768	3.691	3.163	27.410	14.788	3,0%	1,6%
21005	ETTERBEEK	Nombre de bâtiments	4.576	127	6	2.077	643	447	7.876	4.709	0,1%	0,1%
21006	EVERE	Nombre de bâtiments	3.230	630	11	1.147	223	424	5.665	3.871	0,3%	0,2%
21007	FOREST	Nombre de bâtiments	4.477	464	55	2.355	363	778	8.492	4.996	1,1%	0,6%
21008	GANSHOREN	Nombre de bâtiments	1.900	282	15	1.074	130	139	3.540	2.197	0,7%	0,4%
21009	IXELLES	Nombre de bâtiments	7.635	267	44	3.721	1.646	1.154	14.467	7.946	0,6%	0,3%
21010	JETTE	Nombre de bâtiments	4.701	311	106	1.536	400	456	7.510	5.118	2,1%	1,4%
21011	KOEKELBERG	Nombre de bâtiments	1.385	17	2	808	171	165	2.548	1.404	0,1%	0,1%
21012	MOLENBEEK-SAINT-JEAN	Nombre de bâtiments	5.464	131	49	2.709	1.070	1.249	10.672	5.644	0,9%	0,5%
21013	SAINT-GILLES	Nombre de bâtiments	4.149	15	1	1.708	1.180	448	7.501	4.165	0,0%	0,0%
21014	SAINT-JOSSE-TEN-NOODE	Nombre de bâtiments	2.174	5	6	562	506	283	3.536	2.185	0,3%	0,2%
21015	SCHAERBEEK	Nombre de bâtiments	12.358	328	40	3.552	1.877	1.099	19.254	12.726	0,3%	0,2%
21016	UCCLE	Nombre de bâtiments	8.158	3.112	2.182	3.202	778	1.180	18.612	13.452	16,2%	11,7%
21017	WATERMAEL-BOITSFORT	Nombre de bâtiments	3.694	1.691	446	629	147	328	6.935	5.831	7,6%	6,4%
21018	WOLUWE-SAINT-LAMBERT	Nombre de bâtiments	5.400	1.363	174	1.772	314	441	9.464	6.937	2,5%	1,8%
21019	WOLUWE-SAINT-PIERRE	Nombre de bâtiments	3.982	2.596	1.426	1.245	221	390	9.860	8.004	17,8%	14,5%

Statistique cadastrale du fichier des bâtiments			2021						
refnis	localité	compteur détail	Maisons de type fermé (R1)	Maisons de type demi-fermé (R2)	Maisons de type ouvert, fermes, chateaux (R3)	Buildings et immeubles à appartements (R4)	Maisons de commerce (R5)	Tous les autres bâtiments (R6)	Total (R7)
04000	REGION DE BRUXELLES-CAPITALE	Nombre de bâtiments	105.265	15.578	5.821	38.312	15.346	14.548	194.870
04000	REGION DE BRUXELLES-CAPITALE	Nombre de bâtiments érigés avant 1900	17.609	490	205	3.874	6.181	1.898	30.257
04000	REGION DE BRUXELLES-CAPITALE	Nombre de bâtiments érigés de 1900 à 1918	30.446	900	315	6.338	4.786	2.328	45.113
04000	REGION DE BRUXELLES-CAPITALE	Nombre de bâtiments érigés de 1919 à 1945	32.322	4.654	1.345	8.160	3.287	3.054	52.822
04000	REGION DE BRUXELLES-CAPITALE	Nombre de bâtiments érigés de 1946 à 1961	16.555	5.091	1.585	8.370	666	2.774	35.041
04000	REGION DE BRUXELLES-CAPITALE	Nombre de bâtiments érigés de 1962 à 1970	3.314	1.990	941	4.711	183	1.194	12.333
04000	REGION DE BRUXELLES-CAPITALE	Nombre de bâtiments érigés de 1971 à 1981	1.155	651	484	2.405	73	985	5.753
04000	REGION DE BRUXELLES-CAPITALE	Nombre de bâtiments érigés après 1981	3.863	1.800	945	4.337	170	2.261	13.376
04000	REGION DE BRUXELLES-CAPITALE	Nombre de bâtiments érigés de 1982 à 1991	1.250	552	368	890	102	907	4.069
04000	REGION DE BRUXELLES-CAPITALE	Nombre de bâtiments érigés de 1992 à 2001	1.014	499	244	1.241	46	685	3.729
04000	REGION DE BRUXELLES-CAPITALE	Nombre de bâtiments érigés de 2002 à 2011	968	505	199	1.310	12	408	3.402
04000	REGION DE BRUXELLES-CAPITALE	Nombre de bâtiments érigés après 2011	631	244	134	896	10	261	2.176
04000	REGION DE BRUXELLES-CAPITALE	Nombre de bâtiments pour lesquels l'année d'achèvement de la construction n'est pas disponible	1	2	1	117	0	54	175
04000	REGION DE BRUXELLES-CAPITALE	Nombre de logements	183.643	17.403	6.186	340.578	34.451	10.681	592.942

Statistique cadastrale du fichier des bâtiments							2021			
refnis	localité	compteur	compteur détail	Maisons de type fermé (R1)	Maisons de type demi-fermé (R2)	Maisons de type ouvert, fermes, chateaux (R3)	Buildings et immeubles à appartements (R4)	Maisons de commerce (R5)	Tous les autres bâtiments (R6)	Total (R7)
21002	AUDERGHEM	T1	Nombre de bâtiments	4.625	1.327	425	945	247	362	7.931
21002	AUDERGHEM	T3.1	Nombre de bâtiments érigés avant 1900	279	29	18	21	34	31	412
21002	AUDERGHEM	T3.2	Nombre de bâtiments érigés de 1900 à 1918	702	29	15	62	67	34	909
21002	AUDERGHEM	T3.3	Nombre de bâtiments érigés de 1919 à 1945	1.671	243	96	156	94	64	2.324
21002	AUDERGHEM	T3.4	Nombre de bâtiments érigés de 1946 à 1961	1.423	542	135	241	30	69	2.440
21002	AUDERGHEM	T3.5	Nombre de bâtiments érigés de 1962 à 1970	284	307	101	204	14	31	941
21002	AUDERGHEM	T3.6	Nombre de bâtiments érigés de 1971 à 1981	68	63	23	71	2	25	252
21002	AUDERGHEM	T3.7	Nombre de bâtiments érigés après 1981	198	114	37	188	6	107	650
21016	UCCLE	T1	Nombre de bâtiments	8.158	3.112	2.182	3.202	778	1.180	18.612
21016	UCCLE	T3.1	Nombre de bâtiments érigés avant 1900	137	54	26	29	32	24	302
21016	UCCLE	T3.2	Nombre de bâtiments érigés de 1900 à 1918	816	155	90	120	114	90	1.385
21016	UCCLE	T3.3	Nombre de bâtiments érigés de 1919 à 1945	4.379	981	562	1.097	533	458	8.010
21016	UCCLE	T3.4	Nombre de bâtiments érigés de 1946 à 1961	1.662	1.081	629	741	54	320	4.487
21016	UCCLE	T3.5	Nombre de bâtiments érigés de 1962 à 1970	406	356	310	433	17	96	1.618
21016	UCCLE	T3.6	Nombre de bâtiments érigés de 1971 à 1981	151	136	187	289	10	70	843
21016	UCCLE	T3.7	Nombre de bâtiments érigés après 1981	606	348	378	474	18	116	1.940
21017	WATERMAEL-BOITSFORT	T1	Nombre de bâtiments	3.694	1.691	446	629	147	328	6.935
21017	WATERMAEL-BOITSFORT	T3.1	Nombre de bâtiments érigés avant 1900	307	86	45	32	27	57	554
21017	WATERMAEL-BOITSFORT	T3.2	Nombre de bâtiments érigés de 1900 à 1918	958	142	67	54	58	52	1.331
21017	WATERMAEL-BOITSFORT	T3.3	Nombre de bâtiments érigés de 1919 à 1945	1.382	803	140	136	43	73	2.577
21017	WATERMAEL-BOITSFORT	T3.4	Nombre de bâtiments érigés de 1946 à 1961	669	426	99	143	8	55	1.400
21017	WATERMAEL-BOITSFORT	T3.5	Nombre de bâtiments érigés de 1962 à 1970	175	114	36	128	4	28	485
21017	WATERMAEL-BOITSFORT	T3.6	Nombre de bâtiments érigés de 1971 à 1981	49	38	9	67	4	27	194
21017	WATERMAEL-BOITSFORT	T3.7	Nombre de bâtiments érigés après 1981	154	82	50	68	3	35	392
21019	WOLUWE-SAINT-PIERRE	T1	Nombre de bâtiments	3.982	2.596	1.426	1.245	221	390	9.860
21019	WOLUWE-SAINT-PIERRE	T3.1	Nombre de bâtiments érigés avant 1900	66	17	7	8	7	5	110
21019	WOLUWE-SAINT-PIERRE	T3.2	Nombre de bâtiments érigés de 1900 à 1918	577	86	44	54	55	39	855
21019	WOLUWE-SAINT-PIERRE	T3.3	Nombre de bâtiments érigés de 1919 à 1945	1.193	589	278	165	106	79	2.410
21019	WOLUWE-SAINT-PIERRE	T3.4	Nombre de bâtiments érigés de 1946 à 1961	1.585	1.006	439	335	40	80	3.485
21019	WOLUWE-SAINT-PIERRE	T3.5	Nombre de bâtiments érigés de 1962 à 1970	292	496	305	292	8	108	1.501
21019	WOLUWE-SAINT-PIERRE	T3.6	Nombre de bâtiments érigés de 1971 à 1981	76	148	127	168	2	41	562
21019	WOLUWE-SAINT-PIERRE	T3.7	Nombre de bâtiments érigés après 1981	193	254	225	220	3	36	931
	TOTAL 4 COMMUNES	T1	**Nombre de bâtiments**	**20.459**	**8.726**	**4.479**	**6.021**	**1.393**	**2.260**	**43.338**
	TOTAL 4 COMMUNES	T3.1	**Nombre de bâtiments érigés avant 1900**	**789**	**186**	**96**	**90**	**100**	**117**	**1.378**
	TOTAL 4 COMMUNES	T3.2	**Nombre de bâtiments érigés de 1900 à 1918**	**3.053**	**412**	**216**	**290**	**294**	**215**	**4.480**
	TOTAL 4 COMMUNES	T3.3	**Nombre de bâtiments érigés de 1919 à 1945**	**8.625**	**2.616**	**1.076**	**1.554**	**776**	**674**	**15.321**
	TOTAL 4 COMMUNES	T3.4	**Nombre de bâtiments érigés de 1946 à 1961**	**5.339**	**3.055**	**1.302**	**1.460**	**132**	**524**	**11.812**
	TOTAL 4 COMMUNES	T3.5	**Nombre de bâtiments érigés de 1962 à 1970**	**1.157**	**1.273**	**752**	**1.057**	**43**	**263**	**4.545**
	TOTAL 4 COMMUNES	T3.6	**Nombre de bâtiments érigés de 1971 à 1981**	**344**	**385**	**346**	**595**	**18**	**163**	**1.851**
	TOTAL 4 COMMUNES	T3.7	**Nombre de bâtiments érigés après 1981**	**1.151**	**798**	**690**	**950**	**30**	**294**	**3.913**

9. Appendix 9 – Administrative information



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CONSULTATION DU MEMOIRE/TRAVAIL DE FIN D'ETUDES

Je soussigné

NOM : RUBINACCI

PRENOM : ELEONORA

TITRE du travail : BIOMIMICRY AND BIOMIMETIC DESIGN THE HOUSE IN A GREENHOUSE MODEL: ENERGY ANALYSIS, BIOMIMETIC OPTIMIZATION, AND PRACTICAL APPLICATION

AUTORISE*

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Signature

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Figure 69: Scan of official document 'consultation du mémoire / travail de fin d'études', ULB

Re: Master Thesis subject / Research methods subject (AE)

KM KHAN MAHSUD Ahmed Zaib
To RUBINACCI Eleonora

Reply | Reply All | Forward | ...
ven. 12-02-21 14:49

Follow Up. Completed on mercredi 3 mars 2021.
You replied to this message on 14-02-21 10:05.

From: RUBINACCI Eleonora <Eleonora.Rubinacci@ulb.be>
Sent: Monday, February 8, 2021 9:20 PM
To: KHAN MAHSUD Ahmed Zaib <Ahmed.Khan@ulb.be>
Cc: Ine WOUTERS <Ine.Wouters@vub.be>
Subject: Master Thesis subject / Research methods subject (AE)

Dear Professor Khan,

I hope this e-mail finds you well.

I am very much interested in the subject "**Biomimicry and Biomimetic Design**" that you propose for the Master Thesis in 2022. These last years, I had the chance to come across the subject. For example, last semester, in the context of the course "Parametric Design of Transformable Structures", my group and I designed a deployable pavilion that could open up like a flower (the project was called "Blooming Flower").
I would love to further develop my knowledge in that field.

As an ecologically preoccupied student in 2021, I believe that sustainability is without question the way forward towards a better future. Studying in depth biomimicry and other sustainable construction methods is thus highly interesting to me.

Please let me know if you would be interested in working with me on that subject for my Master Thesis.

Thank you in advance!

Best regards,

Eleonora Rubinacci

MA 1 Architectural Engineering
BRUFACE ULB/VUB
Email: Eleonora.Rubinacci@ulb.be

Figure 70: Request for MA thesis' subject and supervisor from Eleonora Rubinacci to Ahmed Khan (February 2021)

Re: Master Thesis subject / Research methods subject (AE)

KM KHAN MAHSUD Ahmed Zaib
To RUBINACCI Eleonora

Reply | Reply All | Forward | ...
ven. 12-02-21 14:49

Follow Up. Completed on mercredi 3 mars 2021.
You replied to this message on 14-02-21 10:05.

Dear Eleonora,

Thank you for your interest, I confirm this subject for your Master Thesis.

best wishes,

A. Khan

MY NEW E-MAIL ADDRESS: ahmed.khan@ulb.be

Prof. dr. **Ahmed Z. Khan**
Chair Sustainable Architecture & Urbanism

BATir - Building, Architecture & Town Planning Department
Brussels School of Engineering
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URL: http://batir.ulb.ac.be

Take a look at our New research project: https://www.co-nature.org

Figure 71: Confirmation of MA thesis' subject from supervisor (February 2021)

BRUFACE-ULB-VUB Master Thesis Title Submission - 2021-2022 - Eleonora Rubinacci

MT Master Thesis Approval <noreply@jotform.com>
To Eleonora.Rubinacci@ulb.be

Reply | Reply All | Forward | ...
mer. 29-09-21 09:54

Eleonora-Rubinacci-Biomimicy-and-Biomimetic-design.pdf
19 KB

Dear Eleonora Rubinacci,

The Master Thesis "Biomimicy and Biomimetic design" has been approved by your Promotor Ahmed Khan.

With best regards !

Figure 72: Master thesis title approval (September 2021)