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Phase Change Materials Trombe Wall

Exploring the potential application of PCMs in a modular design for thermal and daylight comfort

Graduation report
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Phase Change Materials Trombe Wall:

Exploring the potential application of PCMs in a modular design for thermal and daylight comfort

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KEY WORDS

phase change materials, trombe wall, thermal performance,
daylight, modularity, Netherlands

Abstract

The rise in average surface temperature has intensified the need to explore new methods to address climate change. Housing sector is one of the leading contributors to the total energy consumption. As a solution, there has been a growing emphasis on the application of passive strategies in buildings that leverage local climatic conditions

Researchers have been investigating solutions to promote the use of passive design strategies. One promising approach involves integrating Phase Change Materials (PCMs) with certain building components. By possessing excellent thermal and optical properties, PCMs can be integrated into windows to enhance the thermal performance of buildings while guaranteeing light transmittance.

This research specifically focuses on the integration of PCMs trombe walls in existing residential buildings in the Netherlands. Building upon the findings of previous studies, the research envisions to explore strategies that can facilitate the widespread use of PCMs. Currently, the market for PCMs primarily offers products manufactured on request, limiting their broader adoption.

Through simulations conducted on virtual models, the behaviour of PCMs in trombe walls is investigated. The analysis focuses their thermal capacity and light transmittance to strike a balance between the two contrasting building requirements. Multiple room configurations are studied to investigate how the environment impacts the performance of this particular building component.

Finally, the research develops a workflow and identifies trends that can facilitate the application of PCMs trombe walls across various scenarios.

Contents

01. Introduction

The first chapter consists of the **research framework** of this study. Beginning with a brief description of the research's main topics, each theme is described, while benefits and drawbacks are highlighted. The introduction of topics concludes with a problem statement, which is then explained in greater detail. Subsequently, the aim of the research is stated. The study addresses a research question, which is further divided into sub research questions. This simplifies the research process by dividing it into multiple steps. The research methodology is then explained by describing each of the four phases it is composed of. Finally, a plan illustrates the weekly division of tasks.

1.1 Background

Since the Second Industrial Revolution (1870 - 1914) the average surface temperature has increased of 0.07 °C each decade, as figure 1.1 shows (Ghosh, 2021). This temperature change is called **climate change** and impacts the Earth through extreme and irregular catastrophic events.

Climate change is caused by human activities that require the combustion of fossil fuels, which nowadays correspond to 80% of the total energy production (Zhou et al., 2021). Fossil fuels generate gases when burned causing the **greenhouse effect**, where heat is trapped in the atmosphere. This leads to a temperature rise.

At the moment, extreme climatic events are increasingly common (United Nations, n.d.). This can lead to permanent issues as the frequency of catastrophic events

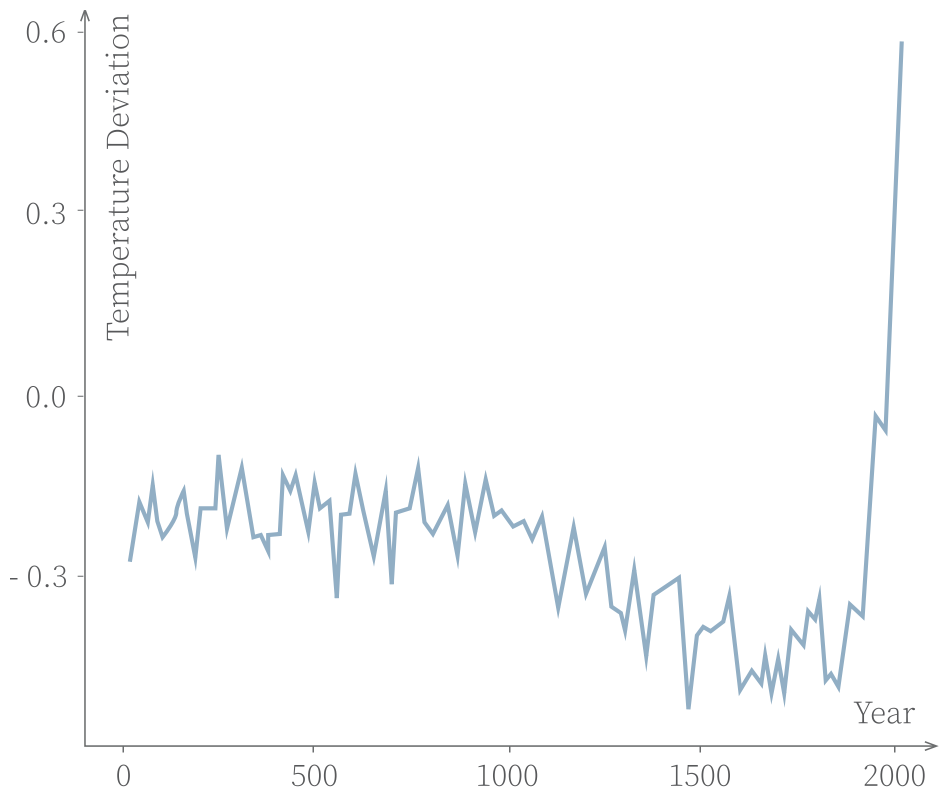


Figure 1.1: global temperature from year 0 to 2019
Source: adapted from *Since 1850, these historical events have accelerated climate change,* by I. Ghosh, 2021, World Economic Forum

- such as drought, fire, and melting of polar ice - is growing.

New methods have been developed to contrast this phenomenon. An example is the application of passive climate design strategies in buildings, aiming at reducing energy demand.

1.1.1 The building sector

The following statement indicates one of the leading sectors of energy consumption:

> ”Housing and tertiary buildings are responsible for the consumption of approximately 46% of all energies and approximately 19% of the total CO_2 emission”
>
> (Kuznik et al., 2011: 380)

If previously buildings had high energy demand, commonly fulfilled with fossil fuels; nowadays the demand is even more on the rise. The requirements for thermal comfort are increasing, while the buildings are designed to be aesthetically pleasing without considering the climate (Zhou et al., 2021).

This dysfunctional design approach, belonging to the last decades, is in contrast with ancient architecture, where buildings took advantage of the local materials and climatic conditions. Recently, we as humans have started to experience climate change, and thus are trying to tackle the issue.

There are two ways to minimize the use of fossil fuels in buildings. Firstly, the energy performance of buildings needs to be as high as possible (Cui et al., 2017). This is achieved by a design optimization based on the local conditions. An example is a façade designed to maximise daylight while controlling solar radiation depending on the thermal needs. The second step is to use renewable energy systems whenever energy is required (United Nations, n.d.).

The application of these methods would reduce the energy consumption of buildings, which, nowadays, are able to reach **nearly zero-energy** emissions.

1.1.2 Computational design

The process where buildings are optimized to solve a problem belongs to computational design. As an example, **energy simulation tools** are used in parametric software to study the energy performance of buildings, thus achieving better efficiency (Glassman and Reinhart, 2013).

Energy simulations allow exploring a building component or the entire building shape. Commonly iterated for both winter and summer situations, they show how the building behaves in a specific location. This allows the application of **passive design strategies** to heat, cool, and lighten an environment. For instance, extruded roofs can block solar radiation in summer months, whilst allowing it to enter during the winter.

When a building component - such as a shading device - is optimized but still adaptable to the user’s needs, it has long-term potential. However, when the shape of a building is given from energy optimizations, a future change in function or temperature could lead to energy inefficiency.

Indeed, Glassman and Reinhart (2013) explain that a drastic change in climatic conditions could alter the need for heating and cooling. At the same time, each occupancy has different requirements and produces diverse amounts of internal loads. Therefore, a future modification in function could cause energy inefficiencies in a building.
Consequently, designers should optimize buildings

considering further possible changes of the internal and external conditions. This can be achieved by taking into account various scenarios and by designing flexible building components.

1.1.3 Thermal energy storage systems

The energy optimization of buildings is commonly achieved by the application of passive design strategies, whose aim is to maximize the buildings' thermal performance. Passive strategies can be classified into several groups, depending on their function. For instance, blinds or extruded roofs control solar radiation, thus working as sun-shading devices. On the other hand, controlled ventilation and trombe walls improve the thermal inertia of walls, and therefore, relate to the **thermal energy storage** (TES) systems.

In particular, TES stores the thermal energy of a system and releases it secondly (Omara and Albenuor, 2020). TES needs a storage medium to work properly, which, in this case, corresponds to the building envelope. A proper envelope is, indeed, able to store solar radiation and thermal energy during winter days to release it at night. Conversely, in summer the building envelope is able to absorb the interior heat, which will automatically cool the environment.

The storage capacity of the envelope is dependent on its thickness and its material's properties. Further explanation can be found in Chapter 2.

1.1.4 Daylight admittance

If the thermal mass reduces the energy demand for heating and cooling, buildings must also have windows to allow the natural light to enter the indoor space. Indeed, windows decrease the building's need for artificial lighting during the day (Tilmann, 2017). Moreover, they are beneficial for many other aspects as they ensure visual comfort and allow solar radiation into the interior, which then heats up the room by generating heat.

Despite the great benefits of windows, they have low thermal mass due to their properties. Indeed, they are composed of thin glass plates alternated to cavities filled with air or gas. Even if the thermal performance can be improved by either filling the cavity with gas or increasing the number of plates, opaque walls have a higher ability to maintain the indoor space at a constant temperature.

For this reason, it is necessary to find a good balance between thermal mass and daylight admittance when designing a building. If compromises can be found for each specific case, the use of passive design strategies that can enhance the thermal inertia can be very advantageous.

1.1.5 Modularity

> "(...) the demand for architecture and design to facilitate our changing needs is clearer than ever"
>
> (Larsson, n.d.)

As Larsson (n.d.) states the need for adaptable architecture has increased in the past years. Indeed, flexible designs can adapt to the user's needs while minimizing the CO_2 emissions required to renovate or rebuild a construction. The same principle is applicable to building components as the trombe wall. An adaptable trombe wall can, indeed, be designed to satisfy both heating and cooling demands based on the user's needs. Moreover, it could potentially be developed to be reused.

The concept of flexibility is becoming increasingly important. This can be considered in the design process by applying certain approaches as modularity. Indeed, modular designs are composed of multiple pieces that have standard dimensions and can be used differently. A contrasting example of this strategy are the first designs of Zaha Hadid Architects, which focused on aesthetic expression (Rocha, 2021). Indeed, their uniqueness required individuality where each piece was different from the other, thus limiting the future life of the building components.

1.2 Problem statement

New methods facing climate change are being explored and developed in the built environment. As in ancient architecture, nature is imitated but, this time, it is visible in fluid and organic building shapes. Designers once again take advantage of climatic conditions.

The application of some passive design strategies is, however, very limited. As an example, buildings integrate shading systems to control solar radiation, but do not apply principles that improve their thermal storage capacity. This issue is emphasized by transparency, which has taken over the buildings from Modern Architecture.

As previously mentioned, there are passive design principles that aim at improving the thermal inertia of building envelopes. For instance, trombe walls act as an additional wall to the building envelope, which enhances the thermal mass of walls. Their traditional design is however massive and permanent.

In the past years, a few researches have been improving the performance of trombe walls. By using phase change materials (PCMs) as infill, these trombe walls are energy performing while being thin, thus ensuring translucency, lightness, and flexibility.

Despite their great potentialities, PCMs trombe walls are hardly ever applied in buildings. Being phase change materials very unknown yet, there are few products for sale in the built environment. These products are designed only on request, thus being unique and customized. For this reason, they are expensive products that require a long design process and are appealing only to a small number of clients.

The problem statement of this research has been outlined and can be summarized by the following statement:

> The built environment is looking for new solutions to face climate change. Despite the potentialities of passive design strategies related to thermal inertia, their application is still limited. Innovative solutions such as PCMs trombe walls could break this gap. However, the application of PCMs is often customized due to their limited expansion. Therefore, great consideration must be given to the design of a modular and energy-efficient PCMs trombe wall that can fulfil the user's needs.

1.3 Focus and restrictions

Buildings vary in many aspects as shape and typology. Each of them is designed to achieve a certain thermal, visual and acoustic comfort, depending on the building function and the climate zone.

For this reason, some factors were defined before the design stages of the research. A reference case study was selected from a list of parametric buildings optimized on their energy performance. Initially, both residential and office functions were considered, but only the residential function was selected later. Public buildings such as museums and concert halls were not taken into account because of their different requirements. Moreover, the research was looking for building typologies that can daily profit from heat storage systems.

Another significant aspect is the location. Indeed, each climate zone has different climatic conditions, thus requiring diverse building designs and strategies. Since PCMs are applicable in certain climate zones, the possible areas were reduced to three. Whereas the final decision was influenced by the knowledge gained by real-world experience in the Temperate climate.

The research focuses on the development of a thermal energy storage system by using Phase Change Materials. The aim is to design a modular component that can be reused in another building. To achieve this goal, the chosen building component is a trombe wall. By placing the trombe wall in front of the transparent envelope, the room will be heated in winter months and cooled during the summer.

Taking into account that the trombe wall will be placed in front of a glazed surface, the design aims at being translucent. Daylight simulations will test its light transmittance to achieve a PCMs trombe wall that ensures the thermal and daylight building requirements.

1.4 Aims and objectives

The aim of this research is to further explore the use of trombe walls with phase change materials as infill. The study focuses on two current aspects explained in the following paragraphs. As a whole, the research could offer a solution to expand the application of PCMs, and more generally, of passive design strategies by designing a modular and energy-efficient panel.

The first objective of this study is to research approaches able to expand the use of passive design principles as, in this case, PCMs trombe walls. This is achieved by exploring how multiple factors affect the thermal and daylight performance of the trombe wall. The results are translated in the design of a modular panel and in a workflow that simplifies the future integration of PCMs trombe walls in the built environment.

The second objective of the research is to investigate the relationship between the thermal performance and daylight admittance of buildings and how the PCMs trombe wall can act as an intermediate element between them.

1.5 Research question

The research evaluates the thermal and daylight performance of a trombe wall with phase change materials (PCMs) integrated in existing buildings that are parametrically optimized to be energy-efficient. This is achieved by answering the following research question:

> How can a **modular** and **translucent PCMs trombe wall** be integrated as a passive strategy in **existing** and **energy-optimized** buildings to work as **heating** during winter and **cooling** in summer?

1.5.1 Sub research questions

To address the main topic of the research, the following sub research questions were formulated.

> Which **passive design strategies** are applied in energy-optimized buildings and **how** do they **affect** their thermal inertia?

> Which **room variables*** are considered to achieve a PCMs trombe wall that could **adapt** to various buildings?

* The term 'room variables' requires an explanation to be understandable. Aiming at a flexible trombe wall to various residential buildings, the panel must be adapted with the least number of changes. Therefore, some of the common characteristics that differ from each room have been taken into account from the design process. They correspond, for instance, to room area and orientation.

How are the **thermal performance** and **daylight admittance** affected by the room variables and the PCMs trombe wall?

What is the **final appearance** of the room and trombe wall if it is researched a **balance** between the **best results** of thermal and daylight simulations?

Which **strategies** could in the future be developed to bridge the **gap** between a **customized** and **unique** PCMs product and a **standardized** and **modular** component?

1.6 Methodology

The research is organised into four phases: theoretical framework, preliminary research, digital design exploration, and final design. A more detailed explanation is given in the following text and figure 1.2.

The **theoretical framework** forms the initial section of the study and is divided into five categories, providing a higher level of detail on the research focus (figure 1.3). It begins with an overview of computational design and parametric design, followed by a description of the building envelope, which represents the outermost layer of buildings. The level of detail is then further increased to focus on a specific building component, the trombe wall. Finally, attention is directed towards the material used in the trombe wall: phase change materials.

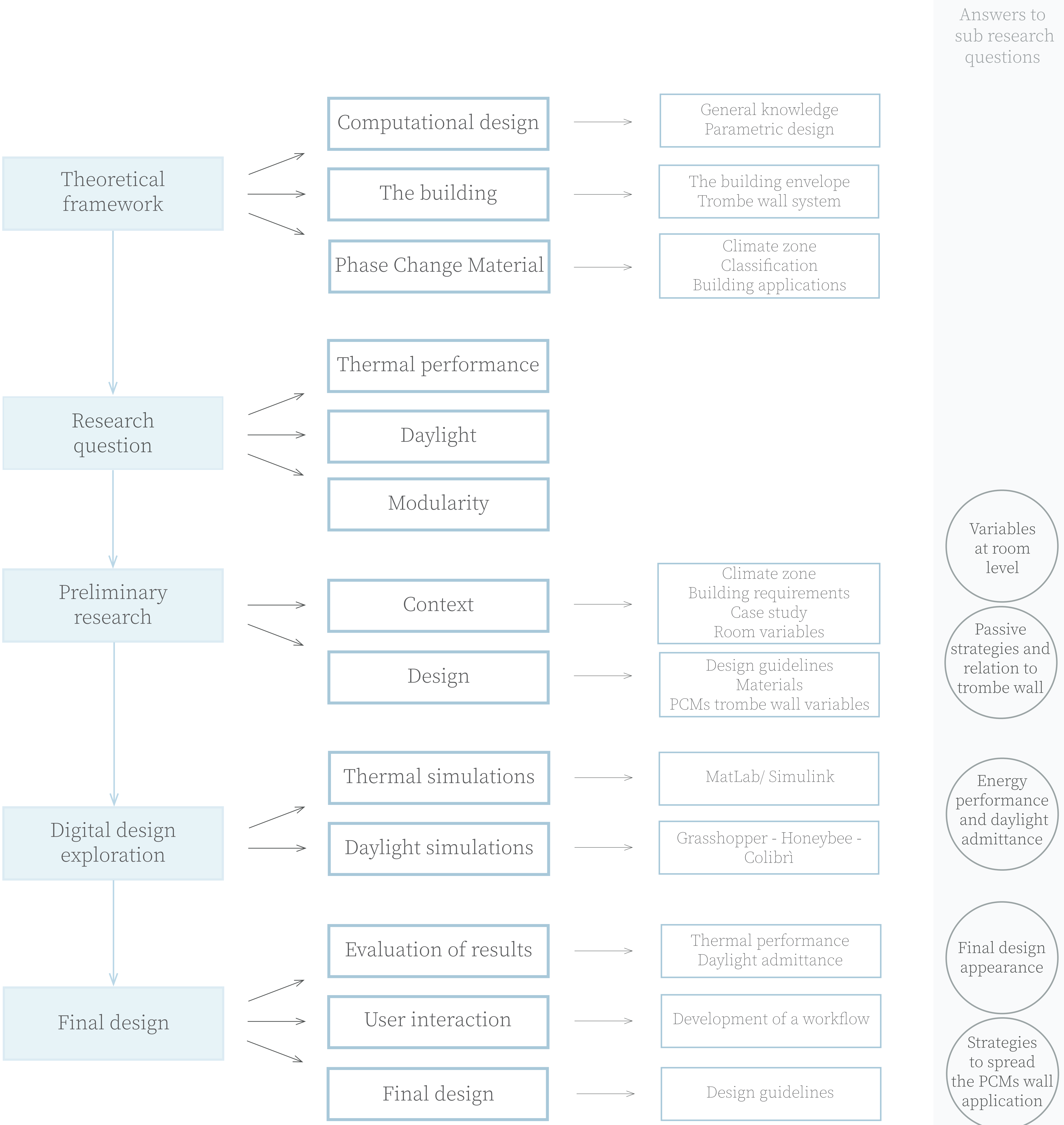
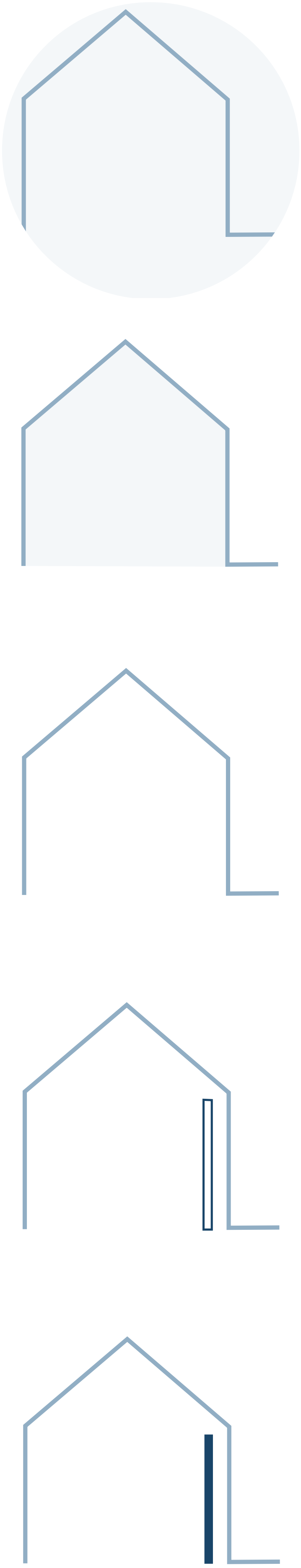


Figure 1.2: research process



CONTEXT
The first part of the theoretical framework consists of a research on computational design. After a definition of the discipline and its subtypes, several case studies are analysed.

BUILDING
The focus is on the building level. Attention is given especially to energy-optimized buildings with a residential function.

EXTERNAL LAYER
The following part relates to only one building layer, corresponding to the building envelope. Its roles are described with a focus on thermal inertia and daylight.

BUILDING COMPONENT
The research keeps increasing in level of detail by focusing on the trombe wall. Its history and physical functioning are explained as theoretical base for the further design development.

MATERIAL
The research analyses the phase change materials, which constitute the infill of the trombe wall. Special attention is given in their application in building walls.

Figure 1.3: description of the five topics of the literature research

The literature that validates the research was found through databases such as TU Delft Repository and ScienceDirect. Some keywords - such as 'parametric design', 'passive design strategies', 'modularity', 'facade', 'trombe wall', and 'PCMs' - simplified the research process. The sources were saved in Mendeley, an online library to organize the references. Then, they were grouped depending on their focus: computational design, building physics, and phase change materials.

During the **preliminary research** phase, all the necessary factors are defined. A reference case study simplifies the data collection for the simulations. Indeed, the selection of a building allows working in a specific context that defines various properties considered constant from the research (ventilation system, glazing system, etc).

After having defined all the contextual factors, the materials for the PCMs trombe wall are selected. On the other hand, the outcomes of previous research are translated into design guidelines. This provides the first boundary conditions for the trombe wall design, where some inputs are considered as variables to test how they affect the thermal demand and daylight admittance of buildings.

The next step consists of **digital research through a design framework**. Once the variables of both the room and trombe wall are defined, the thermal energy simulations are iterated on MatLab/Simulink. The performance of the trombe wall is tested as a heating system during the winter and a cooling device on summer days. The simulations are at room level, and therefore, test the energy efficiency of the entire panel. While the thermal simulations are run in MatLab/Simulink, daylight simulations are performed in Grasshopper to calculate the spatial Daylight Autonomy (sDA) of the room. In particular, the research analyses the effects the various room and trombe wall configurations have on the building demands. This is accomplished by automating the simulation process, which allows to test all the inputs values by automatically changing them.

Once the simulations are concluded, the results are evaluated. Focus is given to the values that fulfil both the thermal and daylight building demands. The software ModeFrontier enables to read from a multitude of results by using post-processing tools. The results of the simulations are integrated in a workflow that illustrates the thermal and daylight performance of the trombe wall for the design configuration selected by a user. In general, the workflow is developed as a strategy to expand the application of PCMs trombe walls by creating an interaction between the customer and the product.

As last step, the most performing design configuration is selected as scenario for the placement of the PCMs trombe wall. On the other hand, the product is developed at macro and micro scale to assume its **final design**.

1.7 Research plan

The Graduation Studio is divided into five periods, where each of them is concluded with a presentation. The student needs to make a research plan in advance, making sure to conclude the research in the established time. The tasks of this research are illustrated in figure 1.4.

In particular, the first presentation (P1) requires only to have selected the reach topic. Whereas, P2 demands the completion of the entire literature research, necessary as theoretical knowledge for the subsequent phases. After the second presentation, the design stages of the research begin. There is then P3, which is an informal presentation to see the student's progress. Contrarily, the research is checked formally in P4. At this time, the thesis should be almost done with, at least, the results for the final design. Lastly, there is the final presentation or P5, where the design and report have been is refined to be graphically pleasing.

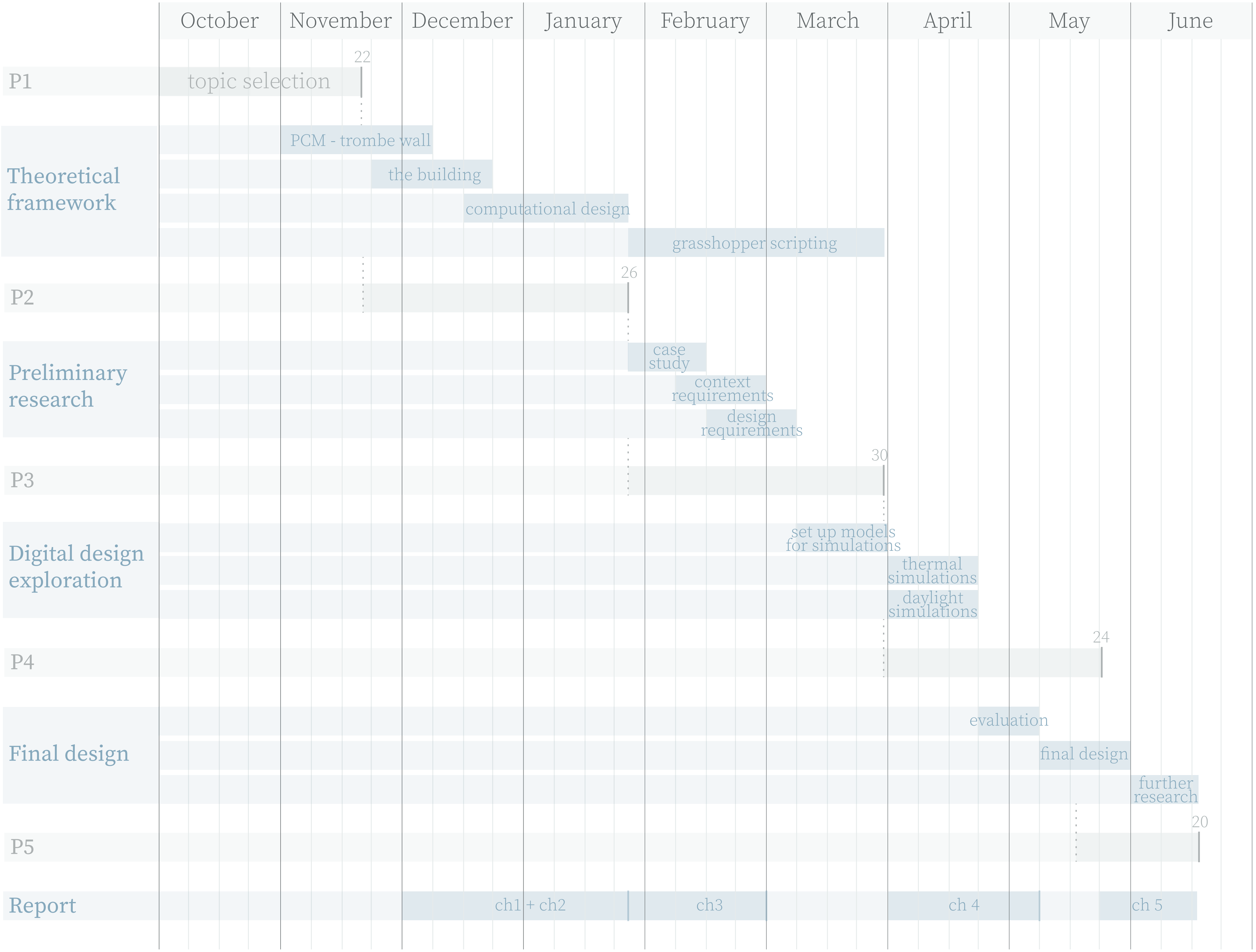


Figure 1.4: weekly plan of the research process

02. Theoretical framework

The second chapter provides an overview of the literature research of this study. The main focus is on the thermal storage capacity and light transmittance of a building component. As a whole, the theoretical framework is classified into five topics.

If the first part briefs the computational design discipline by illustrating some case studies on modularity, the second focus is on buildings developed with parametric design. Subsequently, it is described the most external layer of buildings: the building envelope. Its multiple roles are analysed with a background knowledge in building physics for the thermal mass and daylight. The subsequent topic discusses the trombe wall as a building component. While the last focus is on phase change materials and their potentiality when integrated in trombe walls.

The chapter investigates a sub research question: *which passive design strategies are applied in energy-optimized buildings and how do they affect their thermal inertia?*

2.1 Computational design

The computational design consists of a design approach in which complex problems are solved by using parameters and algorithms in advanced computer software (Ramage, 2022). Specifically, inputs are utilized to create algorithms that generate outputs, as a design model or a design analysis.

The design process is composed of multiple steps to follow the humans approach (Tedeschi, 2014). Commonly, the procedures are defined with codes, which necessitate knowledge of programming languages. However, some software has developed visual tools based on node diagrams that simplify the ability required.

For instance, a known and node-based software is **Grasshopper**, coined by David Rutten at Robert McNeel & Associates in 2007. Grasshopper is a visual programming language that runs within Rhino. It enables the design of complex geometries by using parametric primitives. The graphical primitives are **variables**, thus they can be easily changed to explore form-finding and form-making strategies.

If the use of parametric software has increased, it is critical to design a workflow rather than its outcome. Indeed, this approach enables for the investigation of novel solutions that are beyond human-capabilities. Otherwise, the designer would risk to model a shape that was previously defined. As a consequence, this would limit the form-finding research, as mentioned in Bruce Mau's Incomplete Manifesto for Growth of 1998:

> "(a) process is more important than outcome. When the outcome drives the process we will only ever go to where we've already been. If process drives outcome we may not know where we're going, but we will know we want to be there"
>
> (Tedeschi, 2014: 25)

Computational design has been developing and, nowadays, is classified into three typologies, which correspond to parametric design, generative design, and algorithmic design.

PARAMETRIC DESIGN
The use of parameters and interchangeable inputs within a domain of values, guarantees an interactive design process. The name was coined by Luigi Moretti in 1939. In particular, the world parametric derives from 'para' and 'metric' (Rocha, 2021). With Greek origins, 'para' means beyond. Therefore, their combination states 'beyond measure'. Indeed, the origins of parametric design are in mathematics.

GENERATIVE DESIGN
By using inputs with fixed values, generative design produces multiple design outcomes (Ramage, 2022). Suitable for design optimization, this approach generates a great number of options that are narrowed by the designer, who is able to reach the final design.

ALGORITHMIC DESIGN
This design method uses algorithms, which, as a cooking recipe, include all of the steps required to achieve the desired result (Tedeschi, 2014). It is necessary that each step is precisely defined and in the correct order to achieve the outcome.

2.1.1 Modular design

The concept of **modularity**, as defined in this research, consists in a design approach that involves equal pieces that adapt to various scenarios based on how they are assembled. The following paragraphs describe some reference case studies that explain this design approach and demonstrate their interaction with the user. These examples are intended to serve as sources of inspiration for the design of the PCMs trombe wall.

Design approach I

A reference case study with a modular design is the 2016 Serpentine Pavilion designed by Bjarke Ingels Group (BIG). Since 2000, the Serpentine Gallery in London has yearly commissioned the design of a pavilion to notorious architects. The challenge is given by the short notice and the temporariness required by the structure. Indeed, the pavilion is exposed only during the summer months (Menges et al., 2017).

BIG challenged itself structurally with a complex design of sinusoidal walls of 30 m that converge into a single line on top. The pavilion is composed of a renovated design interpretation of the traditional brick wall. Composed of fibreglass, the bricks, indeed, appear solid longitudinally while dematerializing into thin lines when seen from the front (figure 2.1).

The shape of the pavilion and the bricks were designed with parametric approaches. Specifically, the first part consisted of a geometric exploration for both micro (box dimensions) and macro scales (pavilion height, etc). For the second phase, it was achieved a higher level of detail

Figure 2.1: 2016 Serpentine Pavilion by BIG
Source: from *Serpentine Pavilion and Summer Houses 2016*, by Serpentine Pavilion, 2016 (http://bit.ly/3XD2uW9)

for the design, where structural and fabrication criteria were taken into account. A set of parametric models was used to test the different configurations. This had been possible by using **Re.ARK**, a toolkit developed by the engineering company AKT II. Indeed, Re.ARK allowed to analyse each option at various scales. Subsequently, the iteration of optimizations enabled to achieve the final design, composed of 1800 boxes. The boxes were mostly unique because of their different length or thickness. However, this did not complicate the assembly process. Indeed, Re.ARK allowed to simulate and optimize simultaneously the bricks, connectors, and bolts.

Design approach II

Another example of modular design is the Soundwave acoustic diffusion wall system, designed by Aectual (figure 2.2). The system is developed to mitigate reverberation and noise, thereby enhancing the acoustic comfort of indoor spaces while maintaining aesthetic appeal (Aectual, n.d.).

Figure 2.2: acoustic wall system by Aectual
Source: from *Soundwave.Horizontal*, by Aectual (http://bit.ly/41c0LJe)

The Soundwave system consists of multiple panels that can be assembled either vertically or horizontally. Each panel features a unique pattern designed to seamlessly align when combined together. This provides users with the freedom to customize the final appearance of the Soundwave system according to their preferences.

Additionally, the product is designed to be user-friendle and sustainable. It can be easily maintained by the users themselves, and the entire system is fully recyclable. This ensures that the Soundwave system can have a second life, potentially adapting to the evolving needs of users and buildings.

2.2 Parametrıc design

In the previous sub-chapter, three typologies of computational design were outlined, and this research will specifically focus on the parametric design process. The following section highlights the key aspects of this topic.

The design approach in architecture involves an iterative process accross various disciplines. It can be described as a 'back-and-forth' process where new questions generate different or novel solutions. This complicates and extends the design phase of buildings.

For instance, when working with 3D models, any required change often involves manual modifications to the virtual model (Jabi, 2013). Adjusting or remaking a 3D model can be time-consuming and limited in its potential. Moreover, these modifications are often targeted, lacking an exploration of form-finding.

Parametric design provides a solution to this problem by offering a flexible process where virtual models can be easily modified using parameters (Jabi, 2013). This allows for rapid changes while providing space for design exploration. Another significant aspect of parametric design is its ability to perform optimizations. As Rocha (2021) states, the purpose of parametric design is to create "optimized solution for complex problems". Indeed, the software can find solutions for issues that may not yet be fully understood by the designer.

The potential of parametric design software is beneficial in addressing climate change. By designing energy-efficient buildings, it is possible to limit energy demand and reduce the carbon footprint of the construction sector. The energy requirements of buildings are influenced by various factors, including heat loss and gain through the envelope, internal loads, and performance of mechanical systems (Glassman and Reinhart, 2013). Hence, optimizations play a crucial role, particularly when the design needs to consider multiple passive strategies that are dependent on the season.

2.2.1 Case studies

The next pages illustrate a number of case studies featuring residential buildings that have been developed using the parametric design approach. Specifically, these buildings were optimized computationally to achieve energy efficiency through the application of passive design principles. As a whole, the case studies demonstrate how parametric design can be utilized to create sustainable and energy-efficient residential structures.

Sources

2.3 - from *Citylife Apartments / Zaha Hadid Architects*, by ArchDaily, 2016 (http://bit.ly/3J3pAS5)

2.4 - from *Elements*, by Koschuch (http://bit.ly/3XjZ62J)

2.5 - from *Mecanoo wins tender for nature-inclusive residential building at Amsterdam Zuidas* by Mecanoo, 2022 (http://bit.ly/3ksMmrX(

2.6 - from *La Vallée Verte*, by MVRDV (https://bit.ly/3CYenhv)

2.7 - from *About Spark*, by Smakkelaarspark (http://bit.ly/3CVWK-ik)

2.8 - from *How do you use parametric design to push the boundaries of what is possible?*, by ARUP (http://bit.ly/3IYK2Dj)

City Life

Architects: Zaha Hadid Architects

Climate zone: Temperate (Milan)

Function: residential

Building shape: sinuous fluid form

Façade: load-bearing

Passive design strategies: orientation, sun-shading function, thermal inertia improvement

Source 2.3

Elements

Architects: Kondor Wessels, ARUP, KoschuchArchitects, BOOM Landscape, DGMR

Climate zone: Temperate (Amsterdam)

Function: residential, public

Building shape: rectilinear with sharp angles

Façade: fully glazed window wall

Passive design strategies: orientation, sun-shading function

Source 2.4

Habitat Royale

Architects: Mecanoo, ARUP, BOOM Landscape

Climate zone: Temperate (Amsterdam)

Function: residential, public

Building shape: undulated

Façade: fully glazed window wall

Passive design strategies: orientation, sun-shading function, passive cooling through ventilation

Source 2.5

La Vallèe Verte

Architects: MVRDV

Climate zone: Temperate (Bordeaux, France)

Function: residential

Building shape: based on the daylight requirements with a hollow centre

Façade: load-bearing

Passive design strategies: orientation, sun-shading function, thermal inertia improvement

Source 2.6

Smakkelaarspark

Architects: Studioninedots, ARUP, Lingotto, ZUS, VKZ

Climate zone: Temperate (Utrecht)

Function: residential, office, public

Building shape: rectilinear with sharp angles

Façade: both glazed and opaque window wall

Passive design strategies: orientation, sun-shading function

Source 2.7

Valley

Architects: MVRDV, ARUP, DGMR

Climate zone: Temperate (Amsterdam)

Function: residential, office, public

Building shape: rectilinear or composed of multiple blocks

Façade: fully glazed window wall or load-bearing

Passive design strategies: orientation, sun-shading function, thermal inertia improvement

Source 2.8

2.2.2 Passive design strategies

'Passive Design' refers to the building's ability to maintain a comfortable temperature. This is possible by benefiting from the local conditions to reduce or eliminate reliance on mechanical systems for heating, cooling, and lighting (Altan and Aoul, 2016). Passive principles are effective only if two aspects are considered: climate and comfort.

Since there is a great quantity of passive design strategies, the following paragraphs describe only the methods applied in the previous case studies. These approaches are classified into three groups depending on their role.

Orientation

BUILDING ORIENTATION

The orientation of the building affects its solar gain throughout the year (Ching & Shapiro, 2014). If in winter the solar radiation is maximized to heat up the indoor space, in summer it should be blocked to minimize the cooling requirements. Therefore, a good balance must be found to partially fulfil the two seasons. The building orientation can be optimized by using computer simulations (figure 2.9).

To have an understanding of the building orientation, some guidelines applicable for the temperate climate zone are listed below. It is however necessary to make computer simulations to achieve better results. Indeed, virtual models enable to consider multiple factors such as orientation, but also building shape and wind direction.

The suggestions are the following:
- Windows on only 1 side should face the south.
- Windows located on two opposite walls should be oriented south and north.
- Windows on two adjacent sides should preferably be located on south and east.

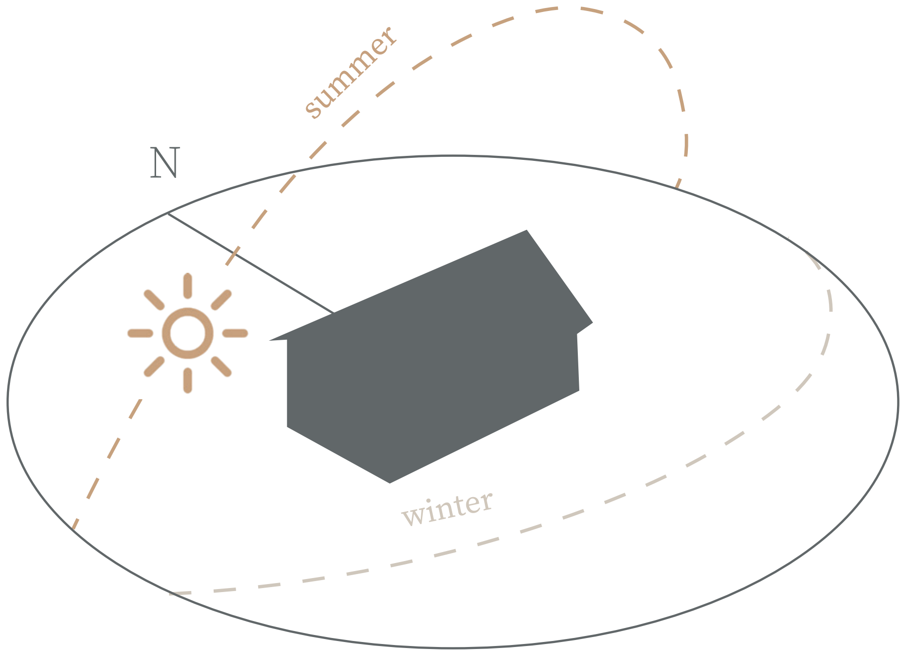


Figure 2.9: yearly sun path of a building with its orientation indicated

Sun-shading function

ADJUSTABLE SHADING SYSTEM

There are two types of sun protections, based on their function: darkening and shading.

In particular, **darkening systems** enable to block completely the solar radiation and daylight. They are, indeed, suitable for bedrooms. Commonly designed to be adjustable, they allow the users to easily open and close them, depending on their needs. They can be installed either indoors or outdoors.

Conversely, **shading devices** obstruct only the sunlight, thus still transmitting the natural light. If installed outdoors, they are more efficacious since the heat is blocked before entering the building. When outside, they can adjustable or permanent systems.

PERMANENT SHADING SYSTEMS

Fixed sun protections control the solar radiation that enters the façade (Ching & Shapiro, 2014). If optimized correctly, they enable the sunlight to enter during winter months, while blocking it in summer (figure 2.10). This is achieved by the different inclination of the solar radiation between winter and summer. They consist of horizontal elements as extruded floor slabs for south and north orientations, and vertical fins for east and west orientations.

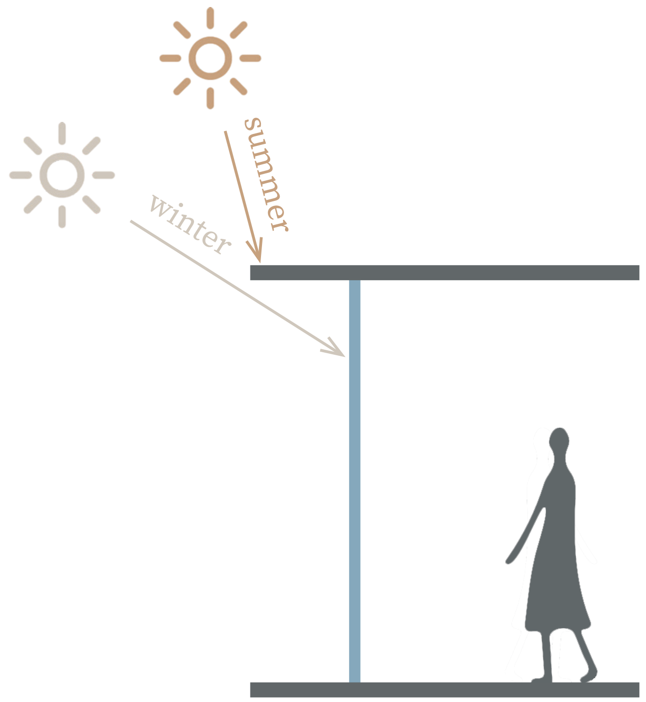


Figure 2.10: the impact of overhangs in winter and summer seasons

PRESENCE OF BIODIVERSITY

Working as a climatic moderator, vegetation can provide many thermal benefits such as controlling solar radiation, lowering ground and air temperature, limiting solar infiltration, increasing ventilation, and reducing glare from reflection (Altan and Aoul, 2016).

In particular, seasonal plants are a great solution. Being lush in summer, they behave as a shading device from direct solar radiation. On the contrary, they are bare in winter, thus allowing the sun to heat the indoor environment in the coldest months (figure 2.11).

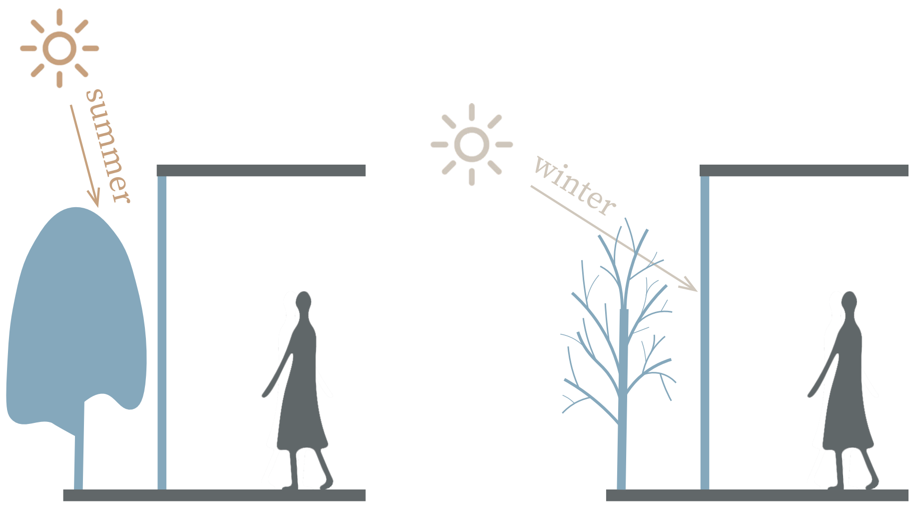


Figure 2.11: graphic explanation of how biodiversity acts as shading system during the summer months

Thermal inertia improvement

WINDOW-TO-WALL RATIO

Limiting the glazed area is a passive strategy that enhances the thermal storage capacity of building envelopes (Altan and Aoul, 2016). This is described by the **window-to-wall ratio** (WWR), which is the percentage of wall area covered by fenestration. Since glass is composed of thin plates, it has, indeed, a lower thermal mass than a wall. A good ratio to reduce thermal dispersions is the design of about 30 - 40% percent of window area in residential building envelopes. However, the proper WWR relates with the building properties and climate zone, thus another ratio might be required.

CONTROLLED NATURAL VENTILATION

Ventilation at night times efficiently cools the building envelope from the heat absorbed during the day. Cooler temperatures at night, in particular, enable the natural airflow to cool the indoor space (Altan and Aoul, 2016). The criteria works properly in walls with high thermal mass. Indeed, thick external walls delay the heat transfer from outside to the indoor space, thus having a slow rise in air temperature. Hence, the maximum indoor temperature is reached only in the evening when the external temperature is already low.

2.3 The building envelope

The external layer of a building corresponds to its envelope. As figure 2.12 shows, the building envelope is the protective layer of the indoor space from local environmental conditions (Knaack et al., 2007). Its role is to define the architectural appearance, guarantee thermal, acoustic, and visual comfort, and protect the user from climatic conditions. Each function is described in the following paragraphs and summarised in figure 2.13.

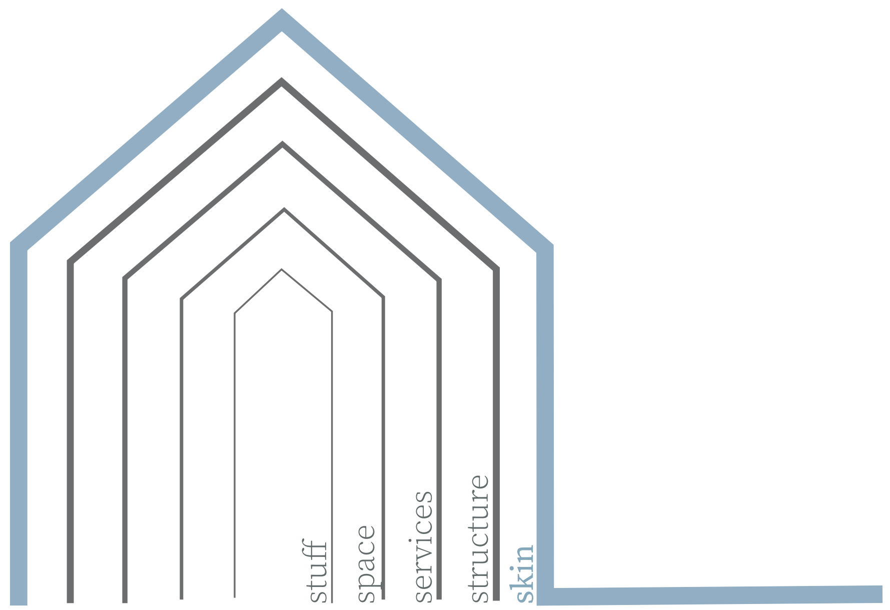


Figure 2.12: the building layers

WATER
Rainwater can penetrate the smallest holes of the envelope. If water touches metallic joints, they could rust. Or even worse, when water enters the external wall, materials could mould. For this reason, it is important to protect the skin from water and humidity (Kalkhoven and Verkuijlen, 2019).

THERMAL CONTROL
As Knaack et al. (2007) describe, the envelope contributes to the building's energy demand. Considering that the façade protects the indoor space from outside, it acts as an intermediary between the two different temperatures. To block as much thermal energy as possible, the envelope needs good insulation, which also depends on the thermal storage capacity of the wall.

ACOUSTIC INSULATION
The building envelope needs to guarantee acoustic comfort. Three types of sound are taken into account (Kalkhoven and Verkuijlen, 2019). **Airborne sound insulation** corresponds to loud noises (an airplane in flight) and can be critical for achieving quiet environments. **Impact sound** (a drill in action) is avoided by a double structure, which interrupts low-frequency sound waves. **Flanking sound** is the noise travelling from one apartment to another, through the side-wall and floors.

DAYLIGHT
The façade should allow both natural light and solar radiation into the building (Kalkhoven and Verkuijlen, 2019). A high contrast in light can, however, cause **glare**. On the other hand, uncontrolled direct sunlight can heat an environment in warm months, thus requiring a cooling system. It is therefore necessary to carefully define a proper window-to-wall ratio and shading system.

VENTILATION
There are two types of ventilation that refresh the indoor air. The **natural airflow** occurs through window or vent openings. While, the **mechanical ventilation** is installed when requiring a continuous air exchange (Knaack et al., 2007).

FIRE
If a building goes on fire, the role of the envelope becomes of major importance. Indeed, when composed of incombustible materials, the façade is able to prevent the spread of fire (Kalkhoven and Verkuijlen, 2019).

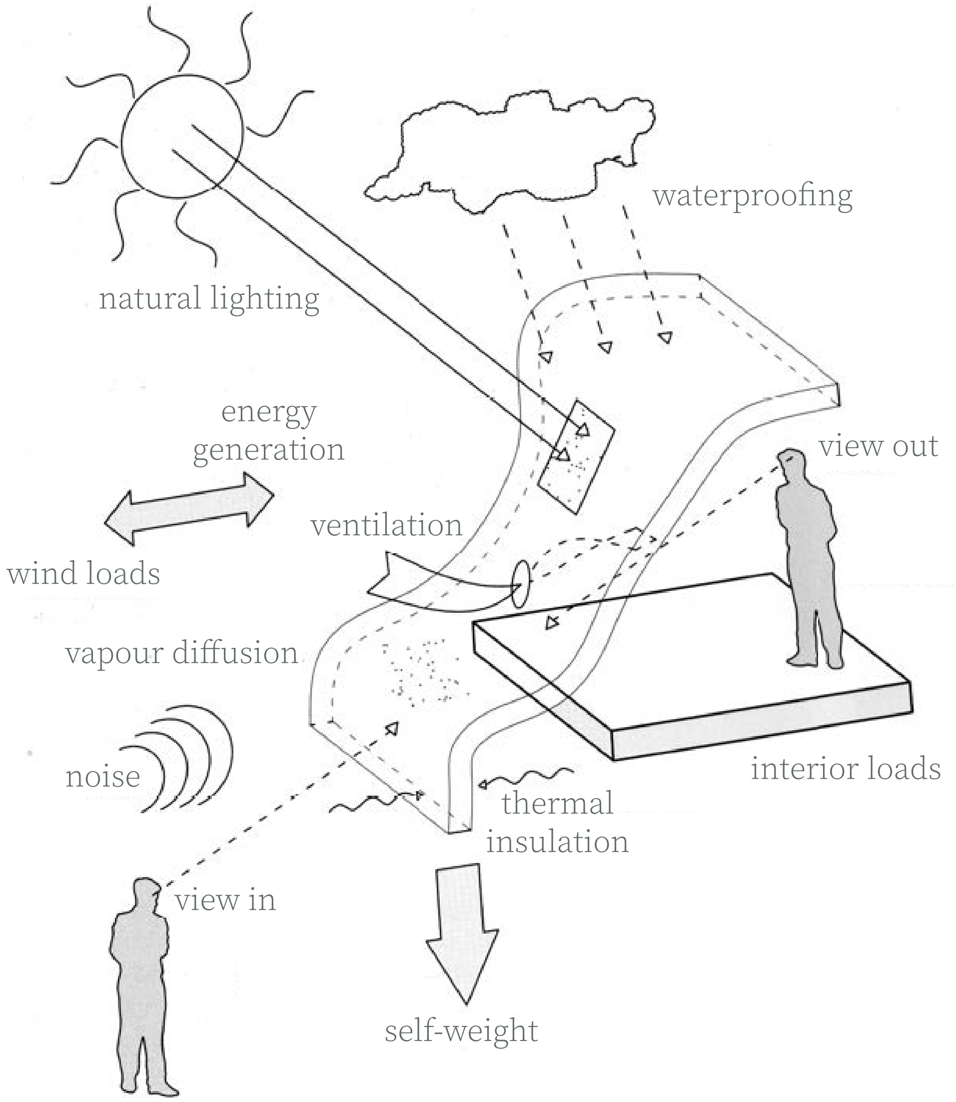


Figure 2.13: brief explanation of the roles of the building envelope
Source: adapted from *Facades: Principles of construction* (p. 36), by U. Knaack et. al., 2007, Birkhäuser Verlag AG. Copyright 2007 by Birkhäuser Verlag AG

2.3.1 Typologies of building envelope

The building envelope is divided in two typologies depending on the materials used: heavyweight or lightweight structure (Knaack, et al., 2007).

Heavyweight constructions consist of materials such as concrete, brick, or stone. The envelope has a solid and thick appearance, necessary to support the loads. Since the bearing structure corresponds to the building's envelope, the quantity and dimension of openings is limited. The same concept applies to the possible configurations of the internal space, obstructed by the massive load-bearing walls.

Indeed, the earliest function of windows was only to let the smoke out. With time, visual requirements gradually assumed more importance. As a consequence, the quantity of masonry walls was reduced to allow more light in until the 1990s, when architects searched for **lightness**, **transparency**, and **flexibility**.

This period is called **Modern Architecture** and is characterized by a bearing structure composed of columns and beams as a skeleton. This transparent and light structure, called **lightweight**, substituted the thick and mostly opaque building envelopes.

Lightweight structures, and the Modern Architecture in general, are associated with the term transparency. **Transparency** is the opposite of opacity and indicates the direct transmission of light. Indeed, opacity completely blocks the visibility and light transmittance between outdoors and indoors.

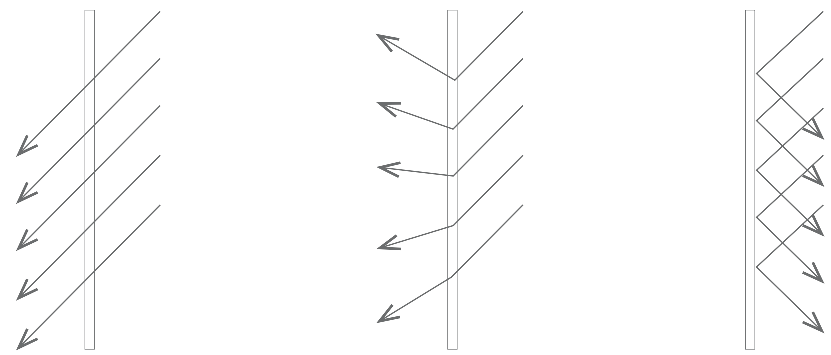


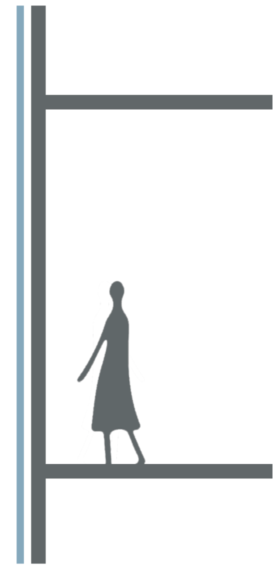
Figure 2.14: graphical explanation of the concepts of transparency, translucency, and opacity
Source: adapted from *Translucent Building Skins: Material in Modern and Contemporary Architecture* (p. 1), by S. Murray, 2013, Taylor & Francis Group. Copyright 2013 Scott Murray

Murray (2013) discusses also an intermediate concept called **translucency**, which is defined as a condition where light is transmitted by diffusing it (figure 2.14). The outcome is a surface with an indiscernible view of the other side.

Façade types

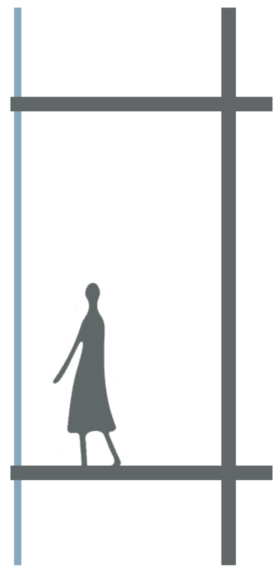
Kalkhoven and Verkuijlen (2019) briefly explain the typologies of façade system, which depend on the position of the load-bearing structure and the connection of the envelope to the floor slab. The types are load-bearing, window wall, and curtain wall façade, and are described as follows.

LOAD-BEARING FAÇADE
Known as the traditional building method, the inner part of the external wall has a load-bearing function.



Generally, the envelope is a **cavity wall**, where the outer leaf acts as a protective layer. It is composed of either solid materials like concrete or of a framed structure with filling materials.

WINDOW WALL FAÇADE
Being non-load-bearing, the façade is supported by floor slabs or beams, between which it is also located. This creates a continuous surface that increases the façade performance, as it avoids thermal bridges and water infiltrations.

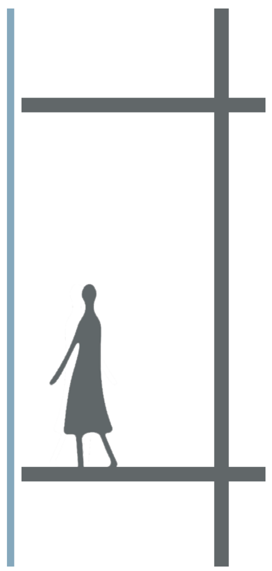


The system is cheaper than curtain walls and is generally applicable for solid claddings, which need a secondary support.

CURTAIN WALL FAÇADE
Commonly used in high-rise buildings, curtain walls are lightweight, non-load-bearing, and fully or partially glazed.

They are composed of **mullions** for the vertical loads, and horizontal **transoms** that carry the glass load and transfer it to the mullions.

The curtain wall is connected to the floor slab with cladding brackets, leaving a gap in-between for tolerances.



2.3.2 Thermal control

Heat is a form of energy that flows from warmer areas cooler ones in order to achieve a balance (Van der Linden et al., 2018). There are three ways to transfer heat and they are convection, radiation, and conduction (figure 2.15). The total quantity of heat transferred with the three methods is called **heat transport**.

Conduction

Heat is transferred through conduction because of the vibration of either molecules in solids or free electrons in conductive materials (Van der Linden et al., 2018). Indeed, the greater the temperature, the faster will the molecules vibrate. Generally, conduction depends on the **thermal conductivity** (λ), which is the ability of a material to transfer and conduct heat. The unit of λ is W / m · k.

Thermal conductivity influences the **heat resistance** (R) of a single layer of a building component. Specifically, the heat resistance defines the difficulty to conduct heat through a material and depends on the thermal conductivity and thickness (d) of that material. Its estimation is achieved by the following equation:

$$R = d / \lambda \quad [m^2 \cdot K / W]$$

A material with a higher heat resistance corresponds to better insulation. Therefore, the thermal properties of a building envelope are calculated to determine the energy efficiency of that building. Ideally, a building should minimize the energy losses with the outdoor space while using renewable resources to produce energy.

Radiation

When objects have a greater temperature than 0 K (-273 °C), they radiate it through electromagnetic waves (Van der Linden et al., 2018). As soon as these vibrations reach the object, they turn into heat. Their intensity is affected by the temperature of the radiative body as well as their distance from the object to be heated. An example is the difference in temperature between seasons, as sunlight has a stronger influence on the summer months than on the winter.

The heat released by a body (q_s) is quantified with the following equation:

$$q_s = \varepsilon \cdot 56.7 \cdot 10^{-9} \cdot T^4 \quad [W / m^2]$$

ε indicates the emissivity of the material's surface, while T is the absolute temperature in Kelvin. Finally, $5.67 \cdot 10^{-9}$ [W / m² · K⁴] is the Stefan-Boltzmann Constant.

Convection

The heat is transferred via the mass motion of a substance caused by buoyancy forces or pressure differences due to wind or fans. In particular, the buoyancy effect is generated from a difference in density caused by a variation in temperature (Farruggia, 2018).

Since the convection occurs only through liquids and gases, the amount of heat transmitted is determined by the flow rate of the medium, as well as the temperature difference between the object (T_1) and the medium (T_2). The heat flow density (q_c) is calculated with the following formula, where α_c indicates the heat transfer coefficient (Van der Linden et al., 2018).

$$q_c = \alpha_c \cdot (T_1 - T_2) \quad [W / m^2]$$

Main factors influencing the thermal storage capacity of a building envelope

When evaluating the thermal control of a building envelope, thermal inertia assumes a significant influence. Reardon et al. (2020) define, indeed, **thermal mass** as "the ability of a material to absorb, store and release heat".

The thermal storage capacity of a material is influenced by various factors as its thickness, density, specific heat, thermal diffusivity and effusivity. In particular, the **thermal diffusivity** measures the material's ability to transmit heat and is related to thermal conductivity and storage capacity. While **thermal effusivity** indicates the material's ability to exchange heat with any type of substance (Farruggia, 2018). Moreover, thermal diffusivity influences the thermal lag of thermal mass.

The time interval between the peak temperatures inside and outside is defined as **thermal lag**. The required thermal lag depends on the climate zone. Its value relies on several factors such as the thickness and surface area of materials, colours and texture of cladding, and the presence of air movement (Reardon et al., 2020). Thermal lag is influenced also by the thermal conductivity of materials. Indeed, a material with high conductivity transfers heat quickly, thus having short cycles of thermal storage (Farruggia, 2018).

Generally, the thermal mass and thermal lag are directly proportional, meaning that if the thermal mass of a material is higher, its thermal lag will be longer (Reardon et al., 2020). However, thermal mass is not always advantageous, as the next paragraph will explore.

Heavyweight and lightweight structures

Wiedenhoff and de Vaan (2010) have investigated the heating and cooling demand for heavy and light structures. The results have demonstrated that both construction typologies have their advantages and disadvantages. Moreover, the required thermal mass for a specific building is dependent on multiple aspects as the climatic conditions, people's behaviour, building's shape and function. It is, therefore, not possible to define a wall typology suitable for any building constructed in the future.

The results of the research show that walls with high thermal mass require more time to change their temperature. This characteristic can be considered an advantage when the building is facing a temperature change (from winter to summer, or vice versa). On the other hand, a heavyweight structure has higher thermal loads when the temperature is stable. Indeed, the wall requires great energy to change its temperature, but once it does, it will keep it for a long time before losing it.

Conversely to masonry walls, lightweight constructions are disadvantageous during a temperature change. Indeed, they lose temperature quickly, requiring energy demand also before the seasonal peaks in temperature (winter and summer seasons). However, since lightweight structures absorb and lose temperature relatively fast, they are beneficial for users that spend a short time in the building.

To conclude, Wiedenhoff and de Vaan (2010) advice the application of heavyweight walls in temperate climates, where temperatures are not extreme in summer or winter. Moreover, lightweight structures are not recommended in this climate zone since also summer nights reach low temperatures. However, the optimal thermal mass is selected by various factors. Therefore, it is advised to select the proper structure based on the numerous aspects that affect buildings.

2.3.3 The light

Light is an electromagnetic wave with different wavelengths (Van der Linden et al., 2018). It can be measured with various units, but the four primary are: luminous intensity, luminous flux, illuminance, and luminance. While the first two metrics relate to the light source, the last two regard the performance of light in a space.

Specifically, luminous intensity (cd) denotes the ability of a source to provide illumination in a specific direction, while luminous flux (lm) represents the light perceived by the human eye. On the other hand, illuminance (lx) quantifies the amount of light falling on a surface, while luminance (cd/m^2) determines the light emitted or reflected from a surface in a specific direction.

Daylighting

Since artificial lighting significantly impacts the building energy consumption, the design of façades that maximize natural light admittance can reduce the energy demand. The amount of daylight entering a room is influenced by various factors such as building location, window size, orientation, and light transmittance (Kuhn, 2017). Depending on the requirements, natural light can be estimated by different metrics, some of which are described as follows.

In many countries, a minimum level of daylight is mandated by the **daylight factor** (D), which is determined for overcast climatic conditions, considering a diffuse sky. The daylight factor is calculated by dividing the indoor global horizontal illuminance (Ev, indoor) by the outdoor global horizontal illuminance (Ev, outdoor).

$$D = (Ev,\ indoor\ /\ Ev,\ outdoor) \cdot 100 \quad [\%]$$

The daylight factor does not take into account the façade orientation and the building location. Therefore, the value is not suitable to determine the lighting demand of a building. Furthermore, studies have demonstrated that the daylight factor does not align with user satisfaction.

Conversely, the **daylight autonomy** (DA) is a metric that considers the weather conditions and orientation. Kuhn (2017: 117) describes DA as "the percentage of working hours of the year when the minimum illuminance requirement at the sensor point is met by daylight alone". The daylight autonomy is calculated by the following formula:

$$DA = \left(\frac{w_h \text{ with daylight illuminance} > \text{threshold}}{\text{total } w_h}\right) \cdot 100$$

Commonly, a high value of daylight autonomy is associated with user's satisfaction. However, DA does not account the presence of glare, which can result from excessive contrast in brightness. Therefore, it is advised to utilize multiple metrics when assessing a control system's performance.

One example is **spatial daylight autonomy** (sDA), which evaluates the distribution of DA within a room while considering whether the daylight levels meet user satisfaction.

Solar Gain

The building envelope consists of transparent components that play a crucial role in enhancing indoor comfort. For instance, windows allow solar radiation and natural light to reach the indoor space (Kuhn, 2017). This enables passive heating of the environment through solar energy and provides illumination with daylight. Moreover, the use of glazing promotes visual comfort by establishing a connection with the exterior and adds architectural value to the building.

In winter, buildings often require high solar gain to maintain warmth. Conversely, during summer, it is essential to block direct sunlight to prevent overheating (Knaack et al., 2007). Indeed, excessive transparency without adequate solar control can result in the need for cooling systems. Therefore, attention must be given to solar gain when designing a façade.

The **Solar Heat Gain Coefficient** (SHGC), as described by Overbey (2015), represents the ratio of incident solar radiation that enters the building. Commonly, it is expressed as a value between 0 and 1, where 0 indicates no solar heat gain, and 1 denotes the maximum heat gain. Different types of glazing have varying SHGC values, which can also be influenced by the presence of shading devices.

In accordance to the International Energy Conservation Code (IECC), the SHGC of an overall fenestration area can be determined by the following methods (First Green Consulting, 2023).

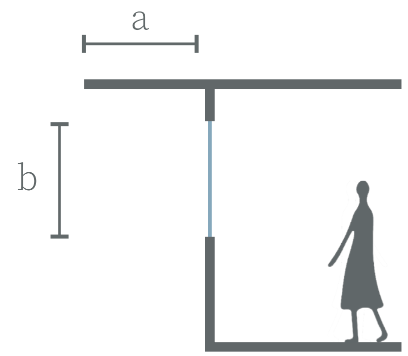
- Glass: the SHGC of only glass is calculated by considering the solar radiation absorbed, transmitted and re-emitted.

- Shading coefficient: the SHGC is estimable with the following formula, where the shading coefficient (SC) of a sun protection is multiplied by 0.86.
  SHGC = SC · 0.86

- Permanent external sun-shading system: the presence of a fixed shading device reduces the solar heat gain. If the element is not adjustable by users, it is frequently optimized by calculations and digital simulations to enhance its performance. For instance, in temperate climates the overhangs and vertical fins of buildings are designed to act as shading device only in summer months. However, there is no specific formula to evaluate the SHGC of permanent external sun protection systems.

  As a result, First Green Consultating (2023) proposes to calculate the Effective SHGC (SEF) by the suggested stepped methodology. However, this approach is applicable only if the projection Factor (PF) has a value between 0.25 and 1.

1. The projection Factor (PF) is calculated by dividing the shading projection length with the window height.
   PF = a / b [mm]



2. If the fenestration is not cardinally oriented, the non-cardinal direction factor (PC) corresponds to the following values. The PC value depends on the orientation of the fenestration.
   PC = 1 (North or south)
   PC = 0.8 (East or west)
   PC = 0.6 (North-east, north-west, south-east or south-west)

3. The ECBC 2017 specifies the maximum Allowable SHGC ($SHGC_{max}$), which is related to the orientation and geographic location.

4. Table I in the Appendix contains the Coefficients of Shading Equivalent Factors (SEF), dependent on the building latitude.

5. The Effective SHGC (SEF) is estimated by the following formula and depends on the latitude. For a latitude ≥ 15° N: C3 = 0.0, C2 = 0.16, C1 = 0.66, and C0 = 0.0. Conversely, a latitude < 15° N: C3 = 0.1, C2 = 0.28, C1 = 0.62, and C0 = 0.0.
   SEF = $(C3 \cdot PF^3) + (C2 \cdot PF^2) + (C1 \cdot PF) + C0$

Energy saving measures

The government of the Netherlands has implemented measures to reduce the energy demand of buildings by promoting the adoption of energy-saving practices. These measures focus on the production of renewable energy and the use of sustainable techniques (Netherlands Enterprise Agency, n.d.).

In addition, new buildings in the Netherlands must comply with the Bijna Energieneutrale Gebouwen (**Almost Energy Neutral Building requirements** - BENG). The BENG standards aim to achieve energy-efficient designs through three strategies, which are described as follows (Rijksdienst voor Ondernemend Nederland, 2017).

1. The building energy requirement is determined in kWh / (m^2 · yr). This calculation sums up the heating and cooling demands of the building, while considering the ventilation system as energy-neutral. The BENG calculation is influenced by factors such as the location, building shape, window-to-wall ratio, thermal bridges.

2. The energy required by a building can be generated by either fossil fuels or renewable sources. Commonly, the energy produced for heating, cooling, hot water, and ventilation belongs to primary fossil energy consumption. For non residential buildings, also lighting and humidification are considered.

3. If a building generates energy from renewable sources, this is subtracted from the primary energy consumption. The renewable energy is calculated by dividing the renewable energy produced by the total energy consumption of the building.

The previous strategies illustrate a correlation between the energy requirement of buildings and window-to-wall ratio. Indeed, glazing has a lower thermal storage capacity and a higher U-value if compared to opaque walls. Therefore, the behaviour of glazing can be considered as lightweight walls, which tend to disperse the indoor temperature more quickly.

Considering the increase in temperatures, buildings risk more frequently to overheat during summer. This phenomenon is mainly influenced by glazed façades. Therefore, balance between thermal inertia and glass must be defined when designing a building.

2.4 Trombe wall system

The building envelope consists of multiple building components. One of these is the Trombe wall, which works as a passive storage system (Xiong et al., 2021). Located at a distance of 3 to 10 cm from the window, trombe walls increase the thermal storage capacity of the façade. Commonly made of either bricks, concrete, stone, or clay, trombe walls have a high thermal mass that allows absorbing sufficient heat from solar radiation. After a few hours, the thermal energy is slowly released to heat the indoor space through conduction and convection.

The inventor of the idea was Edward Morse, an American engineer who patented his design in 1881. However, the Trombe wall was popularised and named by the French engineer Felix Trombe and the architect Jacques Michel. The traditional trombe wall is a massive black wall with a ventilated gap in-between. The wall absorbs the solar radiation transmitted through a transparent surface. The heat is then conducted through the solid

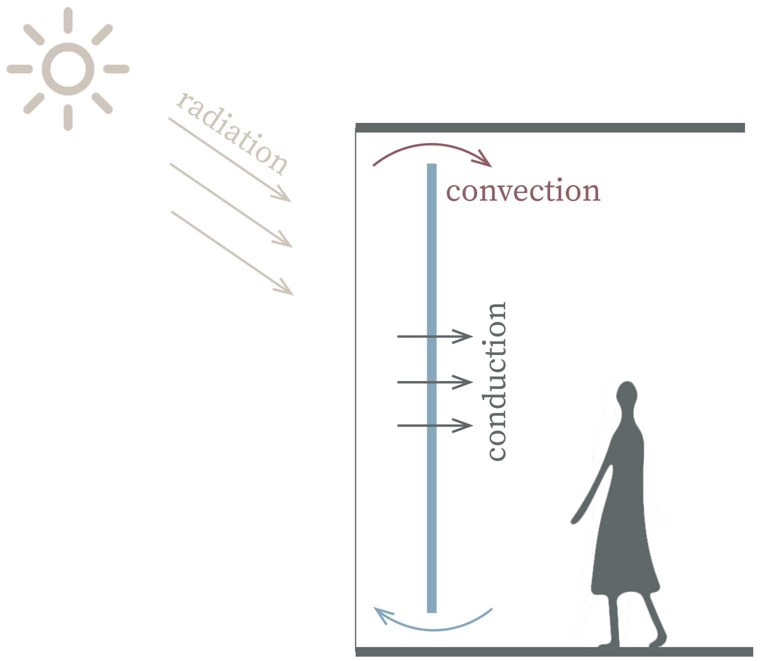


Figure 2.15: heat transfers of a classic trombe wall
Source: adapted from Trombe wall with phase change materials: A review, by A. A. M. Omara and A. A. A. Albenuor, 2020, *Energy Storage, 2*(6), p. 2 (https://doi.org/10.1002/est.2.123). Copyright 2019 by John Wiley & Sons ldt.

mass from the heated side to the back. There the wall releases its heat to the room by convection and radiation. Other systems use grills at the top and bottom of the trombe wall to convey heat that has accumulated in the cavity between the wall and the glass by convection to the other side. In particular, this heat is transferred by the buoyancy effect produced by air circulation.

Traditional trombe walls have limited functionality. For instance, they are suitable in winter situations when heating is required, but are not capable of working as cooling systems in warm months. Consequently, several types of trombe walls have been developed nowadays. They differentiate from the classic design whether because a layer is added (insulation, coating, PV panels) or something is modified (wall thickness, presence of vents).

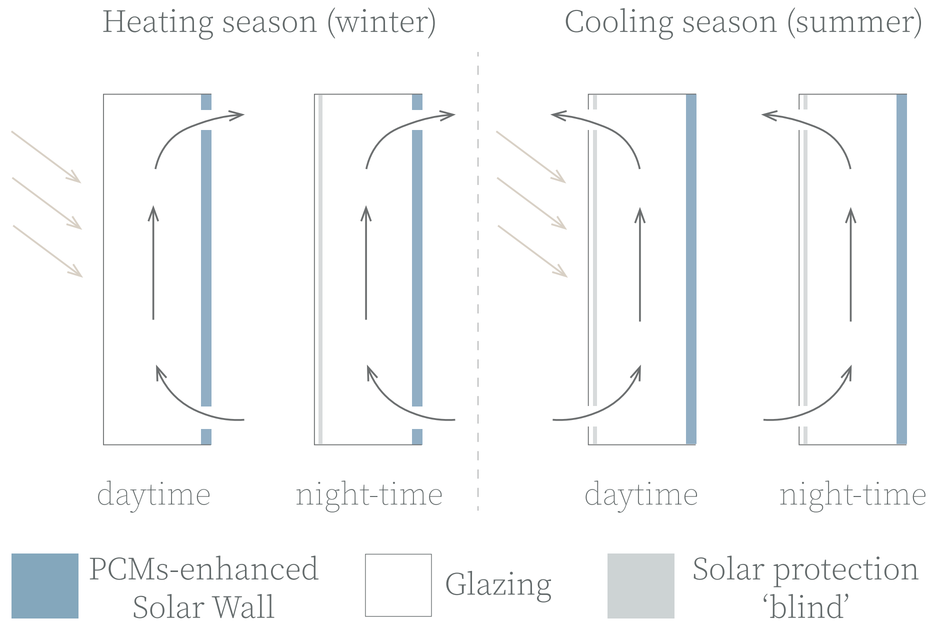


Figure 2.16: mechanisms of PCMs trombe walls
Source: edited from Trombe wall with phase change materials: A review, by A. A. M. Omara and A. A. A. Albenuor, 2020, *Energy Storage, 2*(6), p. 5 (https://doi.org/10.1002/est.2.123. Copyright 2019 by John Wiley & Sons ltd.

An example is the addition of phase change materials (PCMs) as infill of the trombe wall. Commonly, the material is integrated by filling the holes in the masonry wall or substituting the main component (Omara and Albenuor, 2020). As a result, the trombe wall becomes an adaptable element to different situations.

Figure 2.16 describes the operational mode of a PCMs trombe wall. Specifically, the material improves the thermal storage capacity of the trombe wall by the following process. The PCMs melt when the wall is heated by solar radiation to release the heat in the indoor space in the evening.

A few researches have been developing innovative solutions for trombe wall systems. They are described in the sub-chapter 2.5.4.

Thermal energy storage

As previously mentioned, the trombe wall component is a **thermal energy storage** (TES) system. Its main purpose is to store thermal energy and release it subsequently (Omara and Albenuor, 2020).

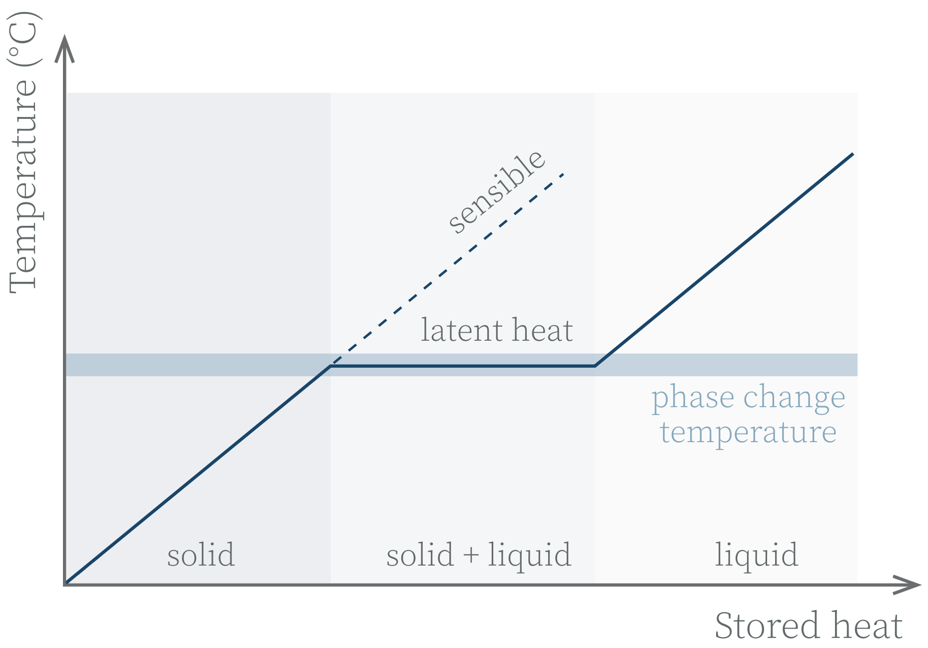


Figure 2.17: explanation of the difference between latent and sensible heat
Source: adapted from Brick masonry walls with PCM macrocapsules: An experimental approach, by R. Vicente and T. Silva, 2014, Applied *Thermal Engineering, 67*(1-2), p. 26 (https://doi.org/10.1016/j.applthermaleng.2014.02.069).Copyright 2014 by Elsevier Ltd.

Thermal energy storage is obtained by the use of latent or sensible heat storage (figure 2.17). **Sensible heat storage** passively stores and releases thermal energy (Kuznik et al., 2010). Indeed, during a temperature change, the materials' temperature increases rather than undergoing a phase change.

Conversely, **latent heat storage** refers to the energy stored by a material during its phase transition (Omara and Albenuor, 2020). The phase change relates to both solid-to-liquid and liquid-to-gas processes. Moreover, this system requires a smaller volume of material than sensible heat storage.

A material that faces a phase transition during a temperature change is called **Phase Change Material** (PCM) (Mehling et al., 2022). By absorbing and releasing thermal energy, PCMs are a great solution to manage incident solar radiation to improve the building's energy efficiency.

2.5 Phase Change Materials

Phase change materials store thermal energy during their transition from solid to liquid by applying the latent heat storage principle (Mehling et al., 2022). Commonly, the material starts melting when the temperature rises. This process is called **endothermic** and corresponds to the absorption of heat. When the temperature cools down, the PCMs start their solidification process. During this transition, the heat previously stored is released by the material (Baetens et al., 2010).

Phase Change Materials have great potential as thermal storage systems. Indeed, their phase transition occurs with even a small temperature change and ensures a high storage density per unit mass. The most common PCMs is water. However, its melting temperature at 0 °C makes it not applicable for buildings. Indeed, the suitable PCMs for building applications are based on their melting temperature and melting enthalpy (figure 2.18) (Baetens et al., 2010).

PCMs have been researched since the 70s when the oil crisis was concluded. However, most of the publications have been produced in the last 8 years. Innovative research has been carried out by applying PCMs in building components. This has shown their greater heat storage capacity when compared to traditional building materials.

For instance, Xiong et al. (2021) state that a PCMs trombe wall can reduce energy consumption by up to 20% as a passive heating system. However, the PCMs performance is affected by the climate zone where the PCM is applied. Conversely, the efficiency of trombe walls is influenced by glazing properties as the transmittance level of glass plates.

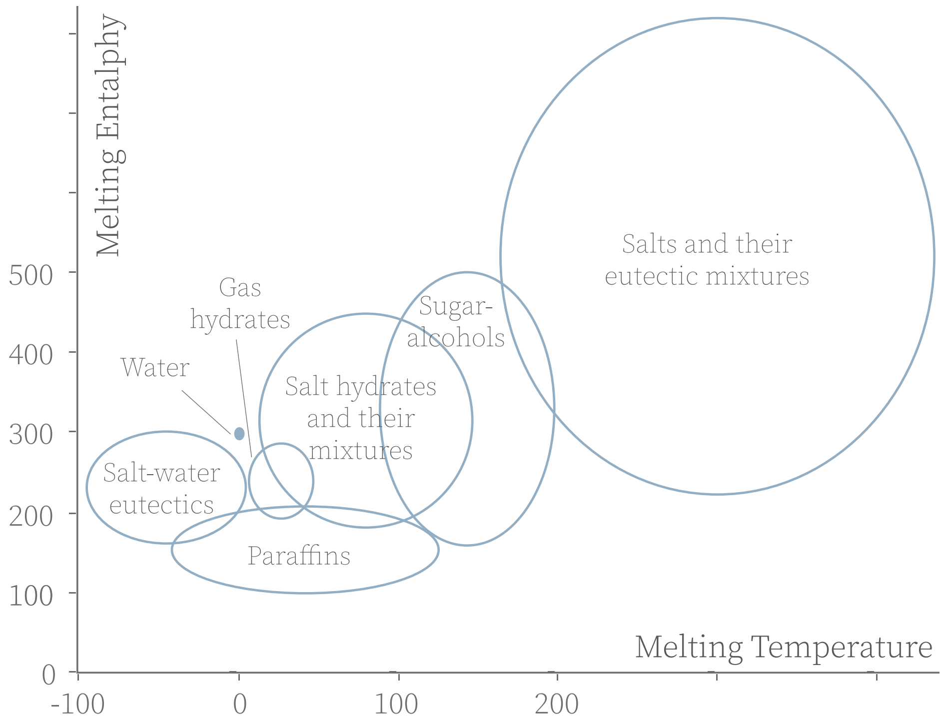


Figure 2.18: PCMs melting temperature and melting enthalpy
Source: adapted from Phase change materials for building applications: A state-of-the-art review by R. Baetens et al., 2010, *Energy and Buildings*, *42*(2010), p.1362 (https://doi.org/10.1016/j.enbuild.2010.03.026)

2.5.1 Climate zones

The world is divided in areas with different climatic conditions. These are called **climate zones** and are organized around 4 main categories listed below, as figure 2.19 illustrates (Meteoblue, n.d.).

TROPICAL ZONE: it includes both equatorial and tropical areas (0° - 23.5°). At noon time, the sun reaches the ground vertically throughout the year. Thereby, the weather is warm. Characterized by water evaporation due to high temperatures, these regions are frequently cloudy.

SUB-TROPICAL ZONE: it is characterized by warm and dry summers and cold and moist winters. Since the moisture is limited, the effect of solar radiation is significant. For this reason, the desert areas are located in this range of latitudes between 23.5° and 40°.

(SUB)TEMPERATE ZONE: the name 'temperate' derives from its weather conditions, which are not extreme. Vegetation has a long period of life, whilst precipitations are regularly distributed throughout the year. Summers are warm and have long days. Winters are cold and have shorter days.

(SUB)POLAR ZONE: with a latitude between 60° - 90°, it corresponds the coldest areas of the world. Because of their geographical position at the poles of the Earth, the solar radiation has a very flat angle. Consequently, days occur only during the summer months.

It exists a correlation between the climate zones and PCMs. Indeed, Cui et al. (2017) investigated where Phase Change Materials are applied to discover that they predominate in two ranges of latitudes: **25 °- 60 °** on the north latitude, and **25 °- 40 °** on the south latitude. The reason is that PCM's melting temperature is not suitable for all climatic conditions. Specifically, the predominant climatic sub-areas in these latitudes are Mediterranean, Temperate, and Subtropical monsoon.

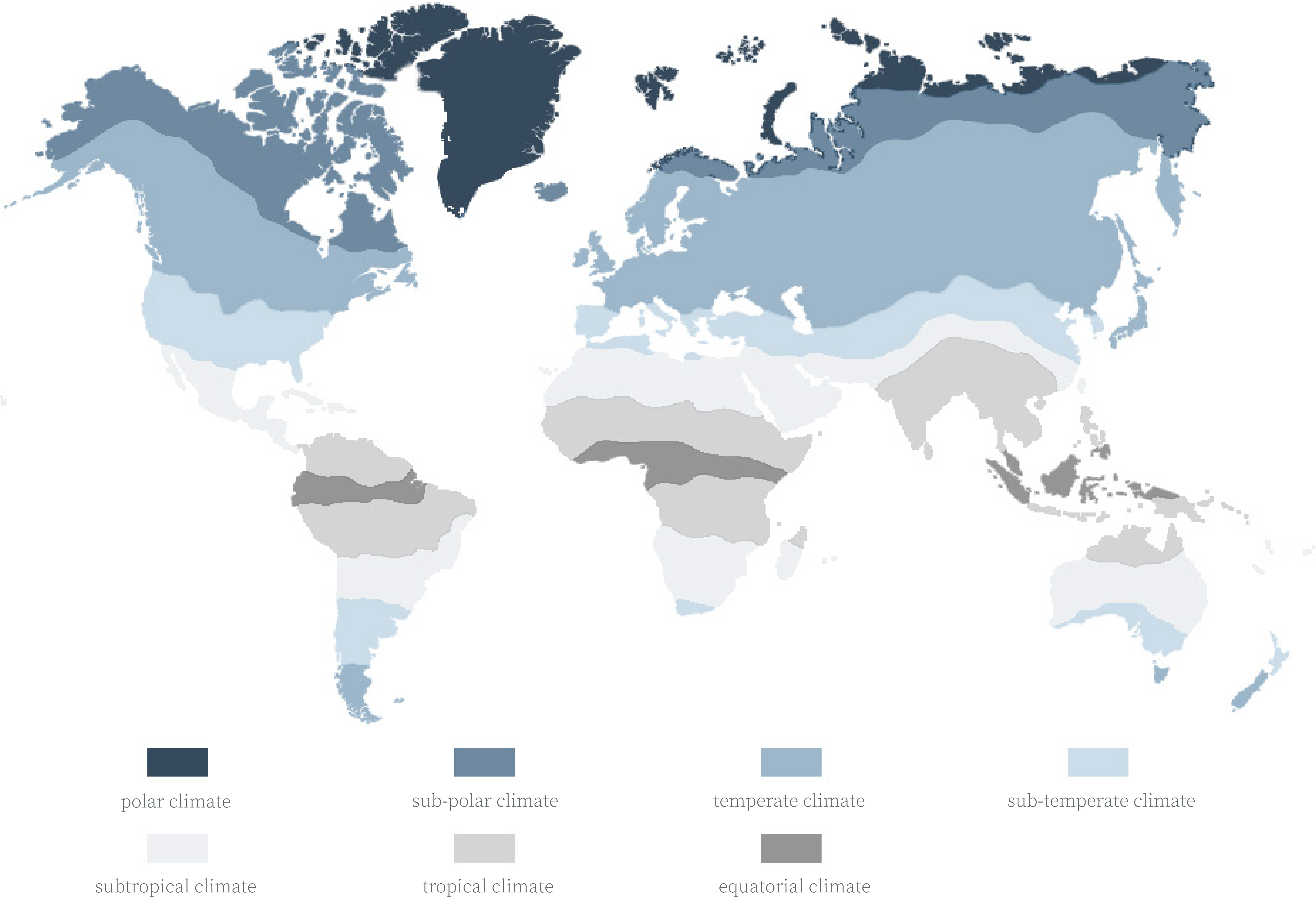


Figure 2.19: classification of the main climate zones
Source: adapted from *Map with world climate zones vector image*, by VectorStock, http://bit.ly/3Xh36Be

2.5.2 Classification

Phase Change Materials are classified into three groups: solid-solid, solid-liquid, and liquid-gas. The most suitable PCMs for thermal energy storage are the solid-liquid, which are classified in organics, inorganics, and eutectics, as figure 2.20 illustrates (Baetens et al., 2010).

Organic PCMs are chemically stable and have a high heat of fusion but are flammable. They are subdivided in paraffins and non-paraffins. Paraffin is the most common material applied in buildings with a maximum frequency of 87.5%. The main reason is its large temperature range between -9 and 100 °C. Whereas, non-paraffins have good melting and freezing properties but are expensive.

Inorganic materials have high latent heat storage and a thermal conductivity of 0.5 W/mk, compared to the 0.2 W/mk of paraffins. They are non-flammable and transparent in both phases. The most common are salt hydrates, which have an **incongruent melting** due to phase separation upon cycling. For this reason, they have uncertain long-term reliability. Furthermore, they suffer from **supercooling**, affecting the transition from solid to liquid.

Eutectics are a combination of two or more components. They have a sharp melting point and do not suffer from phase separation. However, they are rarely used in building applications because of their limited data available on physical and thermal properties.

Figure 2.21 highlights the most widespread PCMs types in building applications, corresponding to paraffins and salt hydrates (Kuznik et al., 2011).

To select the proper PCMs type for this research, a comparison of their properties has been formulated. The following questions were asked to **Martin Tenpierik**, researcher of the Double Face 2.0 (TU Delft), and **Yuliya Sinke**, who worked on the PCM Façade project (Royal Danish Academy). The answers below were reformulated by the researcher of this study and integrated with

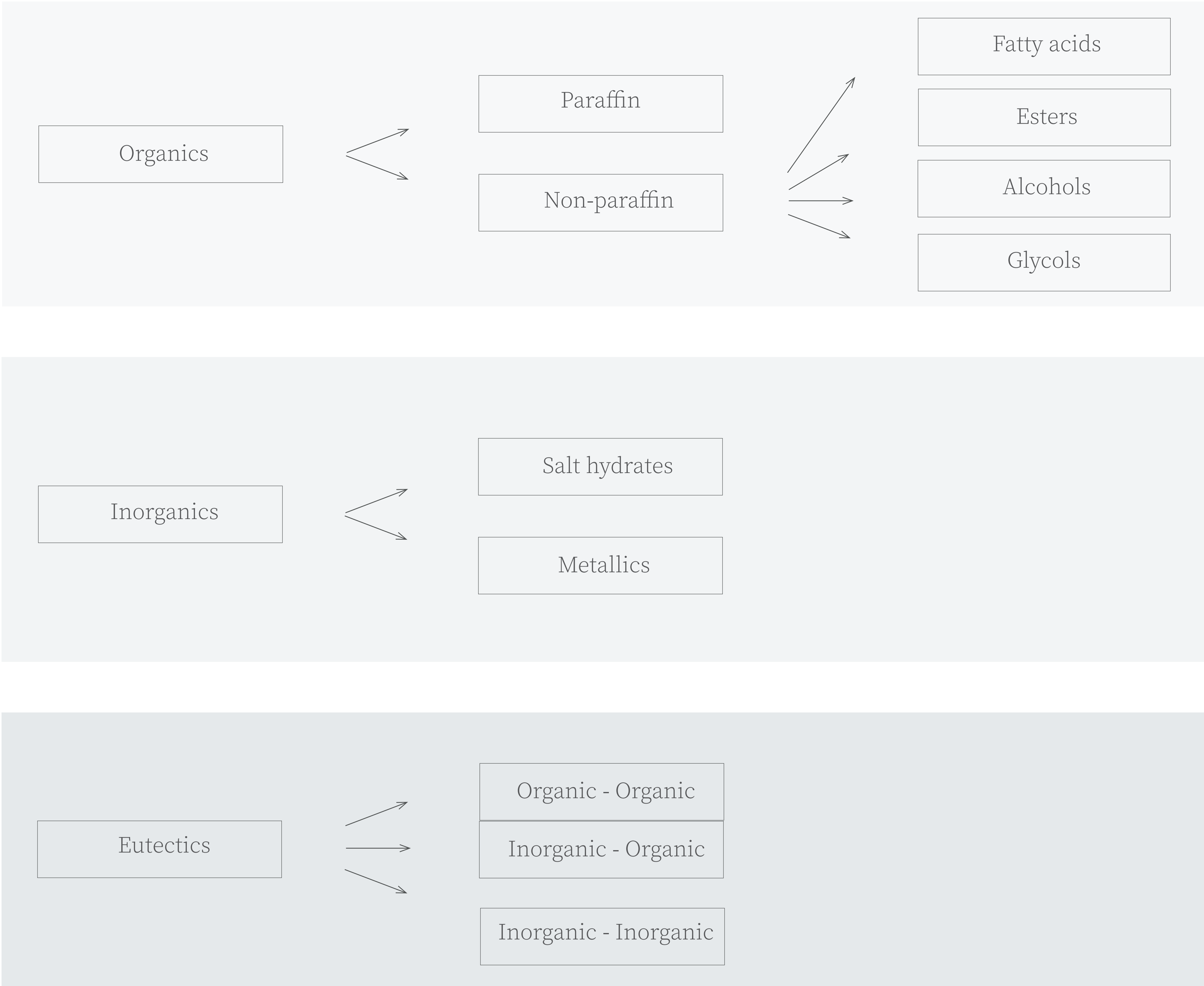


Figure 2.20: classification of phase change materials
Source: adapted from Review on thermal energy storage with phase change materials (PCMs) in building applications, by D. Zhou et al., 2012, *Applied Energy, 92*(2012), p. 598 (https://doi.org/10.1016/j.apenergy.2011.08.025)

other knowledge, when necessary.

1. Which PCMs material type is the research constituted of and why?

   Double Face 2.0: we decided to use inorganic salt hydrates because of their translucency when both solid and liquid. Moreover, the material is non-flammable and easy to recycle.

   PCM Façade: the façade is composed of PET moulds filled with organic paraffin wax.

2. What are the advantages and disadvantages of this material type?

   Double Face 2.0: besides the properties mentioned above, salt-hydrates have a high thermal conductivity. On the other hand, they have an incongruent melting as the salt sinks at the bottom. This is called **phase segregation**.

   PCM Façade: paraffin wax is transparent only when liquid. It is flammable but, during the research, we did not explore any method to make it fire-resistant. Indeed, the purpose of the study was the exploration of the modelling methods for a design with PCMs. Therefore, the façade was not designed to fulfil the building regulations.

3. How could you have solved the downsides of this material?

   Double Face 2.0: the panel rotates horizontally. For this reason, you need to shake it to mix again the salts accumulated at the bottom. However, if the panel rotated vertically, its rotation would mix the substance again.

   PCM Façade: an issue we faced was the leakage of PCMs, which are able to go into any microscopic hole. The PCMs were encapsulated in a PET container, and shaped three-dimensionally to create separate and small areas that could contain the material. This avoids the PET surface to deform from the load of paraffin.

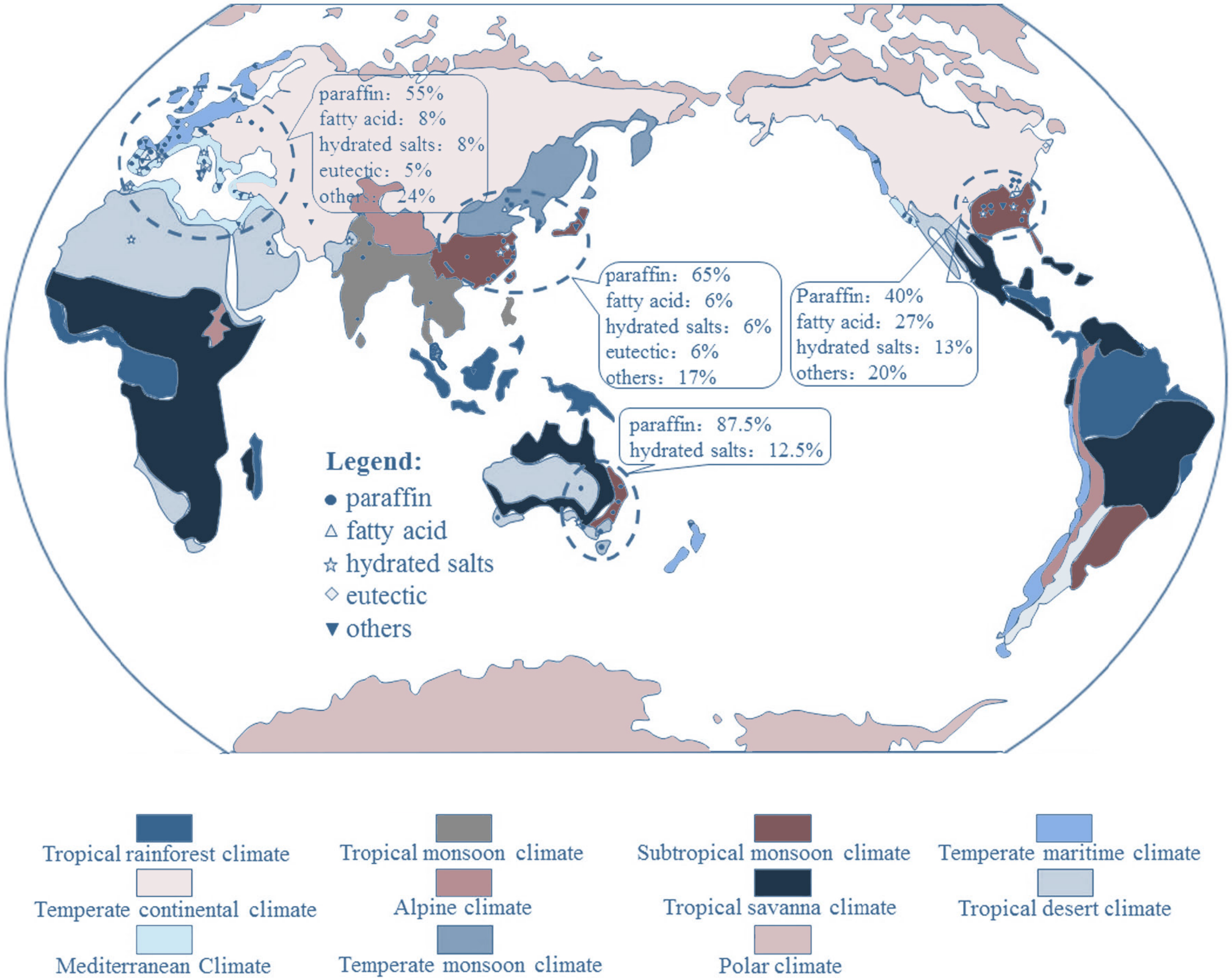


Figure 2.21: worldwide percentage of PCMs types applied in buildings
Source: edited from A review in phase change material application in building by Y. Cui et al., 2017, *Advances in Mechanical Engineering, 9*(6), p. 7 (https://doi.org/10.1177/ 167814017700828). Copyright 2017 by The Author(s)

2.5.3 PCMs incorporation in buildings

Phase Change Materials are incorporated in buildings with several methods, among which there are direct incorporation, immersion, encapsulation, and shape stabilization (Xiong et al., 2021).

Direct incorporation consists of the addition of PCMs in construction mixtures of concrete, mortar, or gypsum. Despite being a simple and low cost technique, the mechanical properties of the construction material are affected by the incorporated PCMs.

When a porous construction material is immersed in a container with the PCMs as liquid, it is called **immersion.** Both direct incorporation and immersion suffer leakage after being exposed to a certain number of cycles. For this reason, and for their undesirable influence on the mechanical properties of the construction materials, they are the least common incorporation methods.

With the **encapsulation** technique, PCMs are contained in shells, which differ in shape and size. The material of the capsule must improve the PCMs properties, thus be durable, corrosion resistant, and structurally and thermally stable. This method prevents the material from leakage and improves its thermal performance. However, it can affect its thermal conductivity and the time required for a phase change.

The most common encapsulation methods are macro-encapsulation and micro-encapsulation. When the container size has a thickness/ diameter larger than 1 cm, it is a **macro-encapsulation**. The technique is suitable for partitions and walls, where the capsules are commonly made of glass, polycarbonate, or aluminium (figure 2.22).

Conversely, the **micro-encapsulation** contains the PCMs in polymer micro-capsules, and therefore, improves its heat transfer. The capsules form a powder that is mixed with the construction material. The container diameter can be decreased even more to have a **nano-encapsulation**, which ensures greater thermal performance.

Finally, the **shape stabilization** incorporates the liquid PCMs into a supporting matrix via a vacuum impregnation technique. The material for the supporting matrix varies widely, from a porous material to polymers and nano-materials.

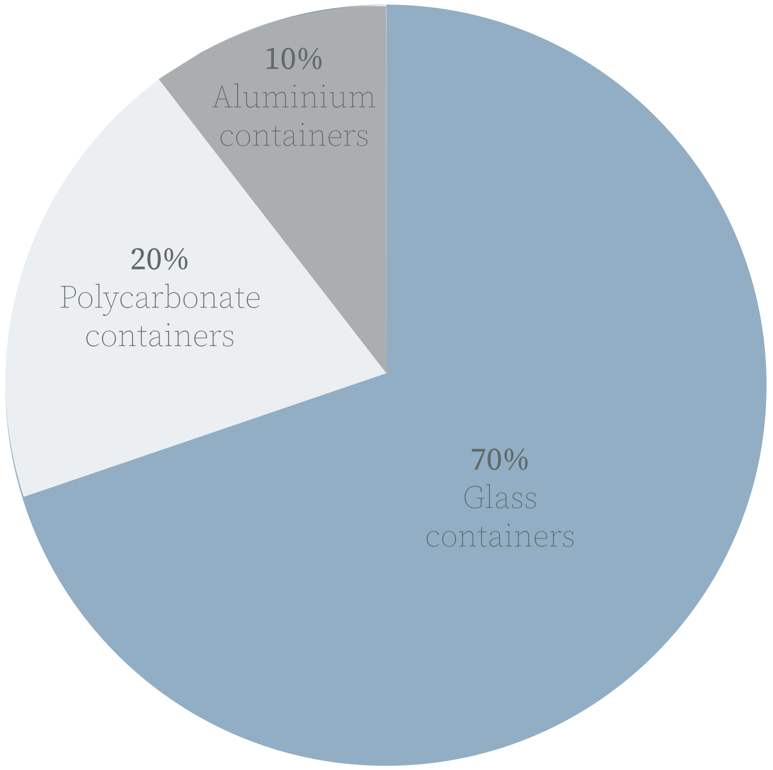
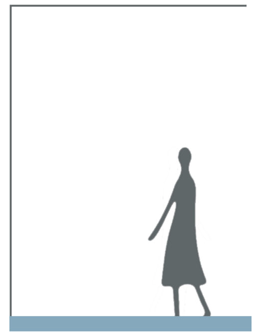


Figure 2.22: PCMs macro-encapsulation containers' materials
Source: edited from Phase Change Materials in Transparent Building Envelopes: A Strengths, Weakness, Opportunities and Threats (SWOT) Analysis by I. Vigna et al., 2018, *Energies, 11*(2018), p. 3 (https://doi.org/10.3390/en11010111). Copyright 2018 by the authors

2.5.4 PCMs applications

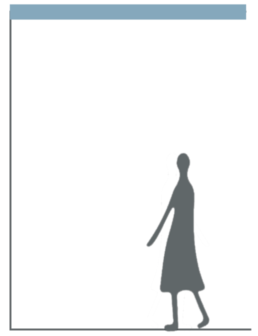
There are two systems in which phase change materials are integrated in buildings: active and passive. **Active thermal storage systems** (ATSS) require the addition of pumps or fans to transport heat, whereas **passive thermal storage systems** (PTSS) do not need any supplementary equipment to operate (Mehling et al., 2022).

The most common PCMs applications in buildings for latent heat thermal energy storage (LHTES) are described on the right. As these diagrams illustrate, PCMs are mainly utilized for opaque building components.



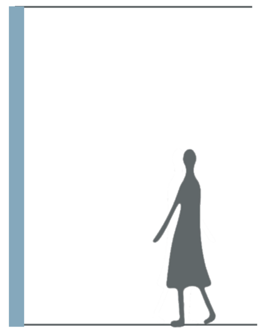
FLOOR HEATING

Commonly used as a heating system, hot air or hot water flows through pipes in the floor. The heat is released and transmitted on the upper floor by free convection, thereby heating the environment.



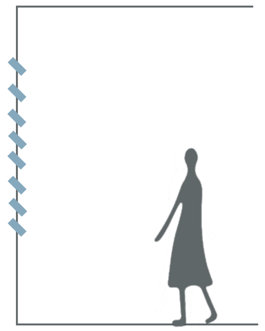
COOLING CEILING

Cold water flows through pipes placed on the ceiling to cool the space below by free convection.



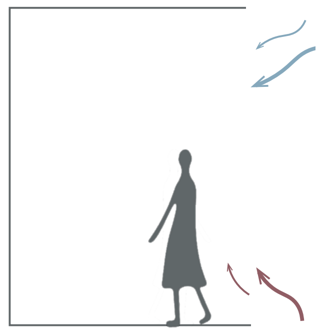
WALL

Phase change materials are integrated in the wall structure to increase the thermal inertia. The most common PCMs products are trombe walls, wallboards, and building blocks.



SHUTTERS

Known as shading systems, PCMs shutters are located either inside or outside the window, and work as energy buffers.



ENERGY STORAGE SYSTEM

A separate storage system contains hot/cold to heat, cool, or ventilate a space. The storage is connected to the technical equipment of the building.

The PCMs applications in transparent building components has grown in the last years. When PCMs is integrated into a transparent envelope, it increases the thermal inertia of the glazing system, thus improving its thermal efficiency. Indeed, because of their translucency when liquid, PCMs act as an extra layer of the building envelope.

Vigna et al. classify the integration of PCMs in three transparent building components (2018): glazing, shutters, and façade system. The products of the company Glass X are an example of PCMs integrated in glazing.

GlassX

GlassX AG is a company that offers PCMs products for the built environment. By integrating a translucent layer of 2.5 cm into glazing systems, their PCMs products are capable of absorbing heat similar to that of concrete walls. In particular, the layer acts as a shading system in the summer, thus preventing solar radiation to warm up the indoor space and maximizing the natural light (GlassX AG, 2022).

The company provides two products: GlassX store and GlassX crystal. **GlassX store** is a modular element specifically designed for curtain-wall constructions. It features a thin layer of PCMs, protected on both sides by glass plates. On the other hand, **GlassX crystal** is a façade element that combines the PCMs with a shading system and an insulation glazing.

Although these PCMs products are on sale, they are currently available only **on request**. Commonly, unique products are expensive, thus being affordable only for a small class of clients. Therefore, it is crucial to continue expanding knowledge and research in this field to make PCMs more widely accessible.

Several innovative applications of PCMs in building façade components have already been carried out, demonstrating their potential. Examples are the following case studies. The following case studies provide examples of these applications and showcase the benefits of PCMs in enhancing building performance.

Double Face 2.0

Double Face 2.0 is a project of Martin Tenpierik and Michela Turrin, professors at the Delft University of Technology (figure 2.23). The panel is a translucent trombe wall and is designed to enhance the downsides of traditional trombe walls. Indeed, the wall is translucent, light, dynamic, and suitable for both heating and cooling (Tenpierik et al., 2018).

The trombe wall was designed as a rotatable element in

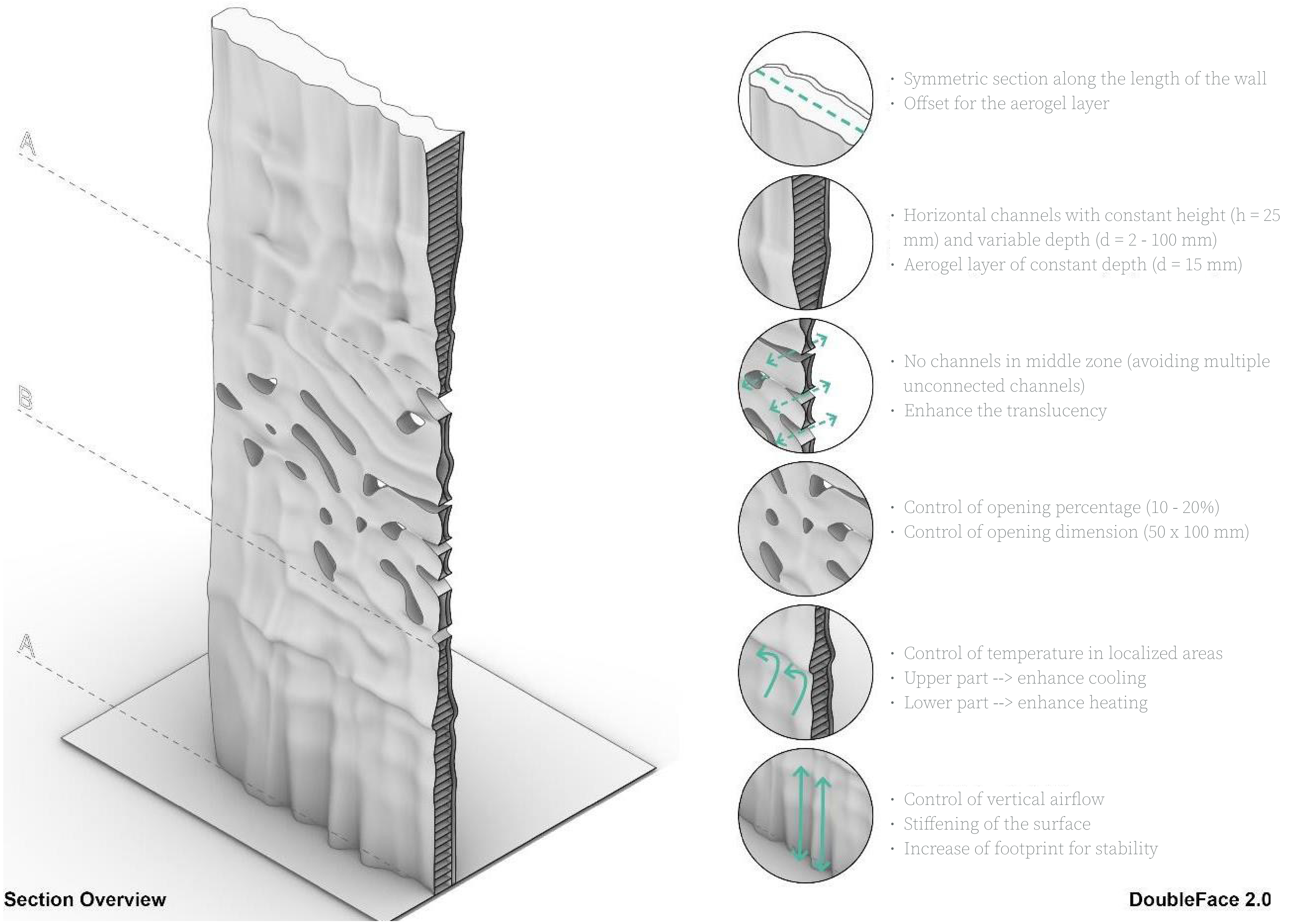


Figure 2.23: visualization and explanation of the Double Face 2.0 panel
Source: edited from *Double Face 2.0: A lightweight, adjustable, translucent Trombe wall* (p.152), by M. Tenpierik et al., 2018, TU Delft Repositories, (http://resolver.tudelft.nl/uuid:01e9d1d2-80a3-4974-a463-8c0d2b20b78d)

the horizontal direction. It consists of 2.5 cm of PCMs salt hydrates and 1 cm of aerogel as insulation. The layer of Phase Change Materials faces the window in winter to absorb the solar radiation during the day. At night time, the panel is rotated to release the thermal energy in the room. Conversely, in the cooling season, the PCMs are towards the indoor space to absorb the heat during the day. In the evening, the trombe wall is rotated to release the heat towards the façade.

The trombe wall was simulated in a Matlab model and in COMSOL Multiphysics. The software were utilized to optimize thermal performance and material durability of the PCMs. The panel was also designed to achieve a certain flexibility, while satisfying the visual requirements.

Thermal Morphology

Further research on Double Face 2.0 was carried out by Eve Farruggia. By working in both temperate and sub-temperate climate zones, the research analyses the impact of geometry in the thermal performance of a PCMs trombe wall panel. The aim is to investigate how a three-dimensional geometry can improve the thermal inertia of building envelopes to reduce their energy consumption (Farruggia, 2018).

The study is developed by modelling the geometry and simulating it in order to determine its effect on the efficiency of the trombe wall. By starting with thermal simulations of a flat panel (iterated in COMSOL), the geometry is step by step morphed by applying several design strategies in different scales: macro, meso, and micro.

The macro scale refers to the entire trombe wall and implies the thermal performance of the panel, the self-shaded area, and surface areas. Meso scale regards the layering of the trombe wall, its thickness, and the material used. While, the micro scale explores in a different level the thermal performance of the wall, self-shaded area, and surface area. An application of geometry is, for instance, the presence of protrusions, which can extend

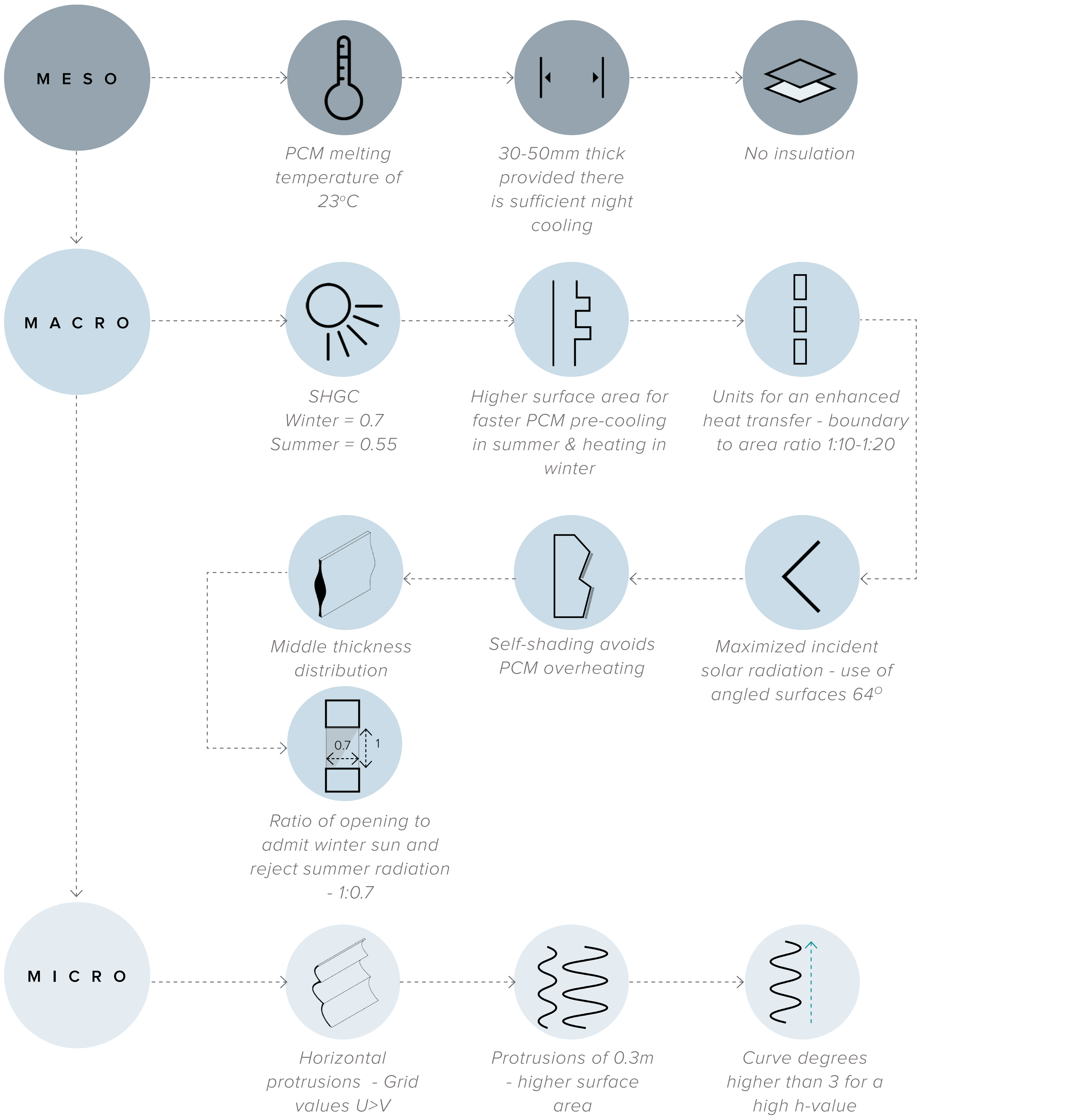


Figure 2.24: geometric guidelines for the design of a PCMs trombe wall in temperate climate
Source: adapted from Thermal Morphology: A Geometrically Optimized Trombe Wall (p.223), by E. G. Farruggia, 2018, TU Delft Repository, (http://resolver.tudelft.nl/uuid:0ad5f3cc-a5e9-45c0-a37e-75e139713409)

the total area but also affect the self-shaded area and the trombe wall performance.

As a whole, the study and analysis of the three geometric scales led to the identification of common features for both climatic areas of the study (figure 2.24). The geometric trends were transformed into design guidelines, suitable for the design of a PCMs trombe wall in each context.

PCM Façade

If the previous projects focused on the application of inorganic salt-hydrates as PCM materials, the PCM Façade project takes a different approach by utilizing organic paraffin. Figure 2.25 illustrates how paraffin becomes translucent only when in liquid state. The research primarily focuses on the modelling methods that enable the control, evaluation, and estimation of phenomena in open thermodynamic systems (Royal Danish Academy, 2018).

Figure 2.25: phase transition of paraffin in PCM façade project
Source: from *Phase Change Material (PCM) Facade*, by Royal Danish Academy, 2018 (https://bit.ly/3Vn4WiY)

The thermal simulations were carried out in parametric software by assuming a steady-state condition, which provides the necessary boundaries to study the heat transfer. This approach is a finite element analysis, which is suitable to work at multiple scales and various subjects. However, the approach operates only for analytic design methods and carries out imprecise thermal simulations because of its limited capacity to handle dynamic flow information. For this reason, the research investigated modelling approaches to work for complex and generative design methods with a dynamic system.

The initial phase of the research involved an analysis of existing architectural modelling approaches. This step was suitable to understand the current state of the field. Several prototypes were developed and utilized to measure and study the thermal behaviour of the PCM Façade system. The achieved information was beneficial to make a virtual model, consisting of simulations and predictions from the data. The result was a modelling platform that predicts heat transfer of new and complex geometries.

2.6 Conclusion

The literature research has been beneficial as basis to carry out the design stages of this study. The theoretical knowledge was investigated to understand concepts related to computational design, daylight, and thermal energy storage systems, trombe walls, and PCMs. The acquired information allows the researcher to critically evaluate the application of these topics in the built environment. Specifically, the theoretical framework consisted of a description of the subject and its way of functioning to, thereafter, explore some reference case studies. Indeed, analysing the work of experts is an efficacious approach to understand the possible applications of these themes.

Following the same principle, notorious building designs developed parametrically were investigated. The research identified some common features in these buildings, which belong to the passive design strategies and can be recognized as architectural trends. More importantly, the mentioned buildings were designed by applying computational design approaches. For this reason, the case studies could be inspiring for the next steps of this research, where daylight simulations will be generated in Grasshopper.

A part of the chapter has explored the theoretical knowledge of the building envelope and relationship with thermal performance and daylight admittance. Firstly, the building envelope is researched to understand its roles and typologies. Subsequently, the thermal inertia and daylight of the façade are briefly explored. In particular, the sub-chapter focuses on the comparison between heavyweight and lightweight structures to demonstrate that the benefiting wall typology depends on the specific building properties.

Considering that the thermal performance relates with multiple factors and might be increasingly required due to the rise in temperature, the use of building components, such as PCMs trombe walls, have great potential. Indeed, trombe walls act as passive heating and cooling systems, thus heating up or cooling down the indoor space. Moreover, when trombe walls are combined with PCMs, their translucency allows the natural light to enter the building.

PCMs trombe walls could, in the future, enhance the thermal inertia of buildings by adapting to multiple situations. On the other hand, their translucency and cooling function could limit the risk of overheating in hot months. Indeed, the building component can act as a shading device to block the direct solar radiation in summer months, while cooling the indoor space.

For these reasons, the last part of the literature research focuses on PCMs and their integration with trombe walls. Notably, great research has already been carried out. Despite these projects focus on the great performance of PCMs products as thermal storage systems, their application is still very limited. This issue is in line with the aim of this research, which envisions the development of strategies for expanding the use of

PCMs trombe walls in the built environment.

03. Preliminary research

This phase defines all the necessary aspects to perform a digital design exploration, which consists of simulations that test the thermal performance and light transmittance of the trombe wall. Specifically, the chapter classifies two categories of requirements: **contextual** and **design** related.

The first consist on the selection of a climate zone, building function, household typology, and room variables. Moreover, a reference case study is selected to set the boundary conditions for the simulations. The second category begins with the definition of the materials that constitute the trombe wall. The previous research outcomes on PCMs trombe walls are also converted into design guidelines, suitable for the further wall design.

As a whole, the chapter investigates the following sub research question: *which room variables are considered to achieve a modular PCMs trombe wall that could adapt to various buildings ?*

3.1 Contextual requirements

The following sub-chapter focuses on the definition of factors that outline the environment where the PCMs trombe wall is located. Firstly, a climate zone is selected and analysed. Secondly, the focus is on the building level. Indeed, the building must fulfil certain criteria to achieve a proper performance of the wall. Subsequently, the Dutch requirements for dwellings are delineated while the household typologies are analysed. A case study is also selected to set the boundary conditions for the design exploration of the trombe wall. Finally, the room variables are defined to consider multiple room configurations.

Figure 3.1: map of the temperate climate zone
Source: adapted from *Map with world climate zones vector image*, by VectorStock, http://bit.ly/3Xh36Be

3.1.1 Climate zone

The selection of a climate zone was achieved by considering where phase change materials properly work. Indeed, Cui et al. (2017) state that PCMs are applicable in only two ranges of latitudes: 25 °- 60 ° on the north latitude, and 25 °- 40 ° on the south latitude. In particular, the climate zones in these latitudes correspond to temperate and sub-tropical regions.

From these two possible climate zones, the selected area is the **temperate climate**. The temperate zones are in the middle latitudes, between the polar and sub-tropical regions (figure 3.1), where day length and climatic conditions depend on the season (Meteoblue, n.d.). Indeed, winters are characterized by frequent rain and cold temperatures that can reach 0 °C, while summer months are warm and have long days.

The temperate climate depends also on the latitude, sea currents, wind directions, and altitudes. It is therefore necessary to define a location to properly analyse the climatic conditions for the simulations. Consequently, a case study was selected and is located in **Amsterdam**. Amsterdam is considered by the Köppen classification with an **oceanic climate**, characterized by cool summers and mild winters (Wikipedia, 2023). Surrounded on three sides by water bodies, the winter temperature hardly ever falls below -5 °C. Conversely, the warmest month is August with temperatures that can reach up to 30 °C. As a whole, the annual mean temperature is of 10 °C.

The graph 3.2 illustrates the monthly dry bulb temperature of Amsterdam in relation to the comfort zone temperature. Observing it, it is discernible that the outdoor temperature is frequently not comfortable for humans. Therefore, the use of heating or cooling systems is required. In particular, cooling is needed in the summer months, while heating is operated in autumn, winter, and spring seasons.

The temperature is affected also by global horizontal, direct normal, and diffuse radiations. In particular, the solar radiation is more intense in spring and, especially, in summer months, while being low in autumn and winter. This relates also with the illumination range which can reach 8 to 10 hours of sunshine in summer. On the contrary, November, December, and January have less than 4 hours of light per day (Energy Design Tools, 2023).

Amsterdam has a yearly sky cover of 65%, with December and January having the highest frequency of sky cover. The city is characterized by frequent rainfalls throughout the year with an average annual precipitation of 838 mm (Wikipedia, 2023). Moreover, Amsterdam has an annual wind velocity around 18 km/h because of its vicinity to the North Sea. More information can be found in the graphs in the Appendix.

3.1.2 Building requirements

The research aims to design a modular trombe wall that is adaptable to multiple buildings. It is, therefore, necessary to define the prerequisites that the building needs to follow to guarantee a proper performance of the wall. The building requirements are listed as follows.

- Located in a **temperate climate zone**: considering that each climate zone has different climatic conditions, they require diverse building designs and strategies. Hence, a building component designed for a temperate area could not work properly if located in another zone.

- **Residential function**: each building function has different thermal and daylight requirements. For instance, offices need to operate heating systems during the day, while residences are heated up at evening and night times, when people come back from their daily routine.

- **Existing building**: the PCMs trombe wall is designed to be integrated in existing buildings. Therefore, the trombe wall is not developed to be integrated during the design process of a building.

- **Energy-optimized building**: the trombe wall is designed for buildings that were developed parametrically by optimizing their energy performance. In particular, optimizations provide the best solution from

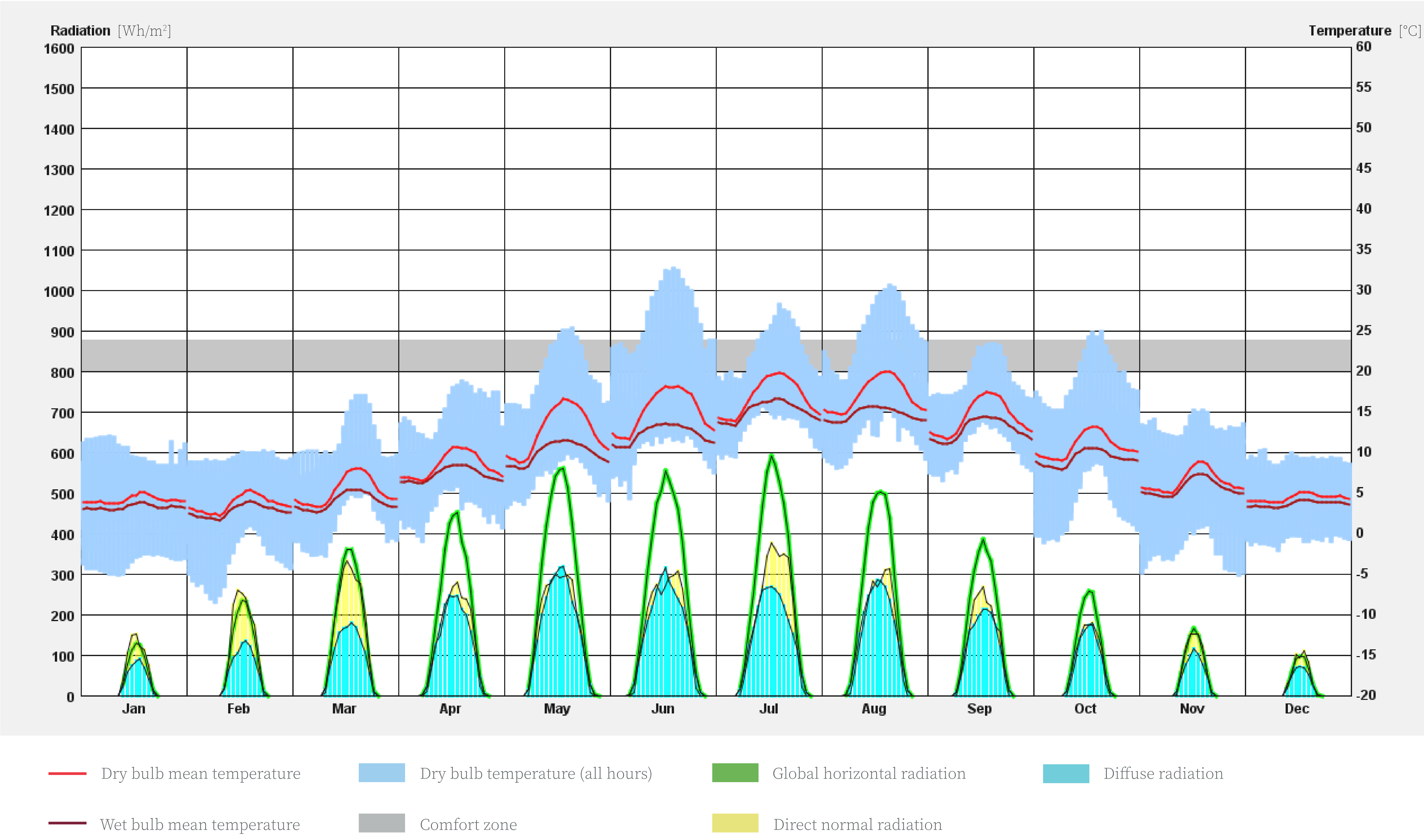


Figure 3.2: monthly diurnal averages in Amsterdam
Source: from *Climate Consultant 6.0*, by Energy Design Tools, 2023

a set of criteria or constraints. However, when one of these criteria changes - such as the building function or the average temperature on Earth - the optimization might not work properly anymore (Glassman and Reinhart, 2013). Considering the rapidity in which the temperature is rising due to climate change, this could lead to building energy inefficiencies. Therefore, adaptable passive heating and cooling systems, such as PCMs trombe walls, assume great potential. If the research considers energy-optimized buildings as scenario to develop the design, the trombe wall could, in the future, be integrated in buildings that were not optimized to be energy-efficient.

- **Room height:** the trombe wall is designed for rooms that have a minimum height of 3 m.
- **Façade orientation:** the PCMs trombe wall is located in the living room and should have a glazed façade oriented south, east, or west. Indeed, the solar radiation in rooms facing north is very limited, thus it is not considered as a possible solution.
- **Shading system:** the building must have a shading system, otherwise the trombe wall could overheat in the summer months. This is avoidable with either adjustable sun protection systems, permanent horizontal elements on the south, or fixed vertical shading devices for east and west orientations. Attention must be given to permanent shading devices, which should limit the solar radiation during the summer months, while maximizing it in winter periods.
- **Natural or mechanical ventilation:** the cavity between the façade and the trombe wall should have a controlled ventilation system to activate in the evenings when the wall is in cooling mode. Indeed, the trombe wall cools down the indoor space by absorbing the heat through the day. In the evening, the heat is released in the cavity, where a ventilation system must refresh the air of the cavity. The airflow can be either natural with an openable window or vent placed in the façade, or mechanical.
- **Single skin façade system**: building envelopes consist of a single or double skin façade system (Knaack, et al., 2007). The single skin façade corresponds to the traditional envelope and is composed of only one layer. Whether opaque, it performs proper acoustic and thermal insulation. Conversely, the transparent single skin system has limited insulating performances. As a consequence, a predominantly transparent building envelope may be more effective with a double skin system. Consisting of two layers with a cavity in-between, the double façade limits the heat transmissions while reducing the external sound. Since the trombe wall design differs depending on the type of façade, a single skin system is selected for this research.
- **Window properties:** the façade should have windows that are fully glazed in height and have a minimum width of 1.40 m. This guarantees that the trombe wall is fully in front of the façade. Indeed, whenever the PCMs face an opaque wall, they cannot work properly. Moreover, the glazing should not control the solar radiation that enters the indoor space. Therefore, reflective glass is not suitable to achieve a proper performance of the trombe wall (AL Windows, n.d.).

Building typology: dwellings

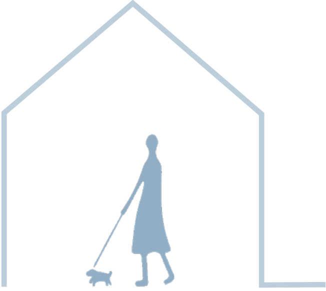
The trombe wall is designed for a residential function. Since each typology has different purposes, the building requirements might differ as well. Moreover, it should be reminded that each country has its housing standard, which could lead to inconsistencies. The focus of the research is, indeed, on the 2012 Dutch Building Decree (**Bouwbesluit**). The standard contains the regulations for construction, use, and demolition of residential buildings in the Netherlands. The housing requirements of the Building Decree are listed as follows (Donner, 2012):

- Thermal comfort: rooms should have a temperature between 19 - 22 °C.
- Room area: living rooms and bedrooms should have an area of at least 11 m^2 for new buildings, and 7.5 m^2 for the existing ones. Living rooms need a minimum width of 3 m for new buildings, which is decreased to 2.4 m for existing buildings.
- Ceiling height: the minimum height is of 2.6 m.
- Daylight: the kitchen and habitable rooms must have openings of at least 1/10 of the floor area.
- Heat transmission coefficient: it should not exceed 2.2 W/ m^2 K.
- Airflow: the staying area, which consists of the entire house, should have a ventilation of at least 0.9 dm^3/s per m^2 of floor area. Whereas, the staying spaces (corresponding to each room) should have a ventilation system that guarantees at least 0.7 dm^3/s per m^2 of floor area. The ventilation requirement reaches the 21 dm^3/s if a cooking appliance is installed. Independently from the specific situation, the air speed should be maximum 0.2 m/s.

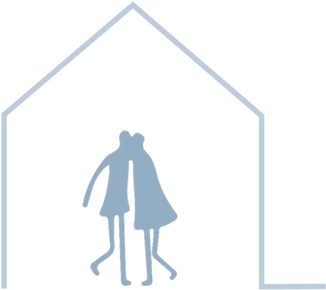
Household types

Guerra-Santin & Silvester (2016) conducted a research to develop household profiles that predict the Dutch energy demands. The results of this study have outlined that the heating requirements depend on the occupancy profiles and occupant behaviour. The following analysis is based on the Netherlands and might not correspond to the occupant behaviours of other countries. Indeed, a comparison between researches carried out in different countries demonstrated that each country might have diverse lifestyles.

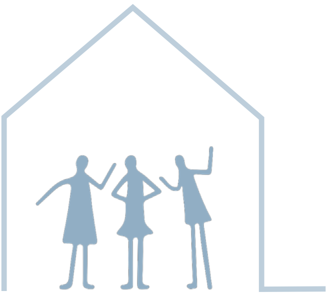
The identified household types are seven - 1 adult, 2 adults, 3 adults, 1 parent with children, nuclear family, 1 senior, and 2 seniors. The subsequent sections provide an overview of each typology.



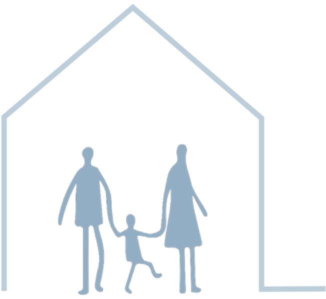
1 ADULT
A person who lives alone frequently stays in a studio. Commonly, this house consists of two rooms: a bathroom and a living space containing kitchen, living room, and bedroom. Studios host people of any age, from young adults to elderly people.



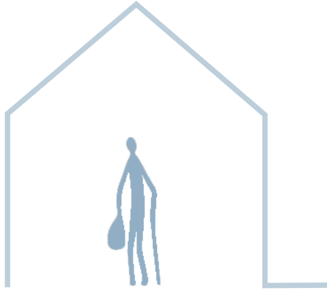
COUPLE
When a couple lives together, the house usually has one bedroom, kitchen, living room, and bathroom. Considering that the median age in the Netherlands is 43.3, the majority of people in Dutch residences live in couple or in a family with children (Worldometer, 2023).



3 ADULTS
Young adults might live in a house with other people of their age. This type of residence could be a student house, having multiple bedrooms, and shared kitchen, living room, and bathroom.



1/ 2 PARENTS WITH CHILDREN
If the family has children, there will be more bedrooms and the living spaces might be bigger as well. During weekdays children have school until 15:00 in the Netherlands (Van Mameren, 2022). Hence, the house might be occupied earlier than if only workers live in it.



1/2 SENIORS
Elderly people might spend the most of the day at home. They might also be weaker than younger people, thus having a higher heating and cooling requirement.

As the analysis outlined, each household typology has different occupancy and heating demands. The only consistency was discovered in the ventilation behaviour, which appears to be similar in each category. However, when the heating system is on, the single parent household ventilates more frequently.

Figure 3.3 illustrates the energy consumption of each group. It is observable that seniors and nuclear families have a higher energy requirement. Indeed, they might spend more time at home, heat up the house for more hours, and set the thermostat to higher temperatures. Conversely, single adults reach the minimum thermal demand since they tend to spend less time in the house.

As a whole, the analysis has shown that households with three adults, nuclear families and two seniors tend to heat more frequently the service rooms, as kitchen and bathroom, than the bedrooms. Moreover, nuclear families and one or two seniors are the household groups that spend more time at home. Indeed, families come back home between 15:00 and 18:00, time when children finish school. Whereas, elderly people frequently stay at home also during the morning.

Habitat Royale

For the purpose of this research, a case study that represents the chosen building typology has been selected. This simplifies the design process of the PCMs trombe wall, as a precise scenario is defined for the simulations.

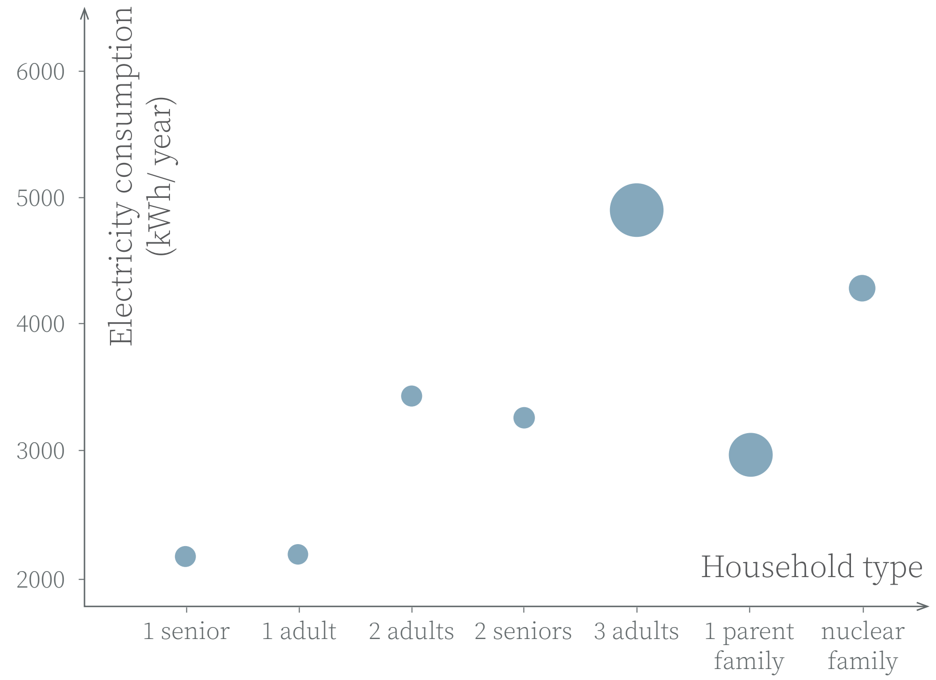


Figure 3.3: yearly electricity consumption of household type
Source: from Development of Dutch occupancy and heating profiles for building simulation, by O. Guerra-Santin and S. Silvester, 2016, *Building Research & Information, 45*(4), p. 401 (https://doi.org/10.1080/09613218.2016.1160563)

The reference is Habitat Royale, a residential complex located at Beatrixpark in Amsterdam. The project, designed by Mecanoo, ARUP, and BOOM Landscape, won the tender. The construction is expected to start in 2024 (Weessies, 2022).

The building is situated in the park to foster human-nature connection. Its function is residential except for the plinth, which serves as a “hybrid zone” between public and private space (Mecanoo, 2022). The complex is composed of 94 apartments with staggered floors and undulated balconies. The dwellings offer six housing typologies based on the household types. Moreover, they can be expanded horizontally and vertically to flexibly fulfil the users’ needs.

The fully glazed façade and the rounded floor plans guarantee a view of the landscape to the residents. Each house has at least 20 m^2 of outdoor space with greenery, which is also present on the façade and roof. Indeed, BOOM Landscape has integrated enough nature to double the greenery already existent in the area where the building will be constructed (figure 3.4). As a whole, Habitat Royale will absorb 33% more CO_2 than its materials emit during construction. This is accomplished by doubling the natural landscape and producing more energy than the building utilizes.

The building's geometry was optimized to reduce its energy demand, primarily through the implementation of passive design strategies. One notable approach is the variation in façade design based on orientation (KondorWessels, n.d.). Specifically, the north side of the building is enclosed and features tall plants, serving as a natural barrier. On the east and west sides, medium-height greenery is incorporated into the design. This vegetation contributes to passive cooling and shading during the warmer months when the plants are at their fullest. Conversely, during the winter season, when the plants become bare, more sunlight can enter through the façade. For the south façade, extensive overhangs and the presence of short plants offer a shading system.

3.1.3 Room variables

Since each room has diverse characteristics, an adaptable trombe wall needs to fit multiple scenarios. These differences are defined as '**room variables**' and are restricted to four elements. Indeed, given the numerous factors that influence the building energy demand, developing a design that can adapt to any environment would be limiting. For this reason, the research envisions to reach only an overview on how the room configurations affect the thermal and daylight demand of buildings. The room variables are described as follows (figure 3.5).

FAÇADE ORIENTATION

The PCMs trombe wall is located in front of the façade. When a room has two glazed façades with different

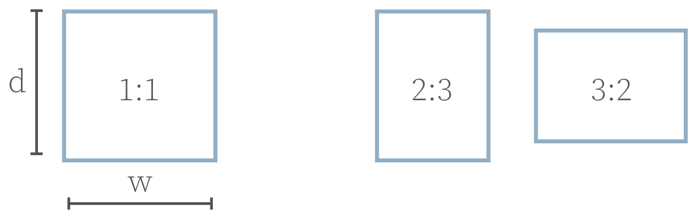
Figure 3.4: graphical views of Habitat Royale
Source: from *Team with Mecanoo and BOOM Landscape designs residential building at Beatrixpark Zuidas*, by R. Weessies, 2022, Architectenweb (http://bit.ly/3DEPV5k)

orientation, the trombe wall should be placed on the side that receives more solar radiation. To understand which orientation suits best the trombe wall in relation with the other room variables, three orientations will be investigated. Indeed, since the sunlight from the north is considered insufficient to satisfy the trombe wall requirements, the orientations are east, south, and west.

ROOM AREA

The area of the room is considered as a variable since the thermal and light demands are influenced by its dimension. The room will be investigated for two widths and two depths. The values are selected by calculating a ratio between them. Indeed, this approach guarantees to analyse the impact of the room area on the thermal and light requirements of buildings, regardless the exact metrics used in this research.

The ratios considered are 1:1, 3:2, and 2:3.Before defining the numbers, the Bouwbesluit was consulted. In particular, the Ducth standard expects that living rooms and bedrooms have a minimum area of 7.5 m^2 in existing buildings (Donner, 2012). The requirement is higher for new buildings, where at least 11 m^2 are expected. Moreover, the rooms must have a minimum width of 3 m, which is decreased to 2.4 m for existing buildings.



WINDOW-TO-WALL RATIO

The window-to-wall ratio defines the percentage of wall area covered by fenestration. Dwellings have a value between 20% and 80%, where the common ratio is 30 - 40%. Ideally, buildings should have high WWR to receive as much natural light as possible. Conversely, the thermal inertia is guaranteed with opaque structures, such as walls, floor, and ceiling. For this reason, it is important to look for a balance between them.

SUN-SHADING SYSTEM

Sun protections control the sunlight that enters the building. This is significantly important in hot months, when the PCMs risk to overheat by reaching their maximum operational temperature. On the other hand, the direct sunlight should be maximized throughout the winter to reduce the heating demand due to solar gains. A shading system on the glazed façade is, therefore, required to prevent the PCMs from overheating.

Sun protections are of multiple typologies. They can be located outside or inside, be permanent or adjustable, and be constituted of various materials and colours. However, each type of system has a different result in terms of shading effect. The impact of a sun-shading device can be calculated with various methods. This research will focus on the SHGC of glass with permanent external shading devices.

Calculation of SHGC

Since the simulations will be performed in an environment similar to the case study, the shading systems refer to Habitat Royale. In particular, the residential complex has overhangs of various length on the south, and trees of medium height on east and west integrated with a shorter overhang.

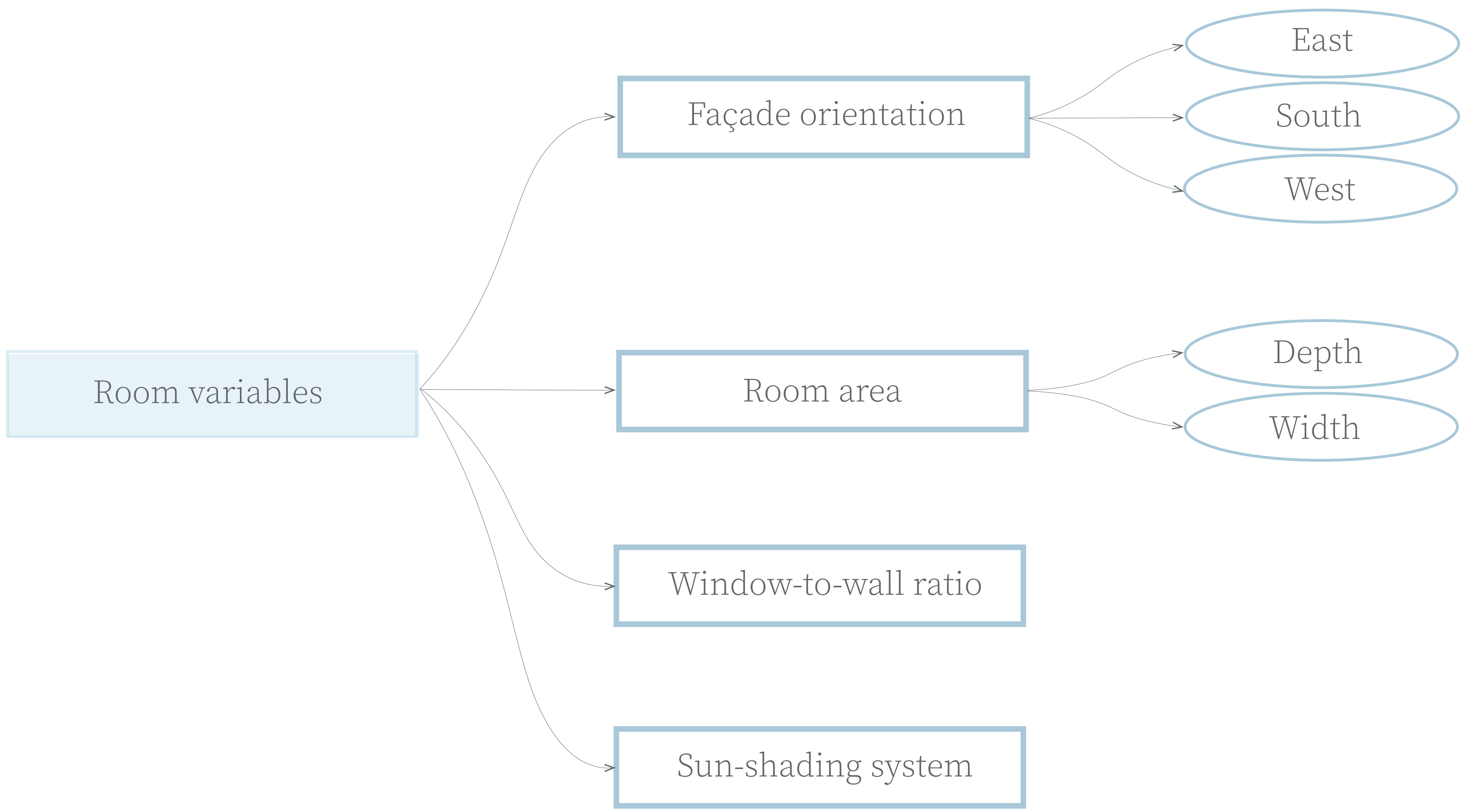


Figure 3.5: flowchart of room parameters

Since there is no specific Dutch standard that indicates a method to investigate the SHGC, an approximate calculation is carried out in Grasshopper. Specifically, a virtual model is used to estimate the incident radiation by the *LB Incident Radiation* tool.

Two calculations are performed for each shading system on the longest day of the year, the 21st of June. Indeed, the incident radiation is estimated with and without the sun protection to calculate a ratio that is, then, multiplied by the SHGC of the glazing system.

The overhang on the south orientation is analysed for three different lenghts. The measures are determined by calculating the Projection Factor (figure 3.6), where the length of the overhang is divided by the window height. This corresponds to the ratios of 1:2, 1:1, and 3:2.

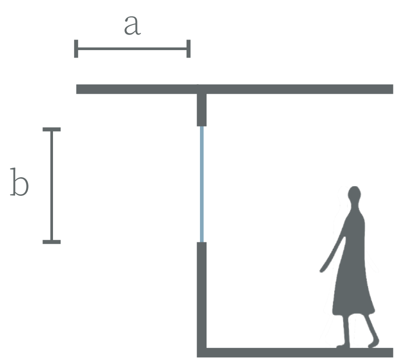


Figure 3.6: calculation of Projection Factor

The following calculations illustrate the estimation of the SHGC for the three overhangs in the summer months. The simulations are performed in a virtual model, whose glazed façade has a WWR of 80%. The room has a volume of 9 · 6 · 3 m (w · d · h).

- Overhang length (1:2)
  radiation with overhang: 1.45 kWh/m^2
  radiation without overhang: 2.1 kWh/m^2
  ratio (overhang/ no overhang): 0.7
  SHGC: 0.5 x 0.7 = 0.35

- Overhang length (1:1)
  radiation with overhang: 1.2 kWh/m^2
  radiation without overhang: 2.1 kWh/m^2
  ratio: 0.57
  SHGC: 0.5 x 0.57 = 0.28

- Overhang length (1:2)
  radiation with overhang: 1 kWh/m^2
  radiation without overhang: 2.1 kWh/m^2
  ratio: 0.47
  SHGC: 0.5 x 0.47 = 0.23

Once the SHGC has been calculated for the south orientation, the focus is on the east and west, where the shading system is composed of a shorter overhang and seasonal plants.

Since the sun protection must have the same shading effect for any room area and the WWR, the research will focus on vertical fins rather than greenery. A Grasshopper script is developed to consider an equal shading effect, independently on the room configuration.

Specifically, the vertical fins are developed to have a length and number of fins dependent on the window width. The fins on the east orientation have a length of 0.5 m and are situated at a distance of 0.5 m between each other. Conversely, a length and distance of 0.375 m characterize the vertical fins on the west side. Indeed, the inclination of the solar radiation is different between the two orientations.

The calculations for east and west are performed for both summer and winter to make sure that the solar radiation is only blocked in summer days. In particular, the shading effect in winter has been estimated for the longest day of the year, the 21st of December.

The following calculations illustrate the estimation process of the SHGC for the east side, and the impact of the shading system in the winter. Figure 3.7 compares the incident radiation in the GH model.

- Small room, summer situation
  radiation with fins: 2 kWh/m^2
  radiation without fins: 2.8 kWh/m^2
  ratio (fins/ no fins): 0.7
  SHGC: 0.5 * 0.7 = 0.35

  Large room, summer situation
  radiation with fins: 1.9 kWh/m^2
  radiation without fins: 2.8 kWh/m^2
  ratio (fins/ no fins): 0.67
  SHGC: 0.5 * 0.67 = 0.3

- Small room, winter situation
  radiation with fins: 0.48 kWh/m^2
  radiation without fins: 0.57 kWh/m^2
  ratio (fins/ no fins): 0.84

  Large room, winter situation
  radiation with fins: 0.47 kWh/m^2
  radiation without fins: 0.57 kWh/m^2
  ratio (fins/ no fins): 0.82

A proper sun protection should not block any solar radiation in winter, thus the ratio should close to 1. Since the research has estimated a value of 0.80, the vertical fins slightly limit the sunlight also in winter.

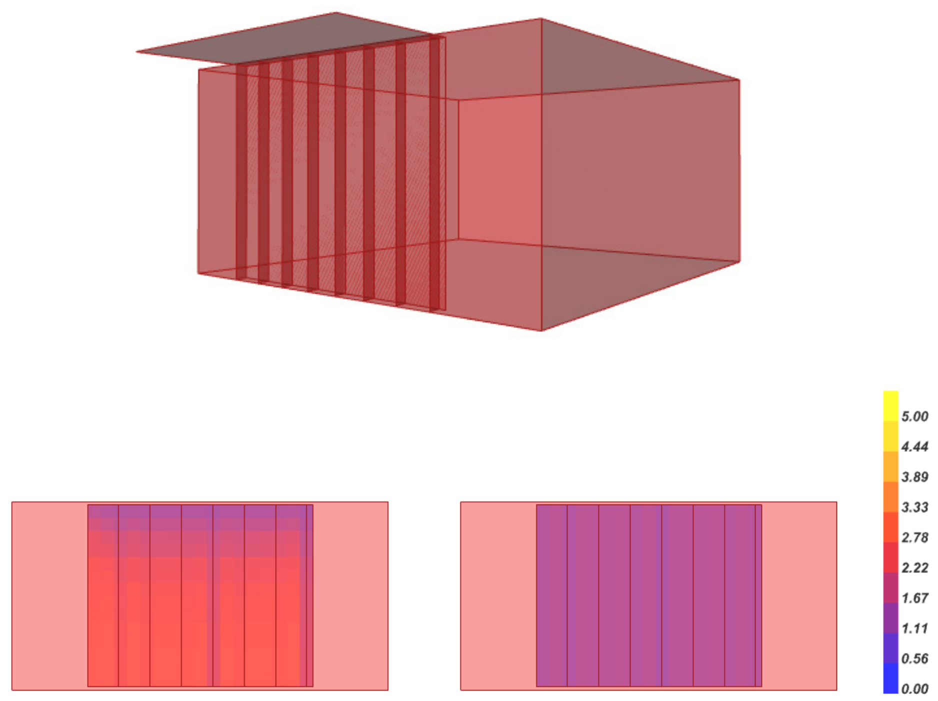


Figure 3.7: GH calculation of the incident radiation in summer (left) and winter (right)

3.2 Design requirements

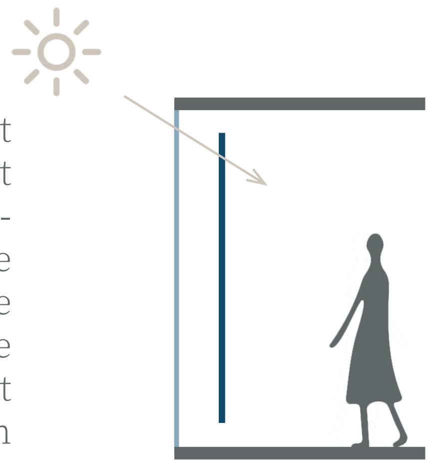
Once the contextual requirements are selected, the focus is on the design level. The materials composing the trombe wall are defined and their properties are analysed. Subsequently, the results of previous research are illustrated to provide the design guidelines of the building component. Finally, the design criteria are highlighted to ensure that the design focuses on the proper aspects. As a whole, the requirements make the theoretical basis for the further development on the PCMs trombe wall design.

3.2.1 Design guidelines

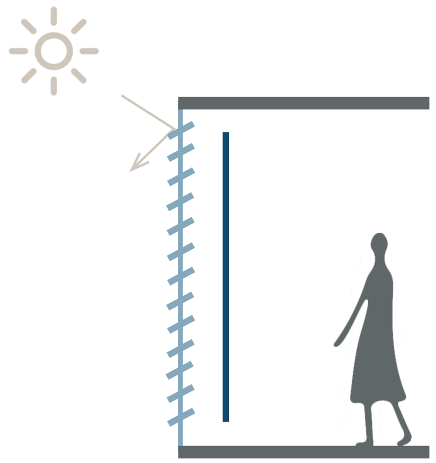
To properly design a PCMs trombe wall with salt hydrates, the outcomes of previous research have been summarized in design guidelines, divided in macro and micro scale. Therefore, the projects Double Face 2.0 of Tenpierik et al. (2018) and Thermal Morphology of Farruggia (2018) will guide the design of the PCMs trombe wall with salt hydrates. The studies were carried out for the temperate climate of the Netherlands. Hence, they might not be suitable for another climate zone.

MACRO SCALE

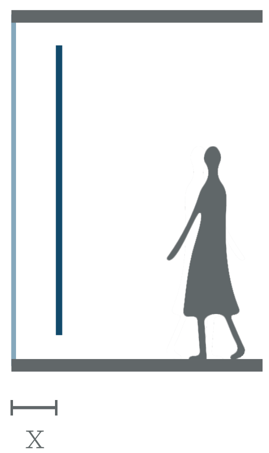
Daylight
To guarantee visual comfort while maximizing the heat storage capacities, openings should not exceed the 10% of the wall area of the panel. Moreover, they are preferred in the middle part and should be not taller than 50 mm.



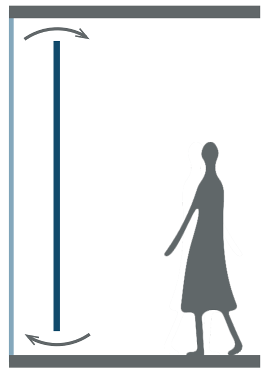
Shading system
Hot months might overheat the PCMs, which should not reach their maximum operation temperature. An ideal ratio for openings in Amsterdam is 1:0.7, where 1 refers to the window height and 0.7 to the opening depth. Indeed, this ratio minimizes the solar radiation in summer months, while maximizing it in the winter periods. When the ratio is not applicable, shading devices can also prevent overheating. Examples of suitable sun protections are adjustable systems, extruded roofs, vertical fins, and the presence of biodiversity. Alternatively, the trombe wall surface can be protruded three-dimensionally to create self-shading.



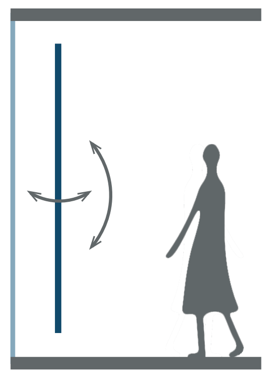
Cavity width
The trombe wall should be placed in front of the façade at a distance between 4.7 and 30 cm. This cavity width range enhances the panel performance by acting as a greenhouse. However, it is suggested to make a solar study to ascertain that the wall is close enough to the façade to avoid sun-shading. Moreover, if a rotation is required, the space needed to properly rotate should be taken into account.



Ventilation gaps
The traditional trombe wall is constituted of vents, consisting of gaps at the top and bottom of the wall. Since the vents enhance the conduction, they are not required when the panel is designed with an insulation layer and a rotating mechanisms. In this way, the trombe wall can entirely store the heat to warm up the room later. Simultaneously, in summer days the vents transmit the hot air acquired from the façade to the indoor space.

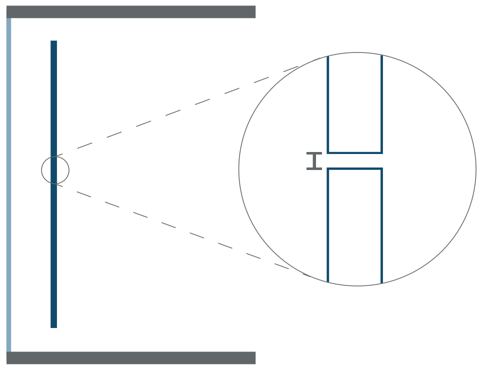


Adjustability
Whenever the trombe wall has an insulation layer on one side, it is more effective to design a panel with a rotating mechanisms. This guarantees a proper functioning for both heating and cooling requirements. In particular, it is suggested to consider a vertical rotation when using salt hydrates as PCMs. This avoids incongruent melting, thus guaranteeing a proper performance. The rotating mechanism functions differently if the rotation involves the single pieces or the entire trombe wall.

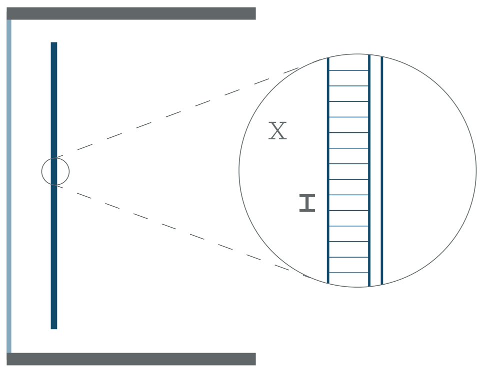


MICRO SCALE

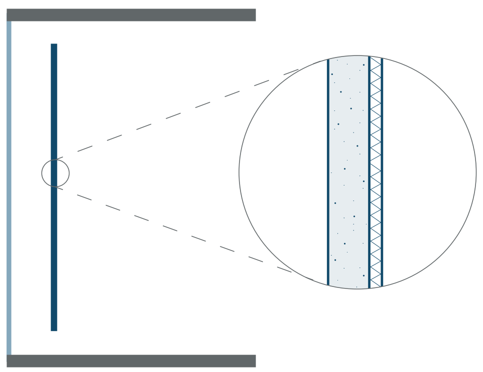
Spacing distance:
If the trombe wall is composed of multiple pieces, the pieces should be assembled at a precise distance between each other. Indeed, a narrow spacing blocks the air flow, whilst a wide spacing decreases the heat transfer.



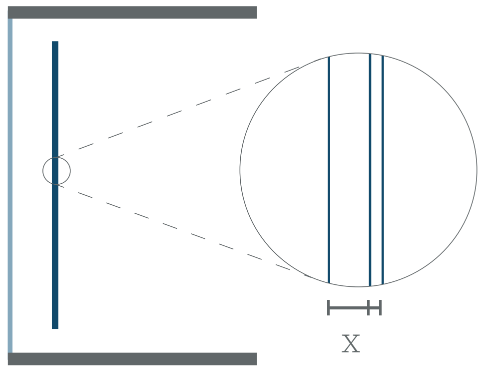
Internal subdivision:
Since PCMs do not melt congruently throughout the entire height of the wall, horizontal channels are suggested. These small units guarantee a better performance of the PCMs, which can heat up and cool down more quickly. In particular, the horizontal channels should have a height of 20/ 25 mm and a depth between 2 and 100 mm. In close presence of openings, channels might be not useful.



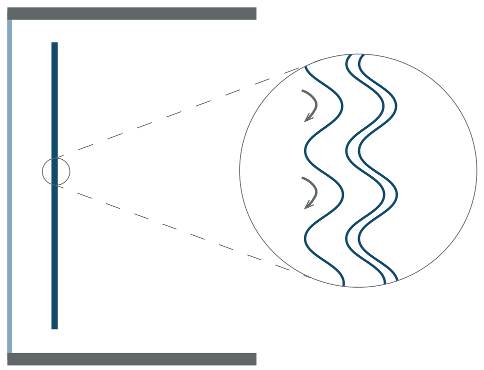
Layering
The trombe wall can be composed of a PCMs layer of variable thickness and an insulation layer of about 10 mm. To guarantee translucency, the insulation material can be aerogel.



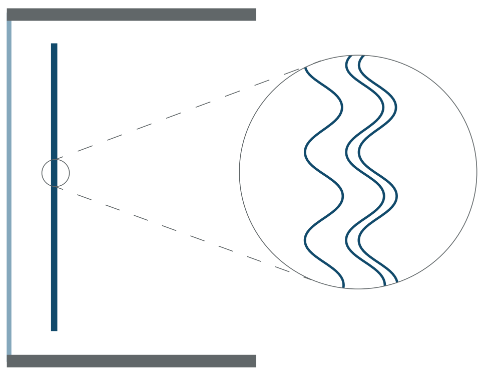
Thickness
Commonly, thicker walls heat up slowly, thus enhancing their thermal performance. However, they also need greater cooling to discharge at night. For this reason, it is suggested a PCMs layer with a thickness between 25 and 30 mm. The trombe wall could also have a variance in thickness, being thicker in the middle area. Indeed, this part is the most exposed to solar radiation.



Heat transfer coefficient
For a greater heat transfer, surface protrusions should be smooth. Indeed, air does not flow fluidly with unsmooth surfaces, where it partly remains in the corners. Moreover, the curve degree of the surface should be higher than 3 ° to increase the heat transfer coefficient.



Three-dimensional surface:
Protrusions increase the surface area of the trombe wall, which enables to achieve a greater performance. It is suggested to design protrusions of at least 100 mm and test if they create self-shading. In order to balance the thermal efficiency of the wall for cooling and heating purposes, the protrusions should be designed horizontally. The surfaces can be oriented towards the winter sun to maximize the incident solar radiation (angled surfaces of 64° are a great solution).



3.2.2 Materials choice

Cui et al. suggest the properties to consider when selecting the PCMs typology (2017). The main characteristics re are four and they are melting temperature, thermal conductivity, latent heat of fusion, and density in solid and liquid phases.

Indeed, the selected material should have an adequate melting temperature for the desired **operating temperature**, which corresponds to the human comfort temperature of an indoor space. Regarding thermal conductivity, the higher it is, the better the thermal energy efficiency is. The **latent heat of fusion** indicates the necessary amount of material to store a certain quantity of energy. This means that a higher value of latent heat of fusion requires a smaller quantity of material. Lastly, a higher density represents a minor volume occupied by the PCMs.

Another important factor is the **thermal stability** of the material (Zhou et al., 2012). Needing to undergo many cycles, PCMs should have a long lifetime of their thermal properties. Paraffins are generally known for being more thermal stable than salt hydrates. Indeed, hydrated salts risk to quickly loose their performances due to their incogruent melting, where the salts sink at the bottom.

As a whole, both paraffins and salt hydrates are suitable for building applications. If, on the one hand, paraffins are cyclically more stable, they are flammable and have low thermal conductivity. Conversely, salt hydrates have higher thermal conductivity, are translucent in both phases, and non-flammable. However, they might deteriorate quickly.

From the analysis of previous research and the compar-

PARAFFINS

pros

- Large temperature range
- Congruent melting
- Long lifetime
- No segregation
- Freeze without much supercooling
- High heat of fusion
- Chemically stable
- Safe and non-reactive

cons

- Low thermal conductivity
- Low volumetric latent heat storage capacity
- Flammable
- Large volume expansion
- Transparent only when liquid

SALT HYDRATES

pros

- High thermal conductivity
- High volumetric latent heat storage capacity
- Non-flammable
- Low volume change
- Low cost
- Safe
- Transparent when solid and liquid

cons

- Incongruent melting
- Supercooling
- Corrosion
- Uncertain long term reliability

Figure 3.8: comparison of paraffins and salt hydrates
Source: edited from Review on thermal energy storage with phase change materials (PCMs) in building applications, by D. Zhou et al., 2012, *Applied Energy, 92*(2012), p.599 (https://doi.org/10.1016/j.apenergy.2011.08.025

ison of properties of paraffins and salt hydrates (figure 3.8), it can be concluded that both materials are performing for building purposes. It is, however, necessary to apply strategies that can improve their drawbacks.

Salt hydrates

The type of PCMs selected for this research is salt hydrates. Nevertheless their great advantages in terms of thermal and visual comfort, attention must be given to their durability. Indeed, salts might separate from the mixture and sink at the bottom. Previous projects researched strategies that might solve the issue, as a vertical rotation that mixes again the material (Tenpierik et al., 2018).

Once the material is selected, its properties must be defined. Indeed, there is a variety of offers on the market for the same material, depending on its melting temperature and heat storage capacity. An example is the German company Rubitherm, which supplies a multitude of salt hydrates from a melting area of - 52 °C to 90 °C (Rubitherm, n.d.).

The project Double Face 2.0 suggests PCMs with a melting/freezing temperature around 23 - 25 °C for trombe wall applications in the Netherlands (Tenpierik et al., 2018). Rubitherm offers two products with these range of melting temperature: SP24E and SP25E2 (Rubitherm, n.d.). However, the enthalpy for the phase transitions of SP24E occurs only when the temperature is at 23 - 24 °C. Conversely, SP25E2 has a more gradual melting and solidification process. Therefore, the selected salt hydrate is **SP25E2**. Figure 3.9 illustrates its properties.

Insulating material

The addition of an insulation material on one side of the trombe wall limits the heat transfers of the wall. When combined with a rotation system, the wall is, indeed, capable of storing and releasing the heat only on the side

SP25E2

Salt hydrates
Inorganic PCMs

24 - 26 Melting area [°C]	**24 - 23** Congealing area [°C]	**180** Heat storage capacity [kj / kg]
2 Specific heat capacity [kj/kg · k]	**~ 1.6** Density solid [kg / l]	**~ 1.5** Density liquid [kg / l]
~ 6 Volume expansion [%]	**~ 0.5** Heat conductivity [W/ m · k]	**45** Max. operational temperature [°C]
Yes Encapsulation requirement	**50** Encapsulation min. volume [ml]	**2 - 3** Limited supercooling [K]

Figure 3.9: properties of chosen PCM (technical sheet in Appendix)
Source: edited from *SP25E2*, by Rubitherm, n.d., http://bit.ly/3wQiNDW

constituted by PCMs (Tenpierik et al., 2018). This minimizes the heat losses of the panel, thus enhancing its thermal performance.

A great insulating material is **Lumira aerogel LA1000**, applied in the Double Face 2.0 project (Tenpierik et al., 2018). The material has greater thermal properties than the usual building insulation products like mineral wool, fibreglass, and rockwool. Indeed, aerogel has a thermal conductivity of 0.019 [W/m·K] at 20 °C (Appendix) (Cabot, n.d.). Moreover, Lumira LA1000 has a translucency of 93% per thickness [cm], which enhances the light transmission. As a result, this aerogel type is ideal for meeting the translucent properties of the chosen PCM.

PCMs encapsulation material

The PCMs and insulating material selected consist of small particles. To ensure that the trombe wall is translucent, the particles are incorporated in a transparent shell. This technique is known as macro-encapsulation and protects the material from any external entity, thus improving its durability (Xiong et al., 2021). Moreover, the utilization of a shell avoids the leakage problem, which affects the PCMs.

The material selected for the shell consists of **PETG** (Polyethylene Terephthalate Glycol). This thermoplastic polyester is durable, affordable and very resistant. The name might remind the PET. If PET is composed of only two monomers, PETG includes also glycol. This enhances PETG's shock resistance, its ability to withstand high temperatures, and UV resistance (the technical data sheet is illustrated in the Appendix).

3.2.3 Design criteria

The PCMs trombe wall must fulfil specific criteria to reach its final design. The criteria are described in figure 3.10 and define the necessary characteristics for the building component to meet the design requirements.

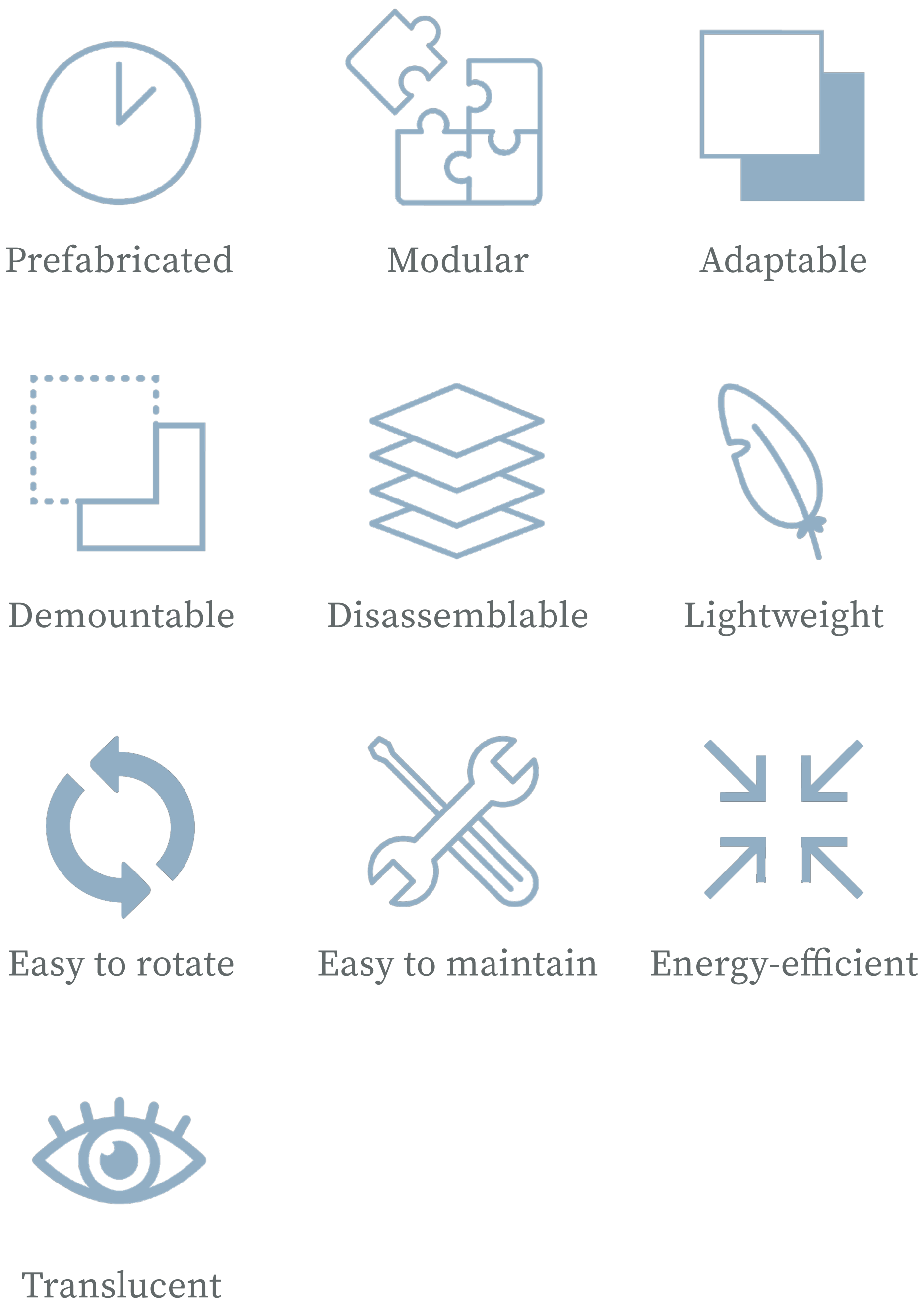


Figure 3.10: design criteria

As a whole, the criteria ensure that the trombe wall is reusable in the future by adapting to the user's needs and being easy to assemble/ disassemble. On the other hand, strategies that extend its lifetime, as being adjustable and easy to rotate and maintain, are applied. Finally, the wall must be energy-efficient and translucent to guarantee a proper thermal and visual performance.

3.3 Conclusion

The preliminary research has defined the boundary conditions, necessary to iterate the simulations. The PCMs trombe wall has not been designed yet, as the simulations will test a flat panel. However, this chapter developed the design both contextually and conceptually.

Indeed, the context has now been determined, and corresponds to energy-efficient residential buildings located in the Netherlands. On the other hand, specific building requirements have been defined to narrow the scope of the research. Moreover, a case study identifies the environment where the PCMs trombe wall is simulated.

The second part of the chapter focuses on the conceptual design of the wall. In particular, the design guidelines, trombe wall materials, and design criteria are selected to set the boundary conditions for the final appearance of the trombe wall.

As a whole, a sub research question has been investigated during the preliminary research phase: *which room variables are considered to achieve a modular PCMs trombe wall that could adapt to various buildings ?* Its answer is discussed in Chapter 7.

04. Digital design exploration

This phase consists in the iteration of simulations regarding the thermal performance and light transmittance of the trombe wall. The development of a strategic approach is required to manage the great amount of data, achieved by the simulations. Once the methodology is defined, the chapter describes the virtual models designed in MatLab for the thermal simulations, and in Grasshopper for the daylight simulations. A detailed explanation states how the variables are defined in each virtual model. Subsequently, an analysis of the results investigates the data management of each software. The digital design exploration phase is finished with a short conclusion, while the results of the simulations are evaluated in Chapter 5.

4.1 Digital design methodology

This chapter investigates the PCMs trombe wall design regarding its thermal performance and light transmittance. To correctly explore both topics, a precise methodology is developed. Figure 4.1 illustrates the workflow that guides the entire digital design phase.

Firstly, the values of each variable are defined, making sure that they have equal values and order for both software. Subsequently, a flat PCMs trombe wall is simulated for all the parameters. Specifically, two thermal simulations are iterated in MatLab/Simulink to investigate both heating and cooling demands. In parallel, another simulation is carried out in Grasshopper to explore how the spatial daylight autonomy is affected by the presence of a PCMs trombe wall.

Subsequently, the outputs of the simulations are evaluated to find the best values of each variable while guaranteeing proper thermal performance and daylight admittance. An Excel table, containing all the data from the simulations, is uploaded in ModeFrontier. Specifically, the software allows to plot various graph typologies for the post-processing analysis.

Finally, it is developed a workflow that ensures an interaction between an ideal customer and the product. By importing the Excel table in Grasshopper, the user is able to define its suitable design configuration by determining the values of each variable. Once all the parameters are selected, the worflow illustrates the thermal and daylight performance achieved by the trombe wall with that room configuration.

4.1.1 Assumptions

Performing simulations in virtual models has some limitations, which require the definition of assumptions. Indeed, buildings in real life are influenced by a variety of factors that cannot be fully reproduced in virtual models.

For instance, the room is designed to perfectly face east, south, or west, thus it is not tested for any angle in-between two orientations. Conversely to the case study, the glazed façade consists of a flat surface instead of a curved building envelope. This approach simplifies the simulation process, but it should be considered that curved façades have a slightly different impact on the building solar and energy performance.

The MatLab/Simulink model consists of adiabatic walls, floor, and ceiling, except for the glazed façade. The construction materials are selected to determine their properties, which, however, could differ for another building. Additionally, the ventilation and infiltration rate are defined by fixed values to approximatively reproduce the real situation.

On the other hand, the daylight simulations assume that there are no obstructions between the aperture and the direct solar radiation. An example of obstructions is the presence of buildings in the surroundings, whose shading effect is not taken into account in the virtual model. Moreover, the *HB Annual Daylight* enables to estimate the annual daylight with a weather data that does not refer to any specific climatic condition, as being sunny or cloudy.

Moreover, both software simulate the PCMs trombe wall as a flat panel with no apertures. This simplifies the investigation of its thermal performance and light transmittance. Therefore, the results do not refer to a trombe wall with 3D protrusions, which would result in different outcomes. Indeed, the improvement of these aspects could either improve or even worsen the wall performance. Hence, a specific analysis for each design is required.

Lastly, the PCMs are simulated as materials that properly work, thus not presenting any of their disadvantages as supercooling and phase separation.

4.1.2 Limitations

The digital design exploration is a phase where some decisions depend on certain limitations. Indeed, only a few software allow to properly simulate the thermal performance of PCMs and they are Design Builder, MatLab, and COMSOL. However, since each of them is suitable for different objectives, aiming to test the PCMs at multiple scales of detail might require the application of more than one software.

For instance, Design Builder and MatLab are suitable to perform simulations at room level, while COMSOL is beneficial for smaller scales. However, Design Builder does not offer the possibility to iterate a panel with a rotation system. Therefore, the software applied to thermally simulate the PCMs trombe wall of this research is MatLab.

Once the software has been selected, the number of inputs is defined. Having a great amount of variables might require days to perform the simulations. Therefore, a first boundary is determined and corresponds to a maximum of 2 days to carry out the entire simulation.

If the PCMs trombe wall is simulated in MatLab for its thermal performance, another software is required to test its light transmittance. The selected software is Grasshopper, where the PCMs can be reproduced by defining its light transmittance.

The application of two different software that cannot be linked together requires the iteration of separate simulations. Indeed, ModeFrontier could have integrated the simulation process if the MatLab model was developed differently. Indeed, the model does not allow to integrate it in ModeFrontier without making great modifications. Therefore, the methodology expects the use of two software that are iterated separately but in parallel.

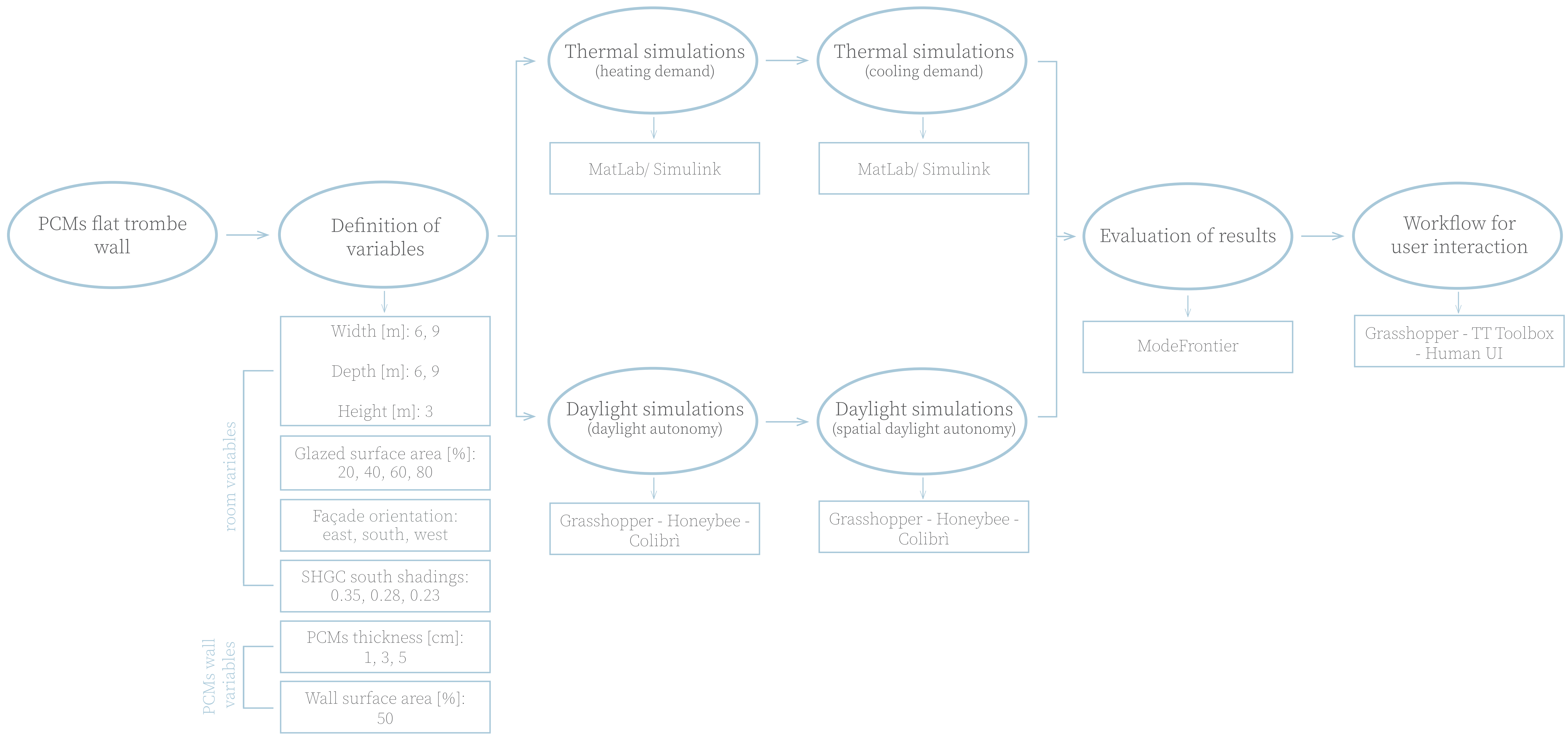


Figure 4.1: workflow of digital design exploration phase

4.2 Thermal simulations

The thermal simulations are performed in MatLab/Simulink by using a model previously developed for the Double Face 2.0 project. In particular, the virtual model requires the application of two software since the inputs are defined in MatLab, but are tested in Simulink. Detailed information on the development and functioning of the model can be found in the Master's thesis report of Jeroen Van Unen (2019).

The model was designed to calculate the heating and cooling demands of a building with and without the presence of a PCMs trombe wall. The high level of detail of inputs enables to define the climate zone, building function, façade properties, and trombe wall properties.

The adaptability of the model to perform multiple scenarios, has shown great potentiality to be integrated in this research process. However, the model was designed to automatically call MatLab in Simulink during updates and simulations. This property is called 'Callbacks' and does not allow to automate the simulation process. Hence, the virtual model is suitable only to manually perform a simulation per variable.

The model has been previously integrated by Jeroen van Unen with a Master file developed in MatLab to automate the simulation process. The file contains the variables tested for multiple values and allows to automatically iterate various simulations. This research will perform the thermal simulations in MatLab/Simulink by using the Master file, as figure 4.2 illustrates.

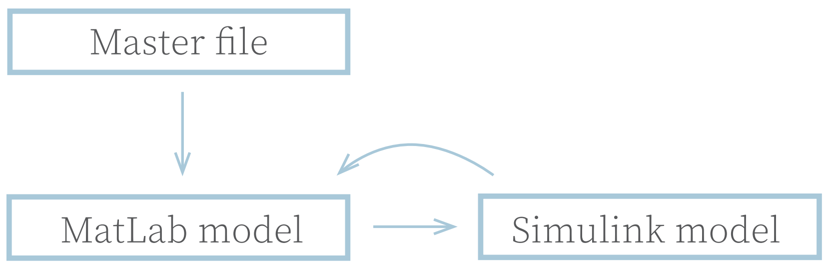


Figure 4.2: workflow of the thermal simulations process

4.2.1 Variables

This research has increased the number of variables of the Master file to include all the parameters tested in the study (table X in the Appendix). The inputs regard either the room or the trombe wall and are listed in figure 4.1. As observable, the parameters are tested in both software in the same order and for equal values.

The MatLab/Simulink model has been implemented to include all the variables (table IX in the Appendix). The following paragraph describes these changes by highlighting the difference with the existing model. Figure 4.3 illustrates the code containing each variable (*letter_matrix*) and their values.

```
MASTER FILE

%Y variables
A_matrix   = [6;9];
B_matrix   = [6;9];
C_matrix   = [3];
D_matrix   = [1; 2; 3; 4];
E_matrix   = [5];
F_matrix   = [90; 180; 270];
G_matrix   = [5];
H_matrix   = [1];
I_matrix   = [1;2;3];

% X variables
M_matrix   = [1;2;3];
N_matrix   = [1]
```

Figure 4.3: variables of the Master file

ROOM WIDTH (A_matrix)
In the previous Master file, the room width [m] was equal to the room depth. Whereas, it is now considered as a variable to test different values.

ROOM DEPTH (B_matrix)
The room depth [m] was already considered as a parameter of the Master file. Its value is suitable for the calculation of the room area and room volume in the MatLab model (table IX in the Appendix).

```
room.volume = room.depth * room.width * room.height;
room.area = room.depth * room.width
```

ROOM HEIGHT (C_matrix)
The research considers a constant height of 3 m. However, the room height is included in the variables to enable future users to investigate multiple values.

GLAZED SURFACE AREA (D_matrix)
The window-to-wall ratio is defined by a number from 1 to 4, corresponding to a percentage of the glazed area. Since the Master file does not accept numbers lower than 1, the four numbers are linked to the MatLab model, which contains the following percentages of WWR (table IX in the Appendix):

```
WWR_values = [
0.2
0.4
0.6
0.8];
```

Previously, the Master file investigated the WWR by defining the vents opening as the height difference between the room and window. On the contrary, this research determines the vents dimension as the following height difference: room.height - 0.3 [m]. This enhances the adaptability of the MatLab model by simplifying its operation for future users. Indeed, the calculation automatically estimates the value from the room height.

GLAZING TYPOLOGY (E_matrix)
The existing Master file explored the effect of diverse types of glazing systems. In particular, it included a double clear glazing, double coated glazing, triple clear

glazing, and triple coated glazing (Van Unen, 2019). For each glazing system the U-value, SHGC, and transmission coefficient were defined.

Although these values are still included in the MatLab model, the research tests only a glazing system added in the list. The typology corresponds to a triple clear glazing system with a U-value of 1 $W/m^2 \cdot k$, as the glazing system of the case study (table IX in the Appendix).

FAÇADE ORIENTATION (F_matrix)
The glazed façade is tested for three different orientations. The virtual model has three opaque walls and a transparent façade, which always corresponds to orien1. Therefore, 90° indicates the east orientation, 180° the south side, and 270° the west.

CLIMATE ZONE (G_matrix)
The previous model was developed to test multiple climate zones. However, this research analyses only the temperate climate of Amsterdam. Hence, the value is considered as invariant. The climate data of the Netherlands is defined by the standard NEN5060_2018.

BUILDING METHOD (H_matrix)
The building method corresponds to the typology of building envelope, which can be lightweight or heavyweight. In particular, this project defines the façade of the case study, consisting of a lightweight structure.

SHADING SYSTEM (I_matrix)
The research aims to investigate the effect of different sun protections by their SHGC. The focus is on overhangs and vertical fins, depending on the orientation. The calculation of the SHGC is described in Chapter 3.

An if statement is applied in the MatLab/Simulink model to differentiate the SHGC of shadings facing south (180°) and east/ west (90°/ 270°). Specifically, the research explores various SHGCs for the south orientation (SHGC_shading), while it considers a constant value on the east and west (SHGC = 0.30). The if statement is illustrated as follows (table IX in the Appendix).

```
if orientation == 180
   SHGC_orien1_SB = SHGC_shading;
else
   SHGC_orien1_SB = 0.30;
end
```

THICKNESS OF PCMs LAYER (M_matrix)
The previous Master file included parameters only regarding the building location and room configuration. However, this research considers the volume of the PCMs trombe wall as a variable. In particular, the volume is divided in thickness and surface area. The two inputs are defined as X variables, while the parameters previously analysed, relating to the room, belong to the Y variables. The division of inputs in X and Y is explained in the sub-chapter 4.2.3.

The addition of the thickness as a parameter is reached by the following approach. Since the MatLab model already integrated the PCMs thickness as an input (panel_pcm.d), a link between the two files has been created. Indeed, the thickness is defined in the Master file as PCM_thickness, which is connected to the MatLab model with an equality between the existing input and the new thickness value (panel_pcm.d = PCM_thickness;). This allows to modify the dimension of the PCMs layer from the Master file.

PCMs TROMBE WALL SURFACE AREA (N_matrix)
The trombe wall surface area is a value dependent on the WWR. Indeed, the WWR is determined as a percentage of the orien1 wall area, while the trombe wall area is calculated as a percentage of the glazed area only. This process guarantees that the trombe wall has always a smaller area than the window. Even if the research has developed the surface area as a variable, it tests, in the end, a constant area of 50%.

4.2.2 Trombe wall function

The trombe wall can act as a **heating** or **cooling** device, depending on the room temperature and user's needs. The two functions are tested in two different MatLab models that are set up for a diverse time period. Indeed, the heating demand is calculated from September 30th to April 30th. While the cooling requirement is estimated from April 30th to September 30th.

The development of two models enables to properly simulate the rotation system of the trombe wall. In particular, the PCMs face the room from 18.00 to 8.00 when in heating mode. Conversely, they are oriented towards the room from 8.00 to 18.00 if the trombe wall is working as a cooling device.

Another difference is in the settings of the sun-shading system. Indeed, the sun-blinds operate within a certain operative temperature range, below and above which they are inactive. The same criteria is developed for the incoming solar radiative power threshold, below which no sun protections are used.

Different values are defined for these settings, depending on the season. Indeed, the trombe wall should receive direct sunlight during winter, thus not being shaded. Whereas, a shading system should avoid the PCMs to overheat when in cooling mode. Therefore, the sun protection is developed to be operated only during summer. The following settings illustrate the values applied for both models (table IX in the Appendix).

Heating mode:
```
ThresholdBoff =   99   (temp. below which sunblinds are not used)
ThresholdBon =   100   (temp. above which sunblinds are used)
ThresholdBIsol = 1000  (incoming solar radiation below which sun
                        blinds are not used)
```

Cooling mode:
```
ThresholdBoff =  0     (temp. below which sunblinds are not used)
ThresholdBon =   1     (temp. above which sunblinds are used)
ThresholdBIsol = 0     (incoming solar radiation below which sun
                        blinds are not used)
```

4.2.3 Analysis of the results

Before iterating the entire simulation, a first try was carried out by simulating 2 values for the room width, room depth, and the PCMs layer thickness. The attempt is suitable to get an estimation of the time required for the entire simulation and to analyse the location of each variable in the table of results.

The Master file is composed of Y and X variables. In particular, the room inputs belong to the first group, while the PCMs parameters correspond to the X inputs. As figure 4.4 shows, the number of rows depends on the Y variables, whereas the columns are affected by the X variables.

Number of columns: X variables

	1	2
1	54.37	53.04
2	67.61	64.38
3	88.53	85.34
4	107.7	101.6

Number of rows: Y variables

Figure 4.4: table of results - function of Y and X variables

The number of possible combinations with 6 values is 8. Considering that one design configuration is tested in less than 1 minute, a simulation with 8 values iterates in about 8 minutes. Figure 4.5 describes the order in which the values are performed. Specifically, MatLab simulates all the values of a, subsequently the values belonging to b, and finally, the values of c.

	1	2
1	$a_1 * b_1 * c_1$	$a_1 * b_1 * c_2$
2	$a_2 * b_1 * c_1$	$a_2 * b_1 * c_2$
3	$a_1 * b_2 * c_1$	$a_1 * b_2 * c_2$
4	$a_2 * b_2 * c_1$	$a_2 * b_2 * c_2$

X variables:
$A = a_1, a_2$
$B = b_1, b_2$

Y variables:
$C = c_1, c_2$

Figure 4.5: table of results - understanding the values

4.3 Daylight simulations

In parallel with the thermal simulations, a daylight simulation is performed in Grasshopper (GH) by using Honeybee. The Grasshopper model, depicted in the Appendix, is developed by the parametric design approach, where the inputs are defined by **sliders** to easily test multiple values.

The virtual model consists of a room with three opaque walls, one glazed façade, a roof, and a floor. The PCMs trombe wall is located in front of the glazed façade in the indoor space at a distance of 11 cm.

Once the model in Grasshopper is completed, the geographical location is integrated by Ladybug tools. **Ladybug** (LB) is a Grasshopper plug-in, suitable to visualize weather data as the sun path (Ladybug Tools, n.d.). It is applied to perform radiation simulations as well as shadow studies. Moreover, it includes various plug-ins as Honeybee, Dragonfly, and Butterfly, allowing the user to simulate also other aspects.

For instance, **Honeybee** (HB) performs daylight simulations by using Radiance. On the other hand, it evaluates the energy performance of a space if used with EnergyPlus/OpenStudio. Honeybee requires the conversion of the GH model in order to iterate the simulations. In particular, the HB model classifies the different building components as walls, apertures, sun-shading systems, etc.

Since Honeybee is able to simulate only one scenario per time, the addition of another tool is necessary to automate the daylight simulations. Indeed, **Colibrì** iterates the simulation process by automatically running all the combinations within the inputs. Moreover, once the simulations are performed, Colibrì saves the results in a desktop folder. Specifically, the folder contains an Excel table with all the results and an image for each combination of inputs.

The methodology of the daylight simulations is described in figure 4.6. As a whole, the GH model is developed by defining different properties than the MatLab/Simulink model. Indeed, the two models have a diverse focus, as explained in the sub-chapter 4.3.1.

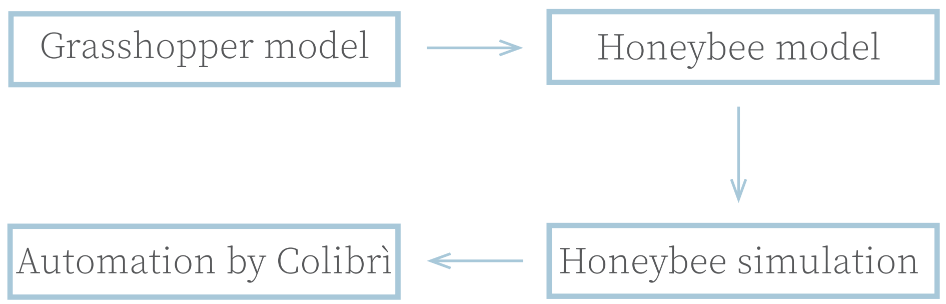


Figure 4.6: workflow describing the daylight simulations process

4.3.1 Variables

ROOM DIMENSIONS
Two variables are defined to determine the room area and they correspond to the room width and depth. Conversely, the room height is defined as a constant value of 3 m.

GLAZED SURFACE AREA
The glazed façade is tested for various WWR. In particular, the ratio depends on the area of the façade, estimated by the room width and height. Since the PCMs properly work only with direct solar radiation, the trombe wall is designed with a full height. Hence, the window must have the same height, achieved by dividing the glazed area with the room height.

The glazed façade does not have a full height in the MatLab/Simulink model. Indeed, the thermal performance of the trombe wall is affected by the WWR and not by the precise location of the window in the wall, as for the daylight simulations.

CLIMATE ZONE
The climate zone corresponds to Amsterdam. This is defined in Grasshopper by the weather data available in the EnergyPlus website. Specifically, the climatic conditions are integrated in the GH model by connecting the data to *LB Download Weather*, attached to *LB Import EPW* tool.

FAÇADE ORIENTATION
Once the climate zone is imported in the Grasshopper model, the *LB SunPath* tool is used to define the orientation of the glazed façade. The tool considers 0° for the south orientation, 90° for the west side, and 270° for east.

However, the façade orientation must have the same order of MatLab: east (90°), south (180°), and west (270°). Therefore, a slider from 1 to 3 is connected to *List Item*, whose input 'list' is connected to a panel that follows the order of MatLab (figure 4.7). The resulting numbers are multiplied by 90 to achieve the values required from *LB SunPath*.

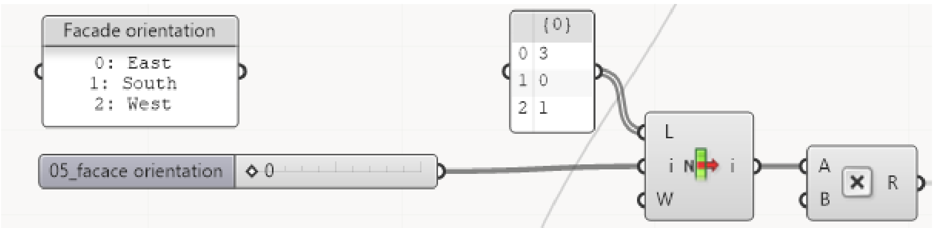


Figure 4.7: GH script that arranges the orientation values in the same order of MatLab

SHADING SYSTEM
If the impact of the shading system is defined in the MatLab/Simulink model by the SHGC, it is considered in Grasshopper by its geometry. Therefore, it was necessary to define an approach that enables to test an equal shading effect on both software.

The aim was achieved by estimating the incident radiation of the sun protections in GH to, then, convert the resulting ratio in the SHGC. The calculations are described in Chapter 3, while this paragraph illustrates how the GH model is able to include a different shading system, depending on the façade orientation.

Indeed, the virtual model is constituted of an overhang when on the south orientation, while a shorter overhang and vertical fins are integrated in the glazing system facing east or west. Specifically, the two configurations are achieved by a script containing an if statement, developed with the *GhPython* component (figure 4.8).

Figure 4.8: inputs and outputs of the GhPython script

The GhPython tool is designed to include the geometry of the overhang for any orientation, even if its length has a constant value on east and west. Conversely, the vertical fins are not included on the south, where c and c_1 equal 0. The GhPython script is illustrated as follows:

```
if orien == 270:                    #East orientation
    a = H_room * 0.5
    c = (W_wind / 0.5) + 1
    c1 = 0
elif orien == 0:                    #South orientation
    a = (R_over * 0.5) * H_room
    c = 0
    c1 = 0
else:                               #West orientation
    a = H_room * 0.5
    c = 0
    c1 = (W_wind / 0.375) + 1
```

THICKNESS OF PCMs LAYER
The project Double Face 2.0 investigated the PCMs trombe wall to conclude that a thickness higher than 5 cm does not enhance its thermal performance. Moreover, a thicker PCMs layer can store more energy but requires also more heat to melt. Therefore, this research explores the following thicknesses: 1, 3, and 5 cm.

PCMs TROMBE WALL SURFACE AREA
The surface area of the PCMs trombe wall is considered as the 50% of the glazed area. Moreover, the trombe wall is designed to have a full height with a minimum width of 70 cm. Indeed, a smaller width might indicate the presence of a little aperture, and it might imply an insufficient thermal performance of the wall. Therefore, a minimum value is applied as boundary condition.

The minimum width is not included in the MatLab/Simulink model as the trombe wall is considered for its surface area and not its geometry. Conversely, the trombe wall of the GH model is defined by its shape. Therefore, the GH model is developed to not include the trombe wall when the width does not follow the requirement. This approach enables to find all the design configurations where the boundary condition is not met.

The process is achieved with an if statement, created by connecting the *Larger Than* tool with the input 'pattern' of the *Dispatch item*. This allows to dispatch the list in list A if True (the criteria is met) and in list B if False (the width is smaller than 70 cm).

Although the trombe is not always equal or wider than 70 cm, the daylight simulation is iterated without this limit to analyse how the trombe wall behaves for every configuration. Indeed, a design configuration that does not work with the selected room dimensions, could however fulfil the requirement with a higher room volume. Hence, it would be limiting to not consider these results. Therefore, each output will be analysed to study the trombe wall behaviour by taking into account when the wall width is minor 70 cm.

4.3.2 Honeybee model

To perform the daylight simulations, it is necessary to convert the GH model in a HB model, which classifies the volume by the function of each building component. Specifically, the geometries must be grouped in rooms, faces, shades, apertures, and doors (TOI-Pedia, 2021).

The **room** is composed of faces, referring to the walls, floor, and ceiling. Since the daylight is not affected by the thermal properties of the construction materials, the faces are bi-dimensional and are not characterized by any thickness. Each face is, indeed, only defined by its material properties, which determine its reflectance. The reflectance influences the daylight and is considered as 0.4 for the walls and ceiling. Whereas, the floor has a value of 0.6 since the case study has a flooring constituted of a light wood.

Once the room is developed, the **apertures** of the HB model are built. Specifically, Honeybee allows to personalize the glazing properties by defining the U-factor, SHGC, and transmittance. The SHGC has a constant value of 0.5, while the transmittance is defined as 0.9 since the glazing system is clear and transparent.

The next step consists in converting the **shading system** in the HB model by connecting the existing geometry to *HB Shade*. Finally, the **PCMs trombe wall** is defined. As previously mentioned, Grasshopper does not properly simulate Phase Change Materials in terms of thermal performance. Conversely, a daylight simulation allows to reproduce the material by defining its reflectance and transmittance. Since salt hydrates are translucent both when liquid and solid, they are constructed as an aperture.

Although salt hydrates are always translucent, they exhibit varying levels of light diffusion depending on their phase. Therefore, the daylight simulations are performed using an average value of their translucency in frozen and liquid state. Since the trombe wall is constituted of a PCMs and an aerogel layer, both encapsulated in PETG, a physical measurement would be required to determine the total translucency of the building component. For this reason, the research will utilizes the values estimated by the Double Face 2.0 project.

Specifically, the project calculated the translucency of a 12 mm layer of PCMs encapsulated in a 2 x 4 mm perspex casing (Tenpierik et al., 2018). In its frozen state, the layer resulted to transmit only 7.5% of daylight, while in its liquid phase, it transmitted 86 - 87% of light. To account of this variability, an average value of 47% is used for the daylight simulations in this research.

The trombe wall also includes another layer consisting of 1 cm aerogel, which has a constant translucency of 83% (figure 4.9). This value is based on supplier data from the Double Face 2.0 report (2018), which states that 1 cm of aerogel exhibits a translucency of 91%. Additionally, the perspex casing with a thickness of 4 mm is determined to have a translucency of 91.2%. The insulation layer is constructed as another *HB Aperture* in the virtual model.

Once the geometries are converted in a HB model, they are assembled by the *HB Model* tool. In the meantime, a grid of sensors is generated in the room. The grid can have a different size depending on the required level of detail. Finally, the *HB Assign Grids and Views* integrates the sensors in the HB model.

The model is linked to *HB Annual Daylight* to calculate the **Daylight Autonomy** (DA). DA is defined as the percentage of occupied hours of illuminance received by each sensor. Even if residences are commonly occupied during the evening, the daylight is calculated from 8:00 to 18:00, hours when there is the natural light. The tool allows to determine the threshold of daylight autonomy, whose value is defined as 300 lux. Since DA is calculated for each point on the grid, its average value is considered as result.

From the daylight autonomy is possible to calculate the **Spatial Daylight Autonomy** (sDA). sDA estimates the percentage area that meets the minimum daylight admittance level for each sensor.

<table>
<tr><th></th><th>layer</th><th>translucency</th></tr>
<tr><td>1</td><td>perspex 4 mm</td><td>91.2 %</td></tr>
<tr><td>2</td><td>aerogel 10 mm</td><td>91 %</td></tr>
<tr><td>3</td><td>perspex 4 mm</td><td rowspan="3">average value: 47 %</td></tr>
<tr><td>4</td><td>PCMs 12 mm</td></tr>
<tr><td>5</td><td>perspex 4 mm</td></tr>
</table>

Figure 4.9: translucency of the trombe wall layers

4.3.3 Optimization of the simulation process

Colibrì enables the iteration of a simulation process by automatically testing all the possible configurations and storing the data achieved. The tool that performs the simulations is the *Colibrì Aggregator* (figure 4.10), whose inputs are described as follows.

- Folder: the path of a folder were the Excel table and images are automatically saved from Colibrì.
- Genome: it is linked with the *Colibrì Iterator*, which contains all the variables. The iterator

specifies the number of configurations, which depends on the parameters.

- Phenome: it requires the *Colibrì Parameters*, containing all the objectives of the simulation.

- Image setting: the *Image Setting* tool is an optional tool used to personalize the settings of the images created by Colibrì.

- 3D objects: the images exported from Colibrì show each design configuration.

- Write: if True, Colibrì iterates the simulation.

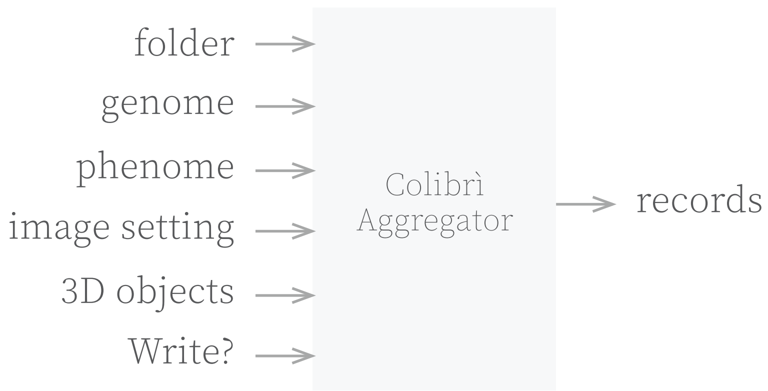


Figure 4.10: inputs and outputs of the Colibrì Aggregator tool

4.3.4 Analysis of the results

The iteration of two parallel simulations that test the same variables requires a specific data management. Indeed, the parameters must have the same values and order for both simulations.

Therefore, a simulation is iterated in Grasshopper as try to analyse how the variables are considered in Colibrì. As figure 4.11 shows, once all the values of the first input (a) are tested, all the values of b are performed. Differently to MatLab/Simulink, the combination of any input generates a new row and never a column.

	1
1	$a_1 * b_1 * c_1$
2	$a_2 * b_1 * c_1$
3	$a_1 * b_2 * c_1$
4	$a_2 * b_2 * c_1$
5	$a_1 * b_1 * c_2$
6	$a_2 * b_1 * c_2$
7	$a_1 * b_2 * c_2$
8	$a_2 * b_2 * c_2$

Figure 4.11: table of results

4.5 Conclusion

This phase has digitally investigated a flat PCMs trombe wall in relation with multiple room configurations to explore its thermal performance and light transmittance. Indeed, after the identification of a methodology for the digital design exploration, three simulations were performed in parallel. As a whole, the chapter mainly describes the development of the two virtual models and how they manage data.

During the simulation process, certain limitations were encountered. Simulating PCMs requires the use of specific software that are hardly integrated in Grasshopper. On the other hand, Grasshopper can only approximatively investigate the thermal performance of PCMs. This has resulted in the application of two different software.

The use of two software that cannot be integrated has been limiting. Great difficulties were experienced especially for the shading system. Indeed, MatLab requires the effect of sun protections by their SHGC. Whereas, Grasshopper considers the shading system by its geometry. As a solution, this required the application of approximative calculations that were able to convert the shading effect, explored in Grasshopper, in SHGC values.

The conversion resulted challenging, especially for lack of guidelines that explain how to properly estimate the SHGC of glass with a shading device. Indeed, there is no Dutch or European standard that describes the calculation process of the SHGC.

05. Evaluation of results

The following phase examines the results of the simulations by comparing the values. A strategy to manage the great number of data introduces the chapter. Indeed, the application of ModeFrontier to plot graphs has been suitable for the data analysis. Subsequently, the results are investigated for each variable to predict how they affect the thermal and daylight building requirements. The individual study of each input will gradually show the design configuration that reaches the greatest balance between the thermal and daylight building demands. Finally, the reduction achieved by integrating the PCMs trombe wall is estimated for a selected number of inputs combinations. As a whole, chapter 5 investigates a sub research question: h*ow are the thermal performance and daylight admittance affected by the room variables and the PCMs trombe wall ?*

5.1 Evaluation process

The variety of combinations between inputs generates a great amount of results. In particular, each simulation produces 240 values. Therefore, a strategic approach must be applied to properly manage the data.

The chosen methodology consists of multiple steps as figure 5.1 illustrates. Before performing the simulations, the inputs were arranged in the same order and for equal values in order to organize the results of all simulations in an Excel table.

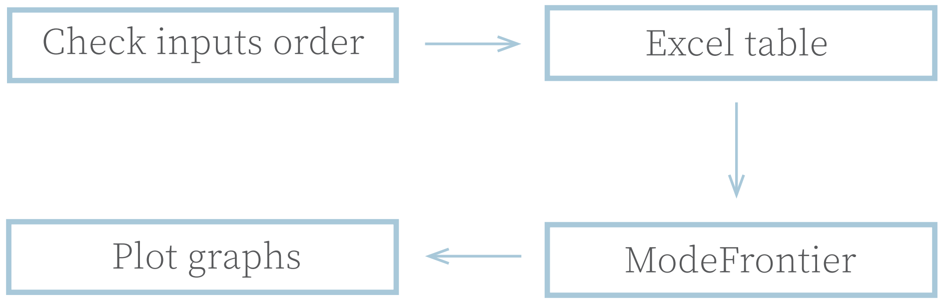


Figure 5.1: workflow of the evaluation process of the results

Once the Excel table is completed, it is uploaded in ModeFrontier. The platform is developed to iterate multi-objective optimizations (EnginSoft, n.d.). In particular, the software is linked to other engineering tools to automate the simulation process and simplify the analytic decision-making. In this research, ModeFrontier is applied only for its post-processing tools, which enable to analyse the results to find the most optimal solution.

Lastly, the Excel table is imported in Grasshopper by TT Toolbox to develop a workflow that ensures an interaction between the customer and the product. Specifically, the workflow shows a window where the customer can easily enter the preferred value for each input to see the thermal and daylight performance of the trombe wall for the selected room configuration. This is achieved by using Human UI, a Grasshopper plug-in utilized to create customer interfaces for users.

5.1.1 The evaluation process

Once the simulations in MatLab/Simulink and Grasshopper are completed, an Excel table is created to organize all the simulations results. In particular, figure 5.2 illustrates the organization of data. Indeed, each column represents a different input and output, whereas the rows show the design configurations and the outcomes obtained from them. The described Excel table is depicted in the Appendix.

	input 1	input 2	output 1	output 2
1	a_1	b_1	x_1	y_1
2	a_2	b_1	x_2	y_2
3	a_1	b_2	x_3	y_3
4	a_2	b_2	x_4	y_4

Figure 5.2: data management of results in an Excel table

By organizing all the data into a single table, it is possible to investigate how the variables affect the thermal and daylight building requirements. Moreover, the table is suitable to highlight the design configurations in which the trombe wall does not fulfil the width requirement of 70 cm.

ModeFrontier

The finalized Excel table is imported in ModeFrontier via *Data Wizard*, a tool that loads data and generates automatically a workflow. The data is, however, imported only if certain conditions are met when the Excel table is uploaded in Data Wizard.

For instance, the tool can load only one Excel worksheet per project and cannot contain any string or empty cell. Indeed, strings must be deleted or extracted by selecting them as “variable names from row” (ModeFrontier, 2022). Once the Excel table is clean, the cells appear white rather than grey, thus indicating that there are no errors. The columns of the table must be assigned to inputs or outputs and the objectives must be defined.

Once the aforementioned steps are fulfilled, the data is finally imported in ModeFrontier in a workflow, illustrated in table XIX in the Appendix. The project is ready to be iterated. When the simulation is concluded, the results are illustrated in the ‘Design Space’, a section that contains all the post-production tools.

A graph typology called *Parallel Coordinates* is generated for this research. Indeed, the graph enables to perform interactive analysis as it is possible to highlight only one variable. This approach allows to examine the influence of a given input on the results. It is also possible to narrow the range of values for an input/output. Moreover, a result can be investigated by looking at which design configuration it corresponds to.

Simplified graphs will describe the influence of parameters in the following paragraph, whereas the Parallel Coordinates graphs are reported in the Appendix.

5.2 The impact of each variable

In the following sub-chapter, the resulting values from the simulations are analysed. In particular, each variable is individually investigated to understand how it affects the conclusive building performance regarding the thermal and daylight comfort.

After the influence of each input has been depicted, the outcome of each design configuration is visualised in graphs. Since this approach compares the results, it also reveals the most advantageous combination of inputs to achieve a performing PCMs trombe wall.

5.2.1 Room width

The following graphs were generated for each input to investigate the influence of its values. In particular, figure 5.3 describes the heating and cooling demand for the two room widths. Conversely, figure 5.4 highlights the daylight performance for the input values. DA refers to the Daylight Autonomy and sDA to the spatial Daylight Autonomy.

As a whole, the research aims to reach the lowest thermal demand, but the highest transmittance of daylight. Therefore, the thermal graphs are more beneficial for the low values in the Y axis, whereas the daylight reaches a better performance with a high percentage in the X axis.

Analysing the graphs, it can be summarized that the thermal and daylight requirements appear lower with a higher room width. Indeed, a wider wall has a greater surface of opaque and transparent envelope, thus enhancing the daylight admittance and thermal inertia. Moreover, since the building envelope is lightweight, its temperature is easily affected by solar gains. Therefore, the heating demand is reduced by a wider façade (figure 5.5). On the other hand, a greater window enhances the natural ventilation, thus reducing also the cooling demand.

Results: a wider façade is beneficial for both lighting and thermal demands.

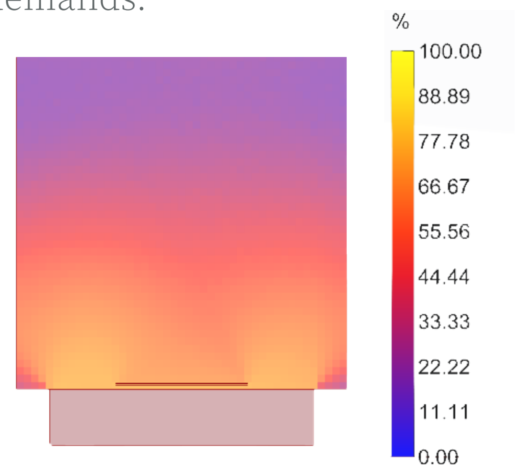


Figure 5.5: Daylight Autonomy of a room 9 m wide

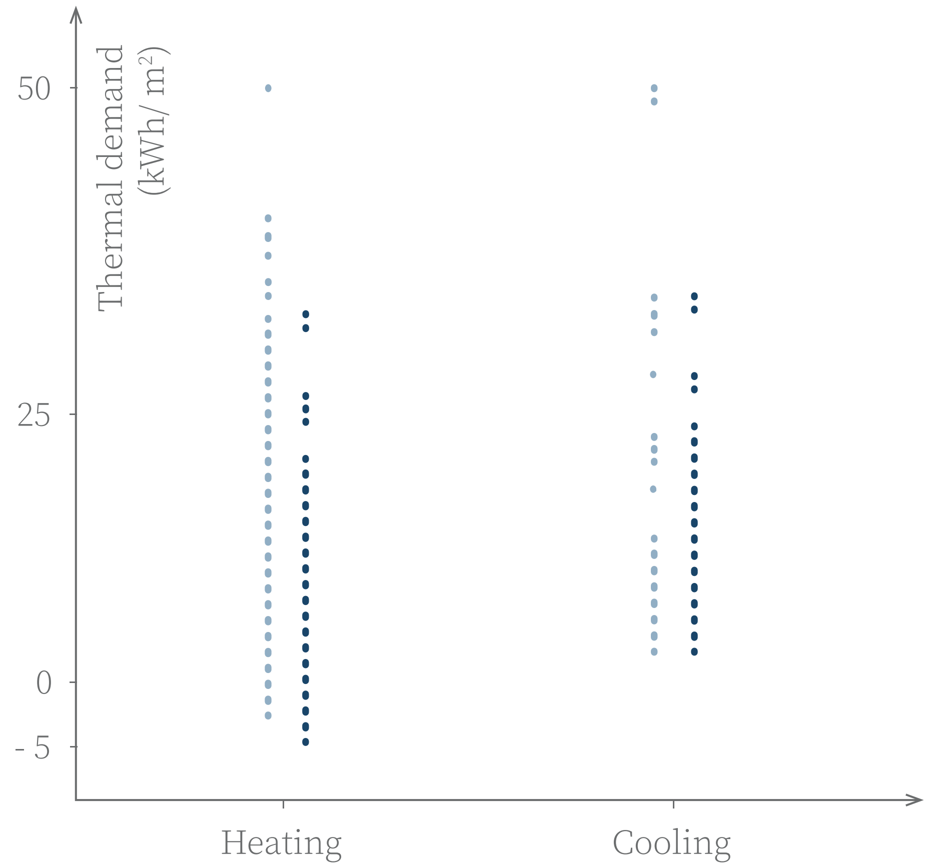


Figure 5.3: comparison of thermal demand
Legend: 6 m room width (light blue), 9 m room width (blue)

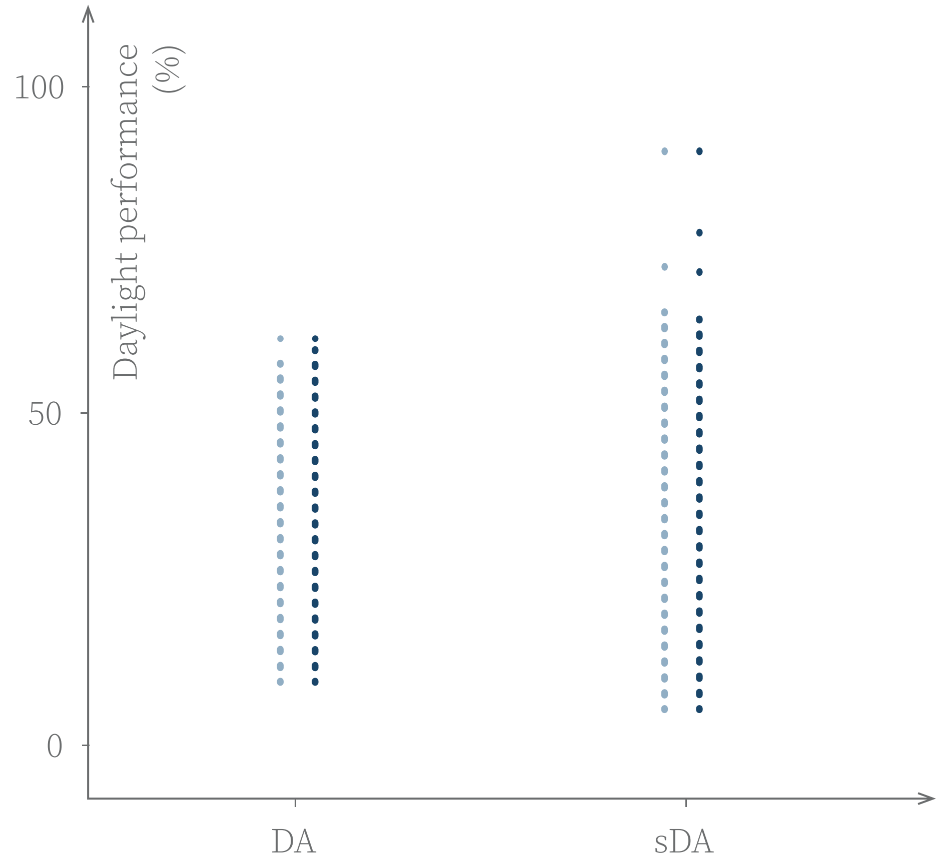


Figure 5.4: comparison of daylight performance
Legend: 6 m room width (light blue), 9 m room width (blue)

5.2.2 Room depth

Graphs 5.6 and 5.7 highlight the impact of the room depth in the thermal and daylight building requirements. It is observable that a deeper room has a lower daylight autonomy. Indeed, the daylight is not able to reach the indoor space after a certain depth, as figure 5.8 illustrates.

The other significant difference is in the thermal performance, which is enhanced by a greater depth. Indeed, since the surfaces are adiabatic except for the façade, deeper walls increase the room volume while the heat transfers remain equal. Hence, the thermal requirement of the room is reduced.

Results:

- The spatial Daylight Autonomy is maximized by a shorter room depth;
- A deeper room is beneficial for heating and cooling.

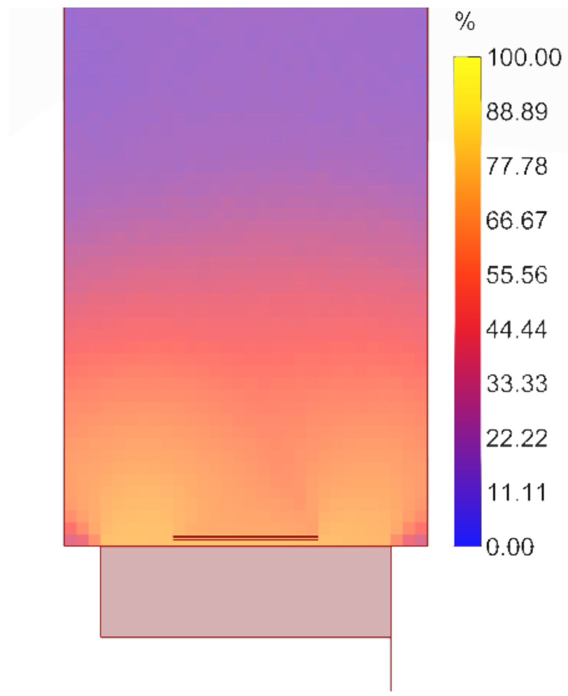


Figure 5.8: Daylight Autonomy of room 9 m deep

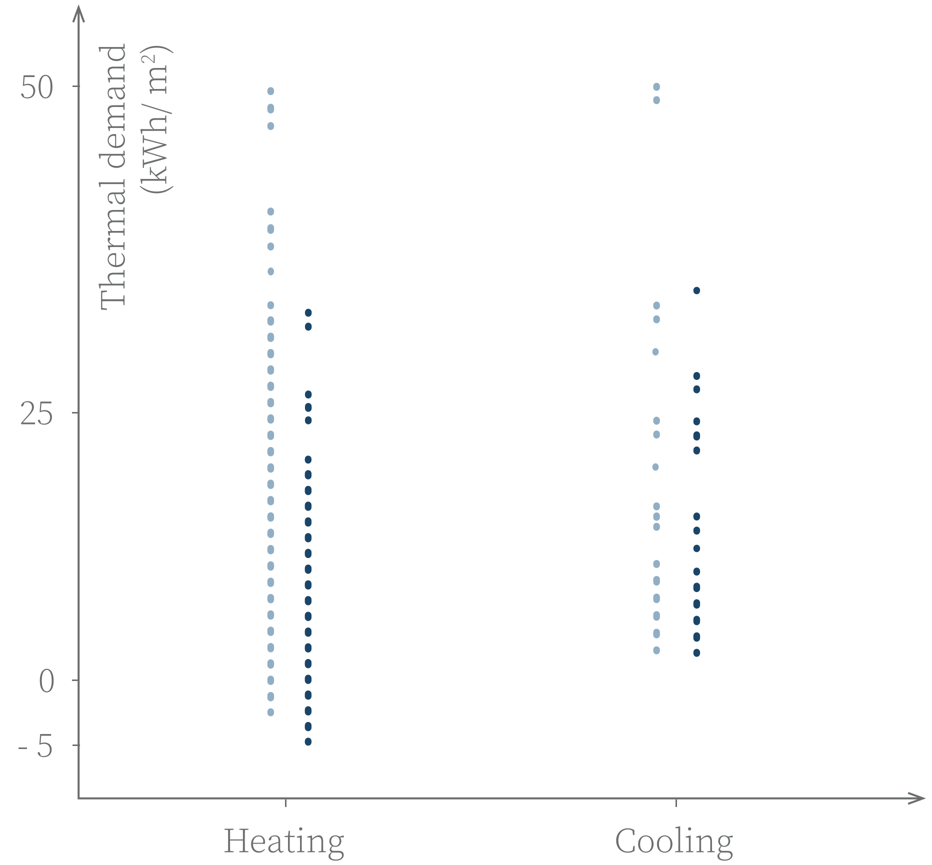


Figure 5.6: comparison of thermal demand
Legend: 6 m room depth (light blue), 9 m room depth (blue)

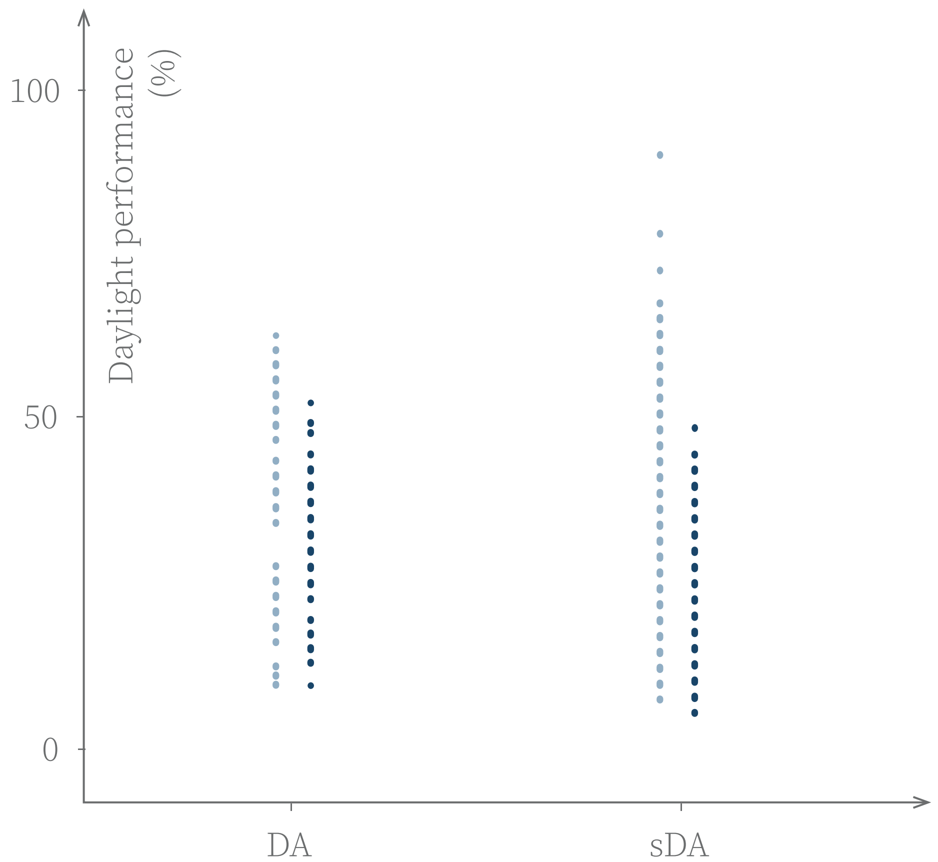


Figure 5.7: comparison of daylight performance
Legend: 6 m room depth (light blue), 9 m room depth (blue)

5.2.3 Glazed surface area

The following graphs 5.9 and 5.10 describe the influence of the window-to-wall ratio in the building requirements. Considering that a higher WWR corresponds to a larger surface area of glazing, the daylight admittance gradually improves when the WWR increases.

On the other hand, the thermal requirements are lower with a smaller glazed area since the thermal inertia of glazing systems is very limited. Indeed, an opaque wall keeps the heat longer than a transparent surface. Moreover, smaller windows increase the insulation value of the façade, while reducing the solar gains. Therefore, a lower WWR has a positive impact on the cooling requirement.

Regarding the heating demand of buildings, smaller windows enhance the thermal inertia and insulation value, but also reduce solar gains, whose solar radiation could passively heat up the indoor space. Hence, low heating demands are reachable also with high WWR.

Results:

- Since higher WWR corresponds to greater solar gains, it is beneficial for daylight;
- Smaller apertures enhance cooling.
- Depending on multiple room factors, the heating demand can be reduced by either a low or high WWR.

5.2.4 Façade orientation

By comparing the daylight autonomy in graphs 5.11 and 5.12, it is notable that the south orientation is the most beneficial for daylight admittance. Whereas, the values are slightly lower in the west and east orientation.

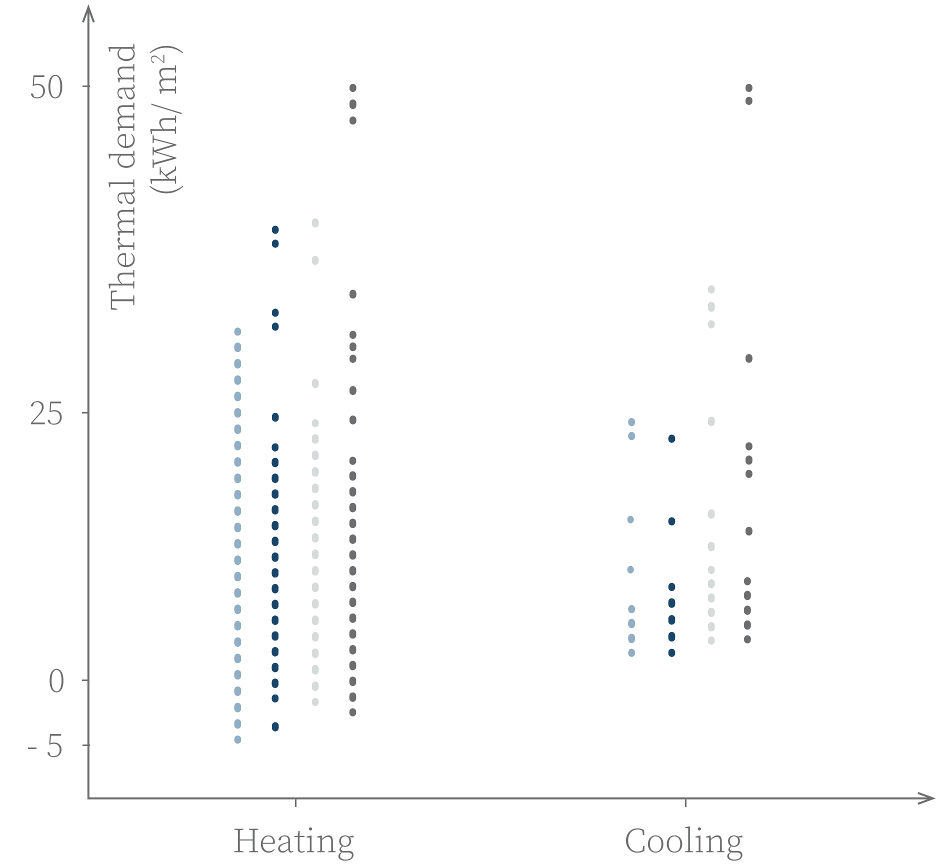


Figure 5.9: comparison of thermal demand
Legend: 20% WWR (light blue), 40% WWR (blue), 60% (light grey), 80% (grey)

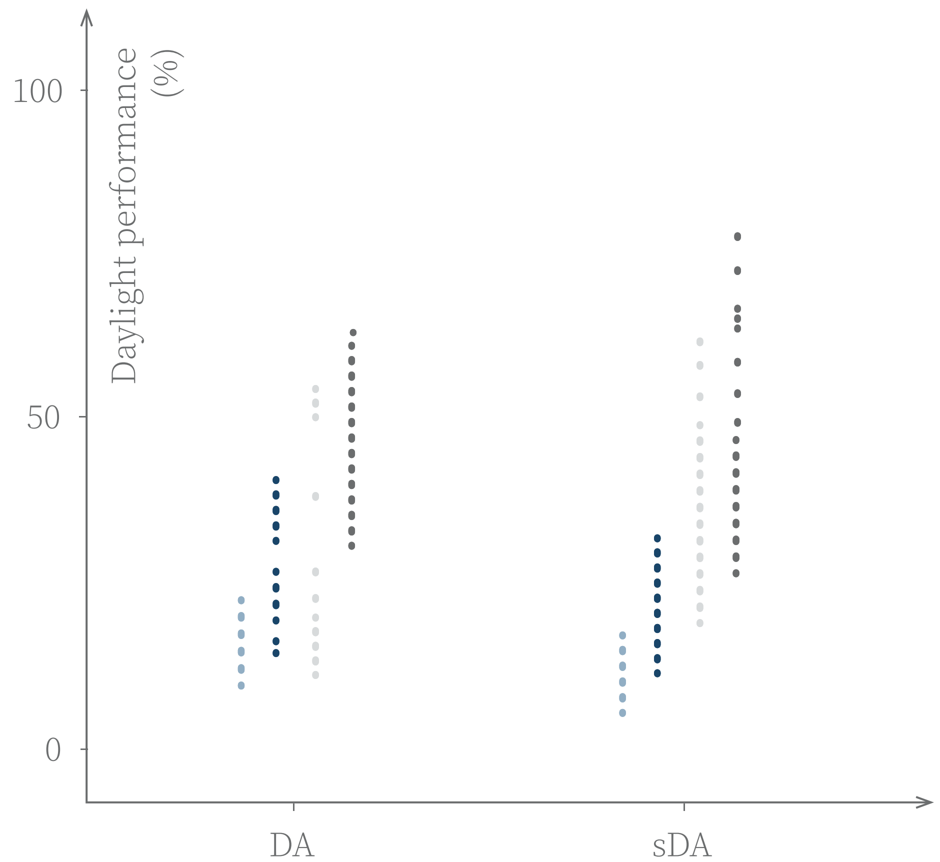


Figure 5.10: comparison of daylight performance
Legend: 20% WWR (light blue), 40% WWR (blue), 60% (light grey), 80% (grey)

Indeed, the orientation that receives the most sunlight is south. However, the south was simulated for three different overhang lengths, where the longest one blocks majority of the solar radiation also in winter, thus achieving significant heating demand levels. Conversely, the west side is the most advantageous in terms of heating requirements by being exposed to the sunlight in the afternoon. Indeed, since it receives direct solar radiation only in the morning, east requires slightly more heating.

Cooling values appear to be great in the south orientation where the overhangs reduce the direct sunlight in summer months. The west side, on the other hand, has the highest cooling demand. Indeed, the angle of solar radiation on west and east is inclined rather than direct, as it is on the south. As a result, the sun protections block less radiation.

Results:

- The daylight achieves the greatest values on the south orientation. West and east are also beneficial. However, west is preferred for its moderately higher values in daylight.
- West, and especially east, have low heating demands. The south reaches both low and high heating requirements, depending on the overhang length.
- The overhangs oriented south limit the overheating effect, thus achieving a low cooling demand. Whereas, east and west, require more energy for cooling purposes.

5.2.5 Shading system

Figures 5.13 and 5.14, describe the impact of a shading system on the thermal and daylight building requirements. The graphs depict the influence of both overhangs and vertical fins. Specifically, the three overhangs

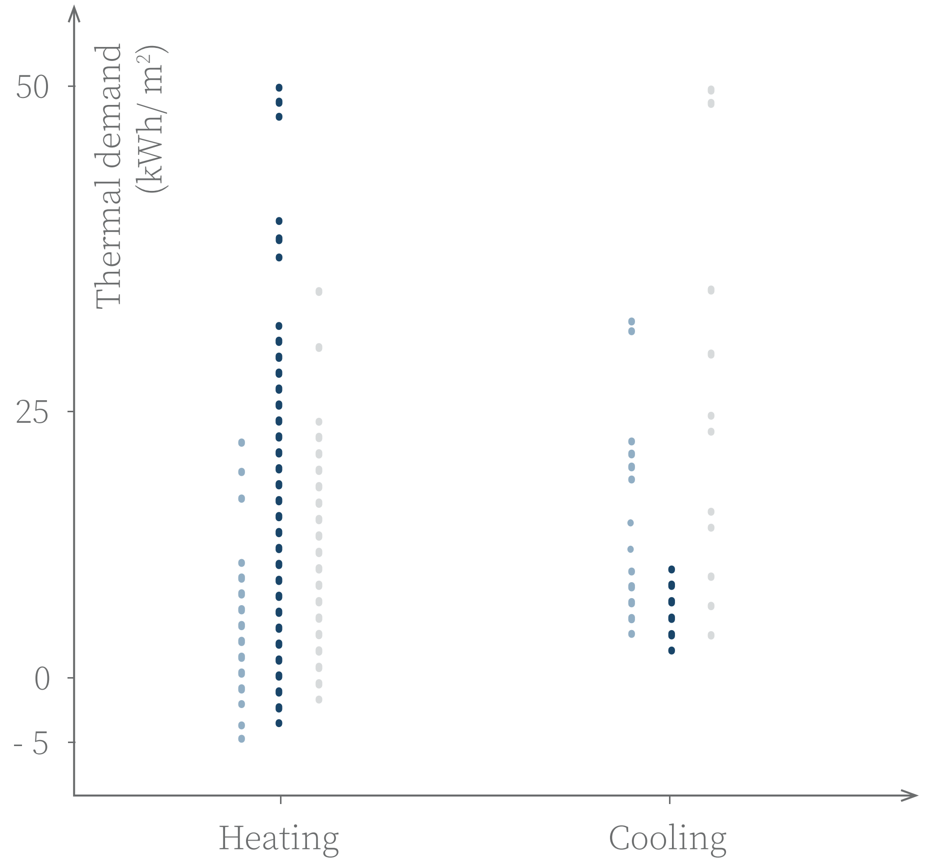


Figure 5.11: comparison of thermal demand
Legend: east (light blue), south (blue), west (light grey)

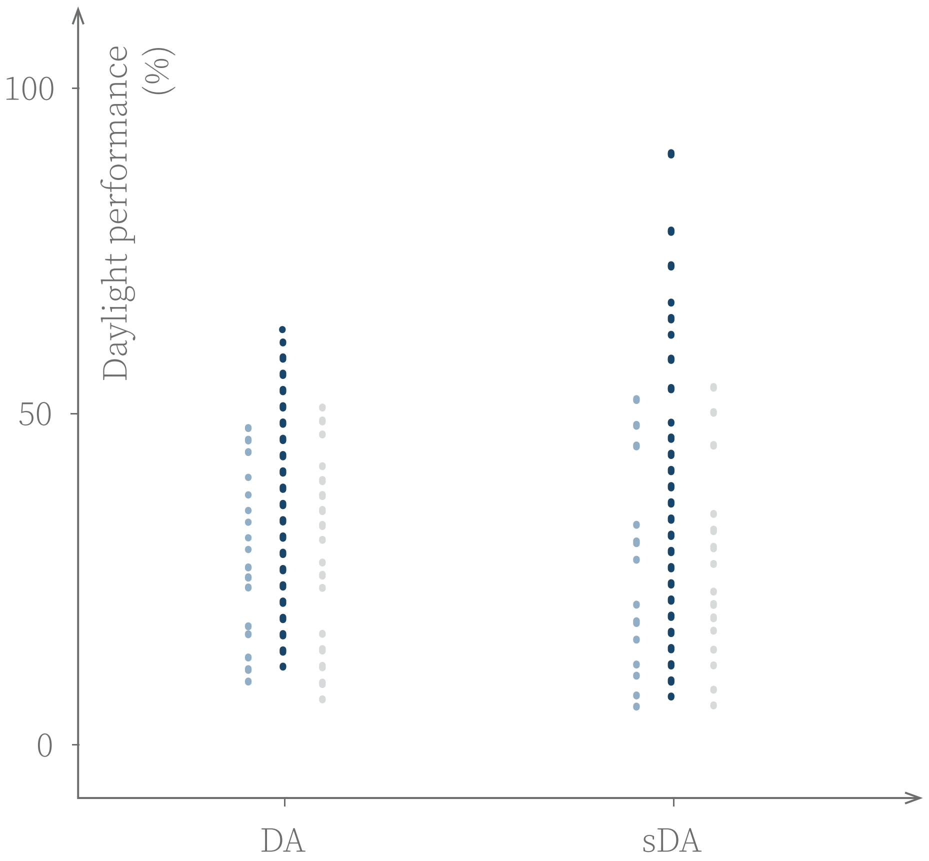


Figure 5.12: comparison of daylight performance
Legend: east (light blue), south (blue), west (light grey)

are on the south side and have a SHGC of 0.35 (shortest overhang), 0.28, and 0.23 (longest overhang). Conversely, the vertical fins are integrated on the façade facing east or west and have a SHGC of 0.30.

Since south receives more direct sunlight than the east and west, the daylight admittance achieves higher values. In particular, a shorter overhang enables more light to enter the building. As an example, there is a design configuration that reaches a Daylight Autonomy of 64% with a spatial Daylight Autonomy of 92%, consisting of a room oriented south with a SHGC of 0.35. This value is close to the maximum, which equals 100%.

As a whole, the sunlight illuminates the reached indoor space, while passively heating it up. Indeed, the heating demand required for the longest overhang is the highest since it blocks the majority of direct radiation. Whereas, a shorter overhang is advantageous by allowing the sunlight into the building throughout the winter.

The design configurations with great daylight admittance are expected to reach higher cooling demands. Indeed, the south orientation with the shortest overhang necessitates a significant amount of energy for cooling. While, a sun shading system with a SHGC of 0.23 enhances the indoor temperature during summer by blocking the radiation.

Regarding the vertical fins on the east and west, the daylight admission is lower, while more energy is required for heating and cooling. Indeed, the solar gains on the east and west are not as beneficial as they are for the south side. Moreover, since a SHGC of 0.30 does not block much solar radiation, the cooling requirement is also high.

Results:

- As a shorter overhang oriented south blocks less direct sunlight, it is beneficial for the daylight admittance and heating demand. Conversely, since more solar radiation reaches the indoor space, the cooling

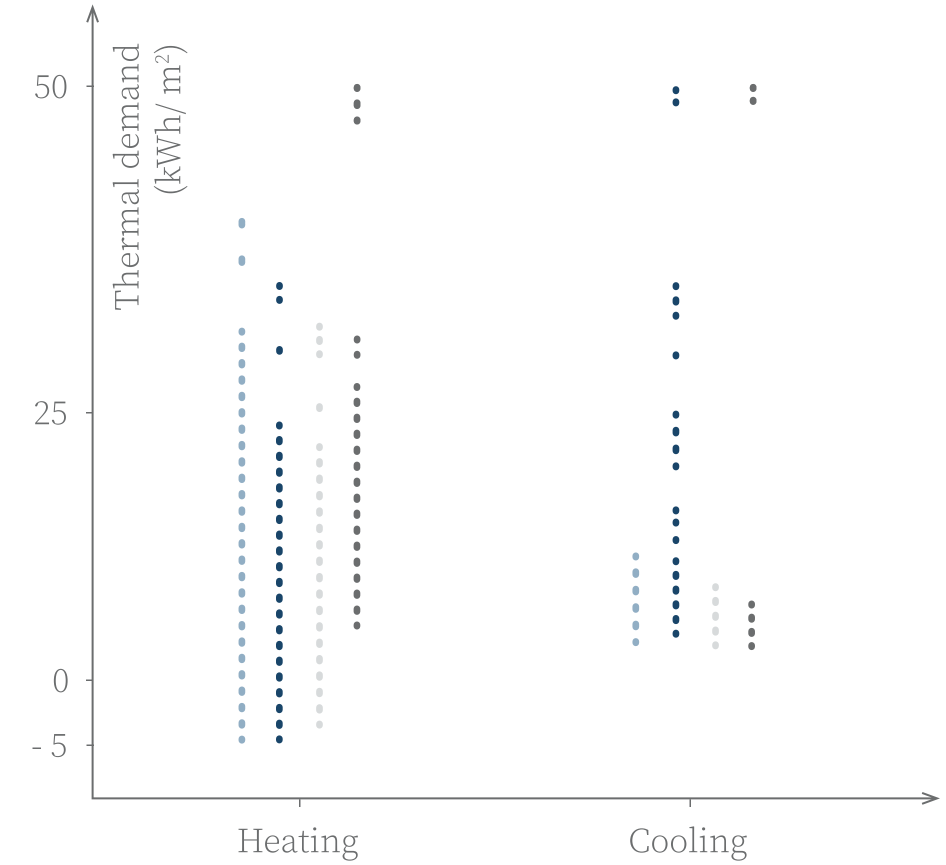


Figure 5.13: comparison of thermal demand
Legend: south SHGC 0.35 (light blue), east/west 0.30 (blue), south 0.28 (light grey), south 0.23 (grey)

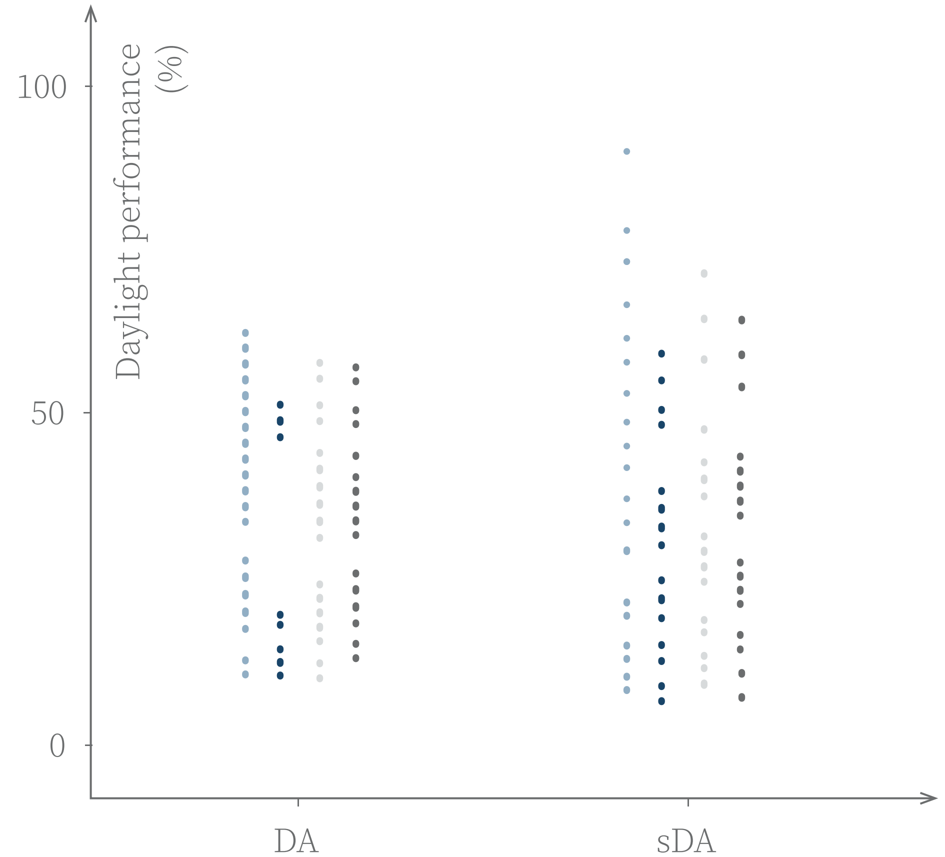


Figure 5.14: comparison of daylight performance
Legend: south SHGC 0.35 (light blue), east/west 0.30 (blue), south 0.28 (light grey), south 0.23 (grey)

requirements are higher.

- As a whole, the south orientation is more advantageous than west and east in terms of daylight and thermal demands.

5.2.6 Thickness of PCMs layer

Graphs 5.15 and 5.16, illustrate how the thickness of the PCMs layer affects the thermal demand and light transmittance of a building. Previous research on the PCMs trombe wall demonstrated that a thicker wall is advantageous for heating since it needs more time to heat up. On the other hand, a thicker layer requires also more heat to melt, therefore it may not completely melt during the summer months.

This research tested three different thicknesses to validate the behaviour of PCMs in terms of daylight and thermal performance. Indeed, since PCMs are translucent, they affect the daylight admittance. However, the three thicknesses seem to have a similar influence on the results in terms of both daylight and thermal performance.

To analyse the influence of each thickness, the results of three configurations are compared in detail, with the only difference being the thickness. Specifically, the design configuration consists of a room 9 x 6 (width x depth), with a 80% WWR, whose façade is oriented south and has a SHGC of 0.28 (medium length overhang).

PCMs thickness (cm)	Heating (kWh/m^2)	Cooling (kWh/m^2)	DA (%)	sDA (%)
1	1.45	3.96	60.15	74
3	1.33	4.01	58.23	66.3
5	1.21	3.95	58.22	66.2

The comparison validates the aforementioned princi-

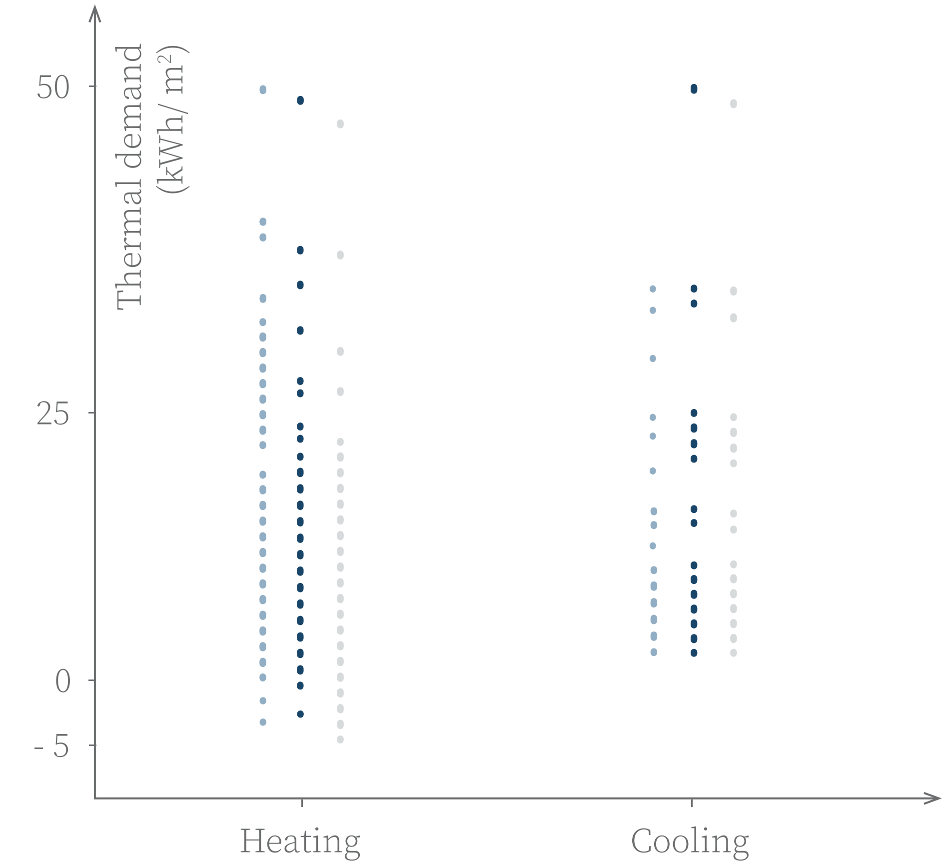


Figure 5.15: comparison of thermal demand
Legend: 1 cm thickness (light blue), 3 cm thickness (blue), 5 cm thickness (light grey)

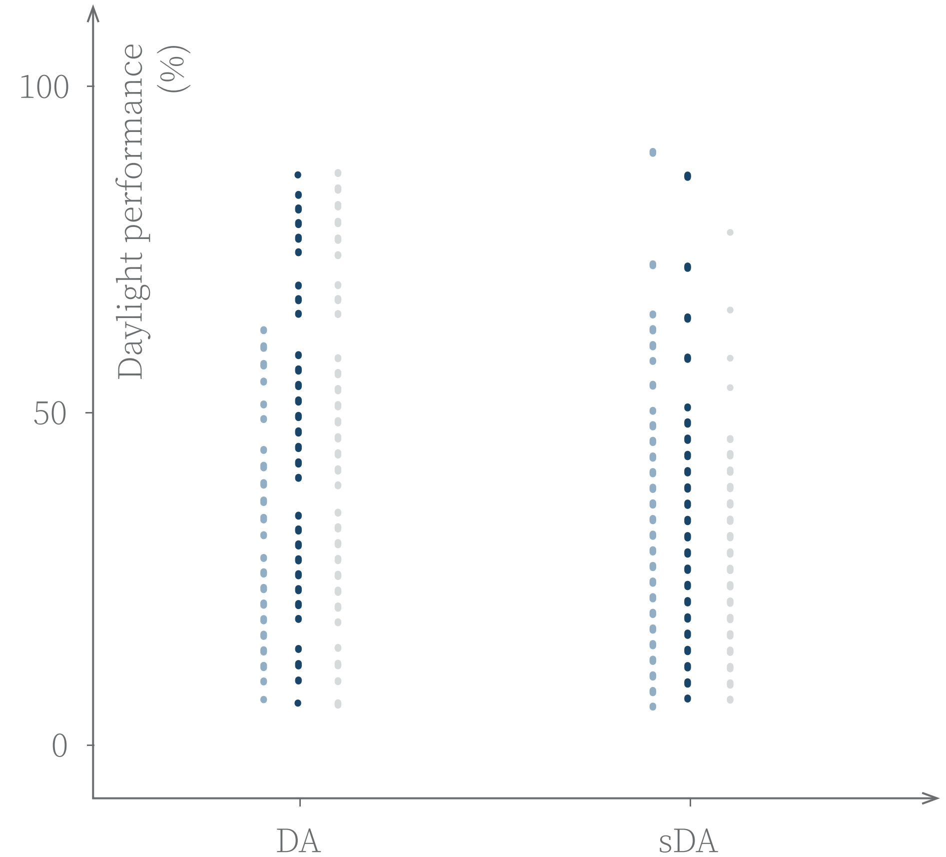


Figure 5.16: comparison of daylight performance
Legend: 1 cm thickness (light blue), 3 cm thickness (blue), 5 cm thickness (light grey)

ples, which can be summarized in the following results:

- The increase in thickness slightly reduces the heating demand while increasing the cooling requirement;
- A thicker wall transmits less daylight.

5.3 Final configurations

The individual analysis of each variable has outlined how they influence the building requirements. The investigation has already highlighted the most performing configurations, which are verified in the graph plotted in ModeFrontier. Indeed, by selecting a range of values for the thermal and daylight requirements, a list of possible design configurations is depicted (figure 5.17).

The configurations are evaluated by assigning a maximum value for the thermal requirements and a minimum percentage for the spatial daylight autonomy. Generally, the heating demand of any inputs combination has low values, reaching a maximum requirement of only 4.72 kWh/ m^2. Therefore, all the results are considered for their great heating values.

Conversely, the cooling demand can reach higher energy requirements. For this reason, it is selected a maximum value of 25 kWh/m^2, which reduces the number of possible design solutions. Finally, the sDA values are considered above 0.5, thus reaching 300 lux for the 50% of the room area for half of the operated hours in one year.

The evaluation process has been facilitated by the analysis of each variable since they achieve different outcomes depending on their value. The only exception is for the thickness of the PCMs layer. Indeed, the three dimensions reach similar results. Therefore, a precise thickness is selected to reduce the amount of data.

The thickness is selected by the design criteria described in Chapter 3 since it does not have a great impact on the building demands. Specifically, a thinner wall is beneficial for its lightness, which enhances also the wall adaptability. Moreover, the trombe wall thickness of 1 cm reduces the quantity of material required, while increasing its light transmittance and cooling performance.

The final configurations are 12 and their results are illustrated in figure 5.18. The input values of each design configuration is visible in table XXI of the Appendix.

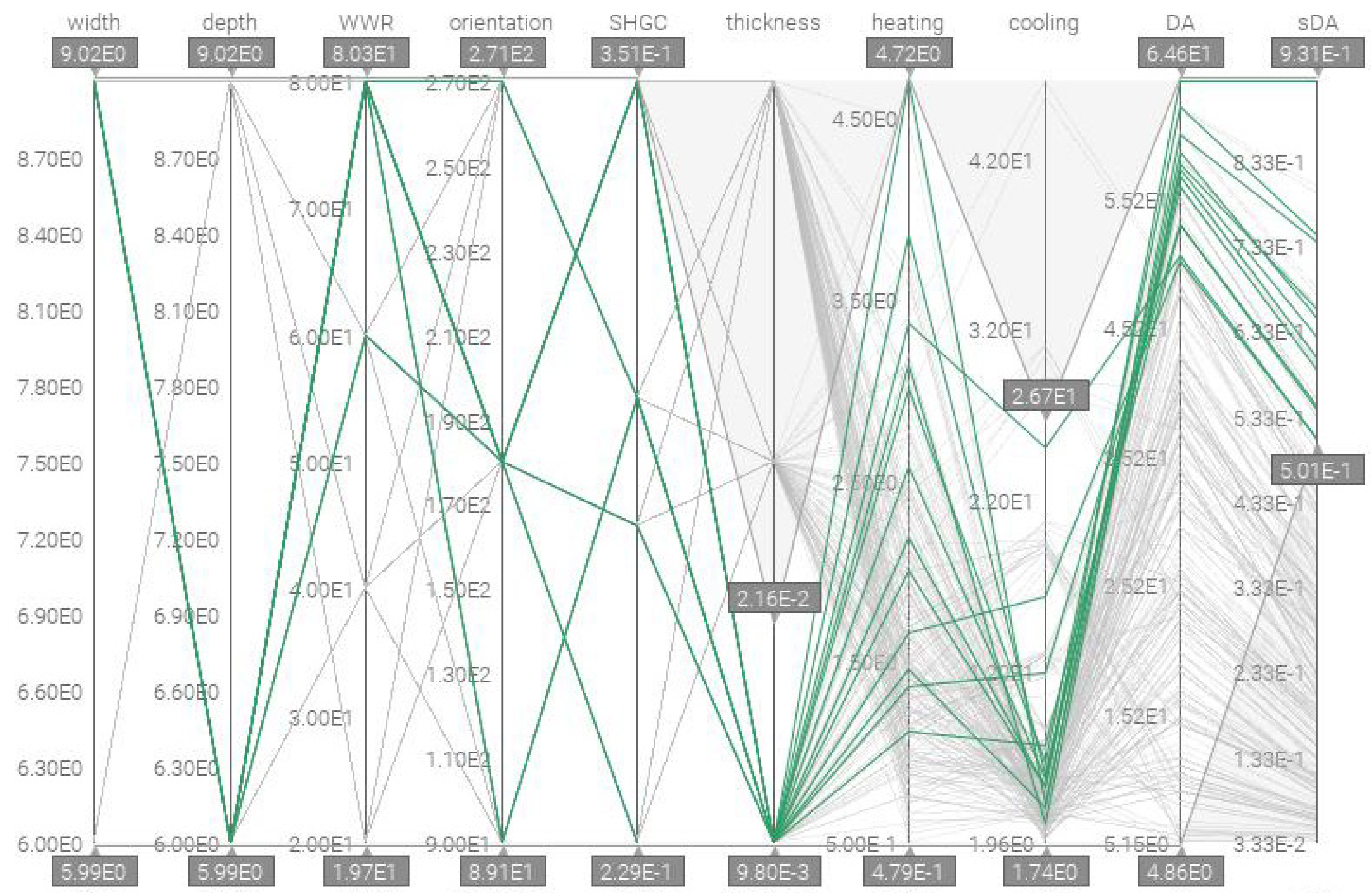


Figure 5.17: design configurations that fulfil the requirements

5.3.1 Analysis of the PCMs trombe wall performance

Design configuration	Heating (kWh/ m^2)	Cooling (kWh/ m^2)	DA (%)	sDA (%)
12	3.84	-2.40	18.08	49
13	2.58	0.20	17.25	45
24	0.76	5.91	11.78	40
25	0.62	0.85	11.19	35
28	1.69	7.80	10.87	25
29	1.19	2.58	10.07	7
44	4.16	13.95	18.65	49
45	3.77	10.67	18.13	45
60	2.52	5.74	11.15	35
61	1.74	10.28	10.86	26
76	- 0.01	4.33	11.15	40
77	0.06	7.38	10.96	34

Figure 5.18: thermal and daylight reduction achieved by the PCMs trombe wall

To calculate the PCMs trombe wall performance of figure 5.18, a second simulation is iterated for each selected design solution. The aim is to test the thermal demand and daylight admittance of the room configurations if the trombe wall is not present. Indeed, the difference of values in the simulations with and without the PCMs is suitable to estimate the performance of the building component.

As a whole, the application of the trombe wall reduces the thermal requirements, while it has a negative impact on the daylight admittance of the indoor space. Indeed, the light transmitted is reduced by the presence of the trombe wall in front of the glazed façade.

5.3.2 User interaction

To ensure an interaction between an ideal customer and the PCMs product, a workflow is developed in Grasshopper (table XIII of the Appendix). The objective of the workflow is to allow the user to define its suitable design configuration by determining the values of each variable. Once the room configuration is selected, the workflow illustrates the thermal and daylight performance achieved by the trombe wall for that situation.

The workflow is developed by following certain steps. Firstly, the Excel table containing all the data of the simulations is imported in GH by *Read Excel Sheet*, a tool of **TT Toolbox**. The Excel table must be cleaned up from empty columns, strings, and any value not required. Indeed, it should contain only the inputs and outcomes for the purpose of this research. Moreover, the design configurations are considered only for a PCMs layer thickness of 1 cm. Therefore, the configurations are a total of 80.

Once the Excel table is imported in Grasshopper and is organized properly, **Human UI**, a GH plug-in, is utilized to create a custom user interface. Indeed, the tool *Launch Window* creates a window for users, where the input values are defined by pull-down menus. As figure 5.19 illustrates, the first five rows require to select a value for each input, while the last five illustrate the trombe wall width, thermal demand and daylight admittance for the chosen design configuration.

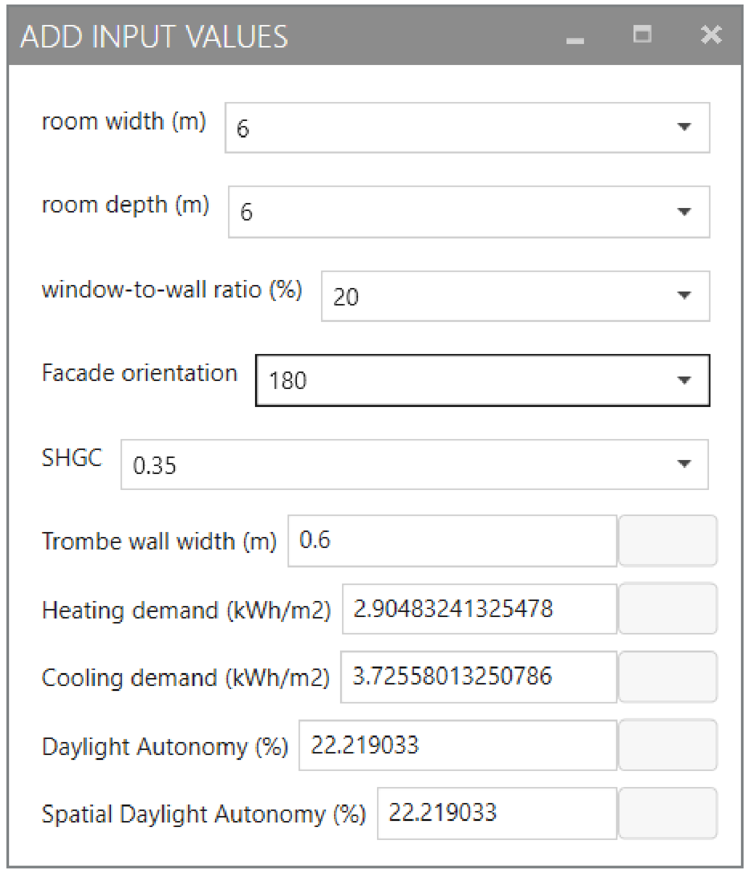


Figure 5.19: custom window developed by Human UI

5.3.3 Selected configuration

The design configuration that reaches the greatest balance between daylight, heating, and cooling requirements of a building has been determined. The configuration was included in the possible solutions of graph 5.17 and corresponds to the input values illustrated in figure 5.20.

In particular, the selected design reaches a reduction of 1.74 kWh/ m^2 on the heating demand, and of 10.28 kWh/ m^2 on the cooling requirement. Conversely, the sDA reaches a decrease of 26 %.

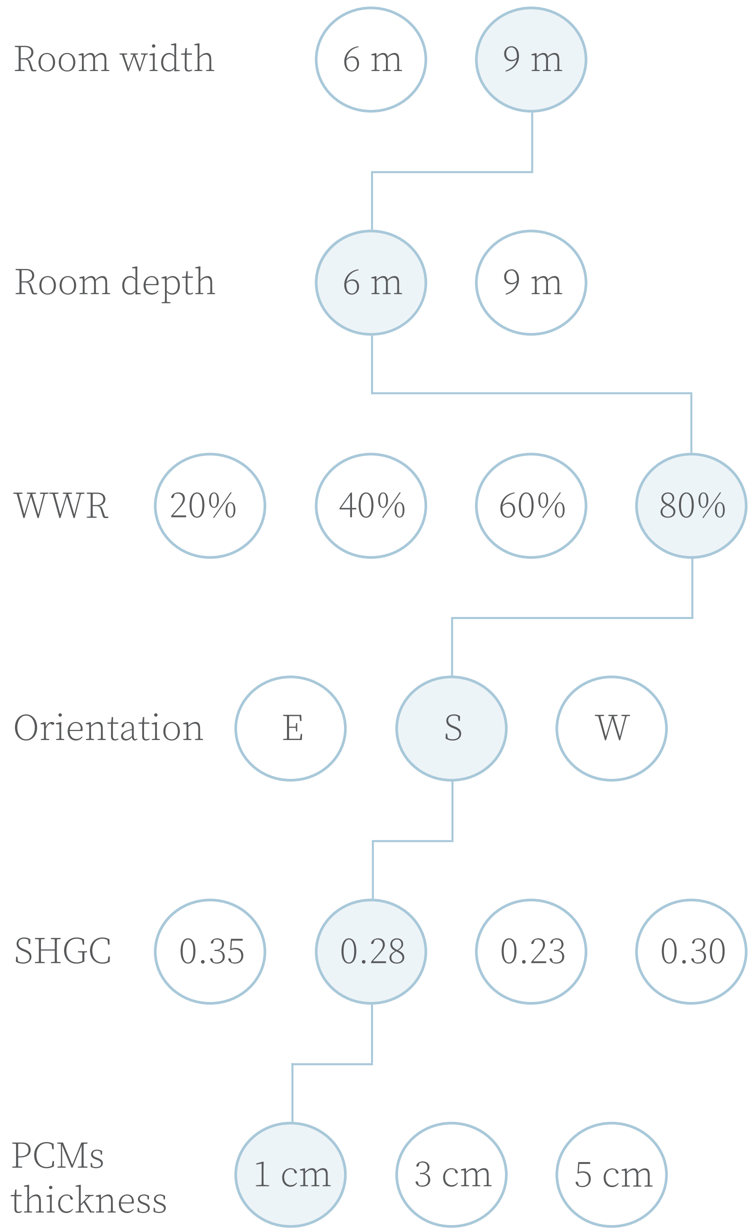


Figure 5.20: values of each variable to reach the selected configuration.

5.4 Conclusion

The chapter investigated the results by analysing how each variable affects the building requirements. Before evaluating the data, assumptions on the influence of the inputs were defined. Hypothesizing the building behaviour has been helpful in understanding how the variables affect the results.

As a whole, this approach has lead to the discovery of the most performing design configuration before assessing the ModeFrontier graph. Indeed, only after the assumption, the graph was used to highlight the best configuration.

The final design includes certain variables values that were not assumed to be the most beneficial. As an example, the thickness of the PCMs was predicted to have a greater influence. Conversely, the slight difference in results between each thickness allowed to base the selection on other factors, as the design criteria.

As a whole, the data evaluation resulted a helpful approach to examine the PCMs trombe wall behaviour in relation with the room configuration. Although there are only 12 configurations that ensure a proper daylight admittance, the workflow for the user interaction is developed for any input combination with a PCMs thickness of 1 cm. Indeed, a reduction in the trombe wall area, which was tested for a constant surface area of 50%, might increase the daylight while still being beneficial for the thermal demand. Therefore, the workflow is developed as a base for further research.

To conclude, the chapter has explored the following sub research question: h*ow are the thermal performance and daylight admittance affected by the room variables and the PCMs trombe wall ?*

06. Final design

Chapter 6 develops the final appearance of a PCMs trombe wall that fulfils the design guidelines of previous projects and the design criteria defined in the preliminary research phase. The design is also determined by the results of this research.

The exploration of a modular design that can assume various configurations and is easy to assemble/ disassemble results in the selection of a geometric shape. By developing the design of the trombe wall, the research investigates the last sub research question: *What is the final appearance of the room and trombe wall if it is researched a balance between the best results of thermal and daylight simulations ?*

6.1 Final design

The simulations have generated all the necessary information to design the PCMs trombe wall. As defined in Chapter 3, the design must satisfy certain criteria. Some of them have already been achieved by the selection of proper values of the variables. For instance, the final design configuration is evaluated regarding the trombe wall thermal performance and light transmittance. Moreover, the thickness selected for the PCMs layer guarantees a lightweight product, which facilitates processes like demountability, disassembly, and rotability.

The trombe wall design is developed by following certain design requirements. Indeed, the wall should be composed of modular pieces, whose size is manageable by humans. The geometry of the pieces should reach different patterns depending on how it is assembled. Lastly, the modules should fit together without large gaps.

6.1.1 Micro scale

The trombe wall design is firstly described at micro scale. The micro scales refers to the single pieces that confer a pattern to the wall when assembled together. The pieces consist of rhombuses, a geometrical quadrilateral composed of four sides with the same length. The rhombus has two internal diagonals that indicate its length and height (figure 6.1).

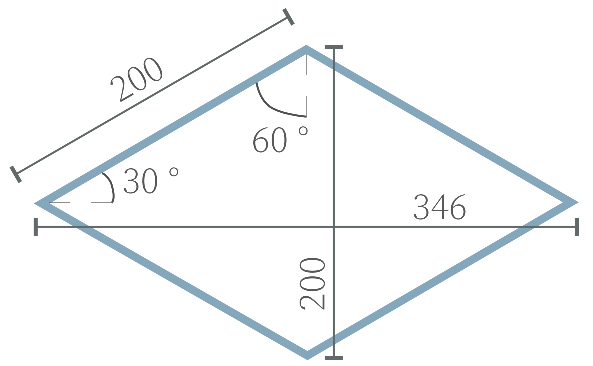


Figure 6.1: measures of rhombus [mm]

Each rhombus is composed of a PETG capsule that contains two layers of 1 cm each, one for the PCMs and the other one for the insulation layer (figure 6.2). In particular, the capsule divides the materials contained in four smaller areas. This ensures a proper blend of salt hydrates when the rhombuses are rotated vertically. The division consists of PETG separators that follow the path of the two rhombus diagonals. The separators have a hole in-between, used to connect together the rhombuses by metallic wires.

The wires are connected to a wooden structure of the trombe wall. Consisting of two vertical elements and a horizontal base, the structure ensures the stability of the building component. Moreover, the design of simple and dry connections ensures a product that is easy to assemble and disassemble. One of the vertical elements contains also a manual handle, which enables to rotate the rhombuses, whenever utilized. The next pages will illustrate the appearance of the trombe wall and its functioning.

1. PETG capsule - 4 mm
2. PCMs layer - salt hydrates - 10 mm
3. PETG capsule with holes for metallic wire - 4 mm
4. Insulation layer - aerogel - 10 mm
5. PETG capsule - 4 mm

Total thickness: 32 mm

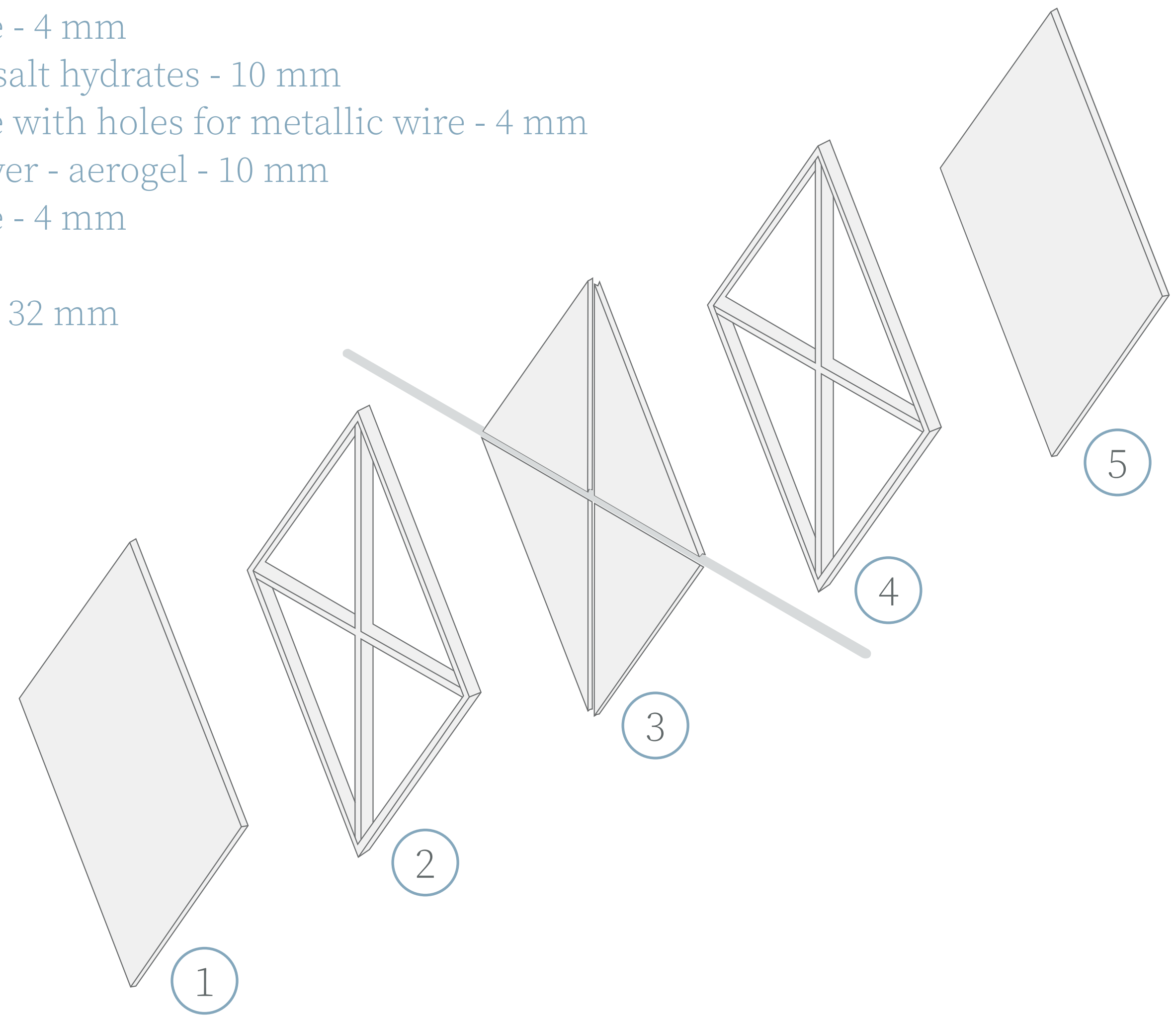
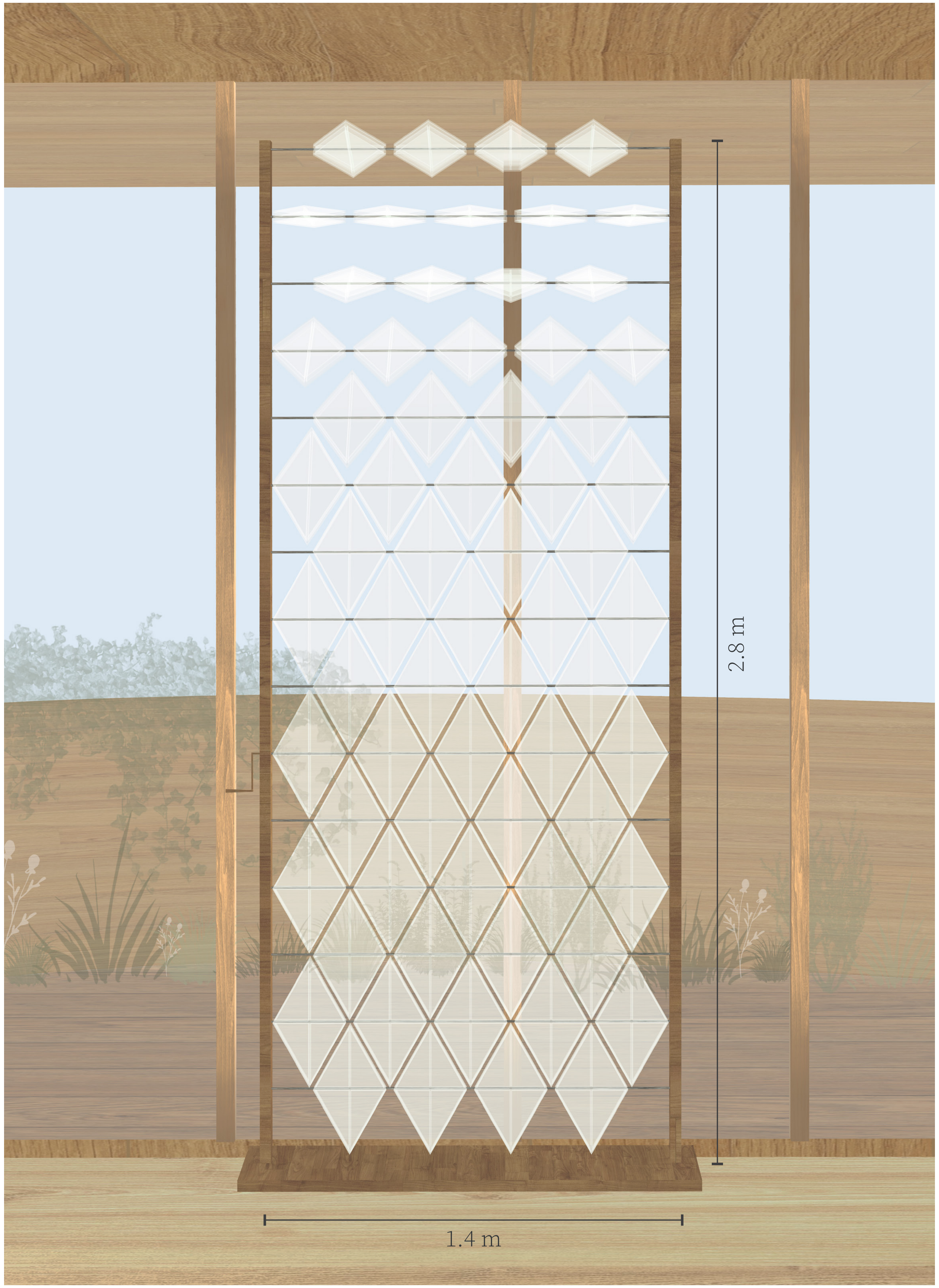


Figure 6.2: axonometric exploded view of the rhombus

6.1.2 Macro scale

The PCMs trombe wall has a constant height of 3 m and a width that depends on the room configuration and the assembly of the rhombuses. Indeed, the rhombuses are designed with an angle of 60°, which enables to combine them on their edges or their sides. As a result, the trombe wall can assume various patterns, which confer a different width to the panel.

Moreover, since the trombe wall is composed of modular pieces, its width can be enlarger by assembling horizontally other rhombus. This confers flexibility to the trombe wall, whose design is suitable for any configuration of variables that was simulated in the research. Indeed, the trombe wall was tested as a constant percentage of the surface area of the glazed façade, corresponding to 50%.




32 mm

6.2 Design guidelines

This sub chapter illustrates the guidelines of the PCMs trombe wall if the product was on the market. The objective is to explain the trombe wall behaviour by using simple graphics. This simplifies to customers the complexity of phase change materials and the building component. Specifically, the instructions describe how to utilize the worflow and the trombe wall, the assembly and disassembly procedure, and give useful tips to the customer.

WORKFLOW

Since each room has a different outcome of the PCMs trombe wall performance depending on its configuration, it is necessary to insert certain values in the window depicted in figure 6.6. In particular, the window requires the use to insert certain inputs, listed as follows:

- Room width and depth (m): it requests a value of 6 or 9 m.

- Window-to-wall ratio (%): it is the percentage of glazed area of the façade. It requires to insert one of the four values tested in this research, 20, 40, 60, or 80%.

- Façade orientation: utilize 90 ° for the east side, 180 ° for south, and 270 ° for west.

- SHGC (Solar Heat Gain Coefficient): it indicates the shading effect of a shading system. There are four possible values, three for the south orientation, and one for east and west. Depending on the sun protection, the south could reach a SHGC of 0.35, 0.28, or 0.23. Conversely, the window accepts only 0.3 as value for the east and west sides.

Once all the values are determined, the window illustrates the proper trombe wall width for the selected room configuration. Also the thermal demand and daylight admittance are showed. Attention must be given to the spatial Daylight Autonomy, where a value lower than 50% indicates that insufficient natural light reaches the indoor space.

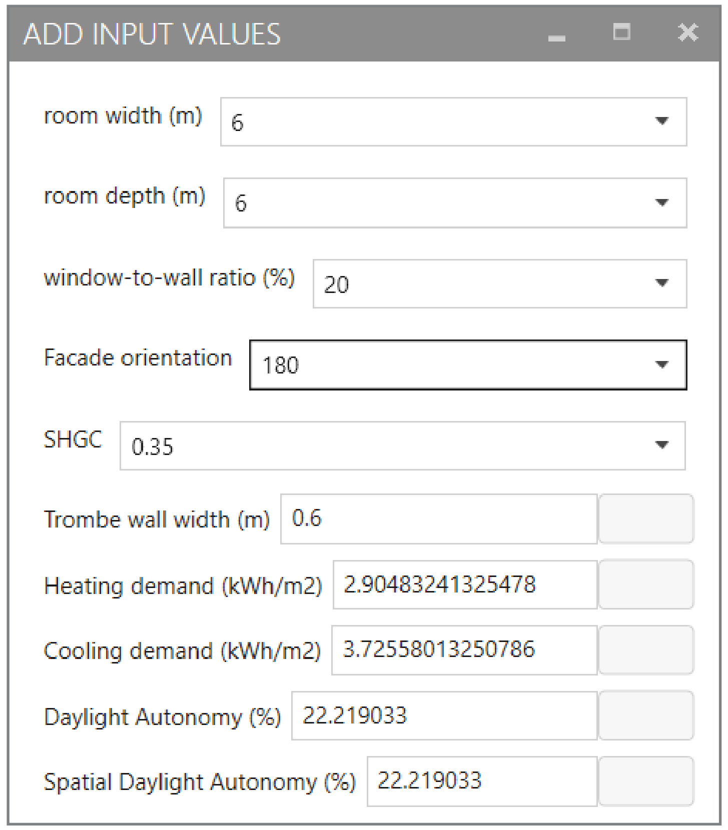
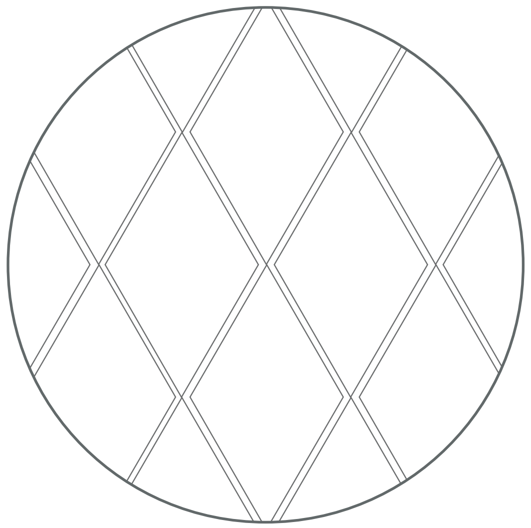
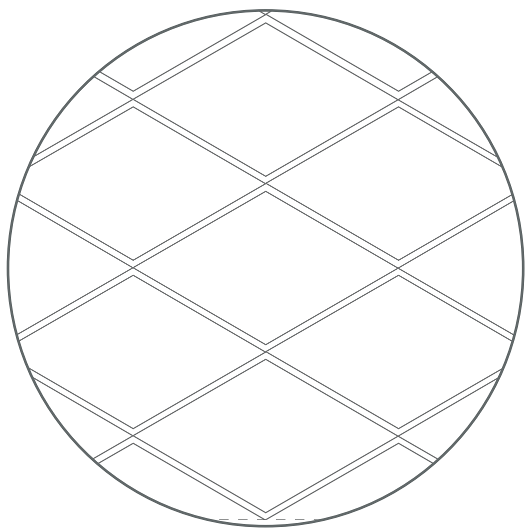


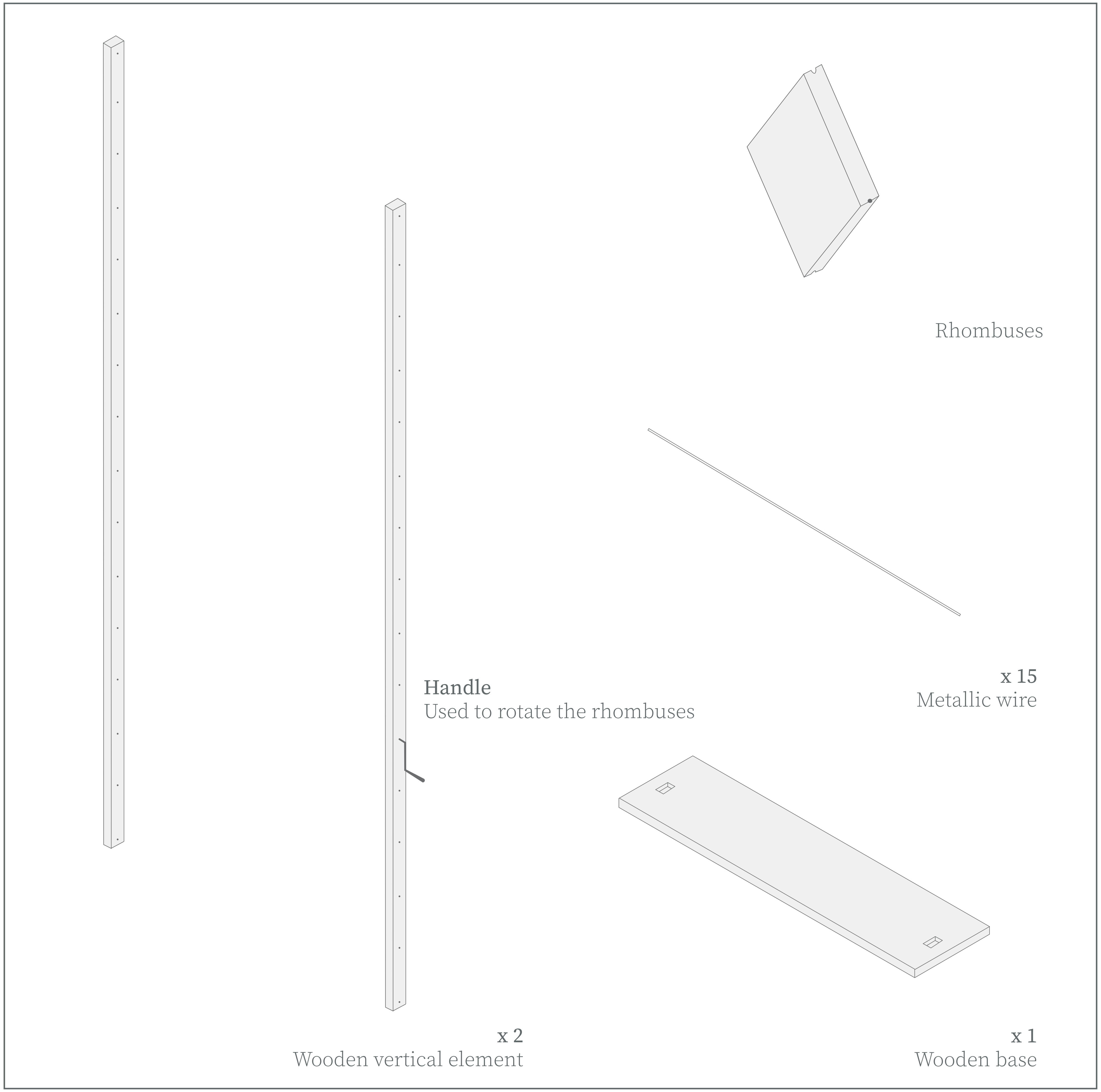
Figure 6.6: window where to insert the values of the room configuration

CONFIGURATIONS

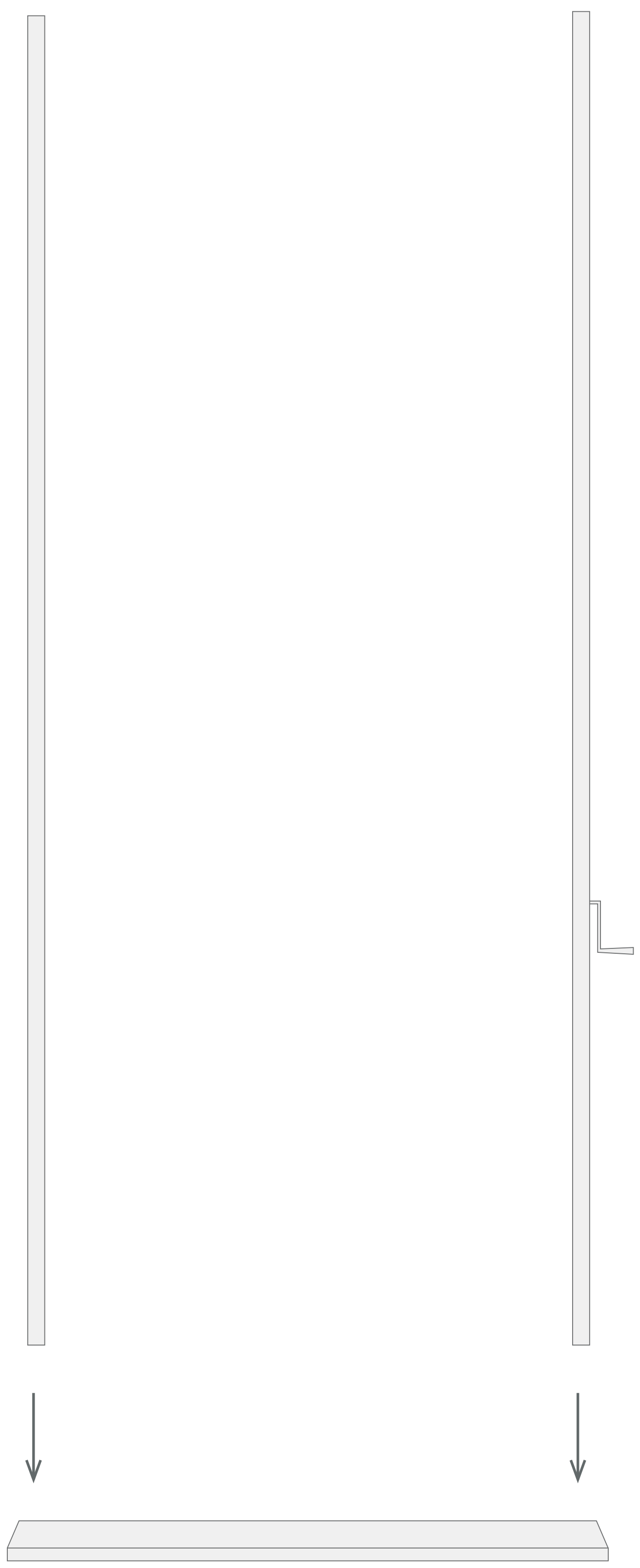
The trombe wall can be assembled with the rhombuses displayed either vertically or horizontally.





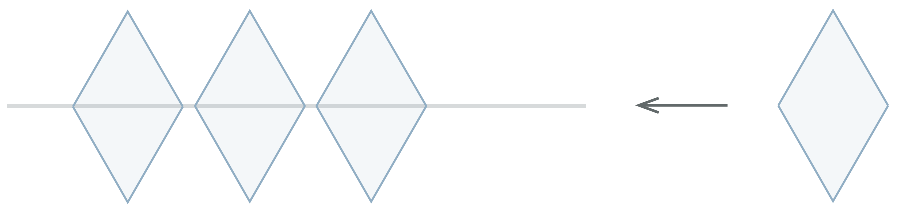


1.



Attach the vertical wooden elements to the base

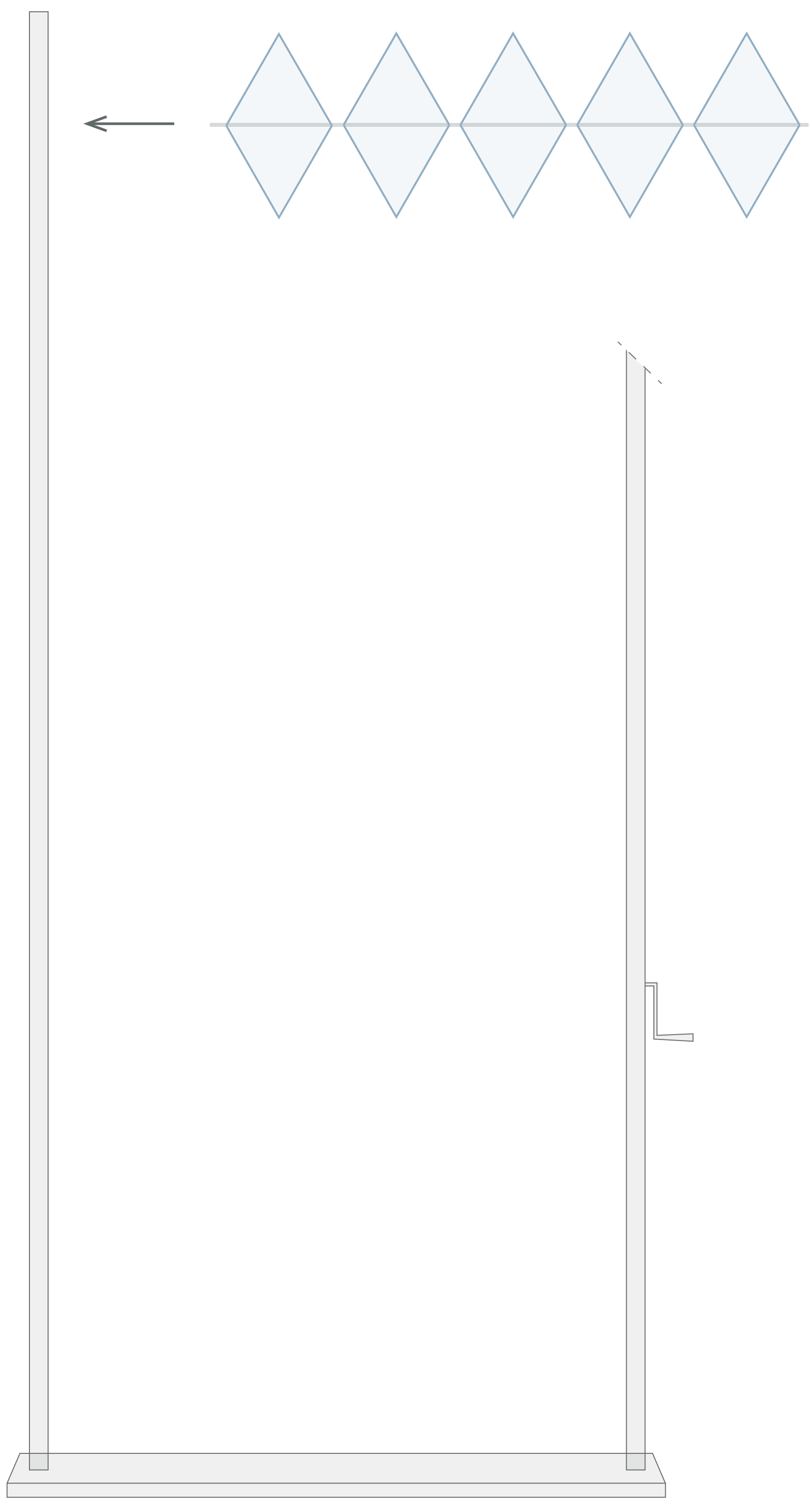
2.



Put the rhombuses in the metallic wire

! Make sure that the PCMs layer of each rhombus faces the same side

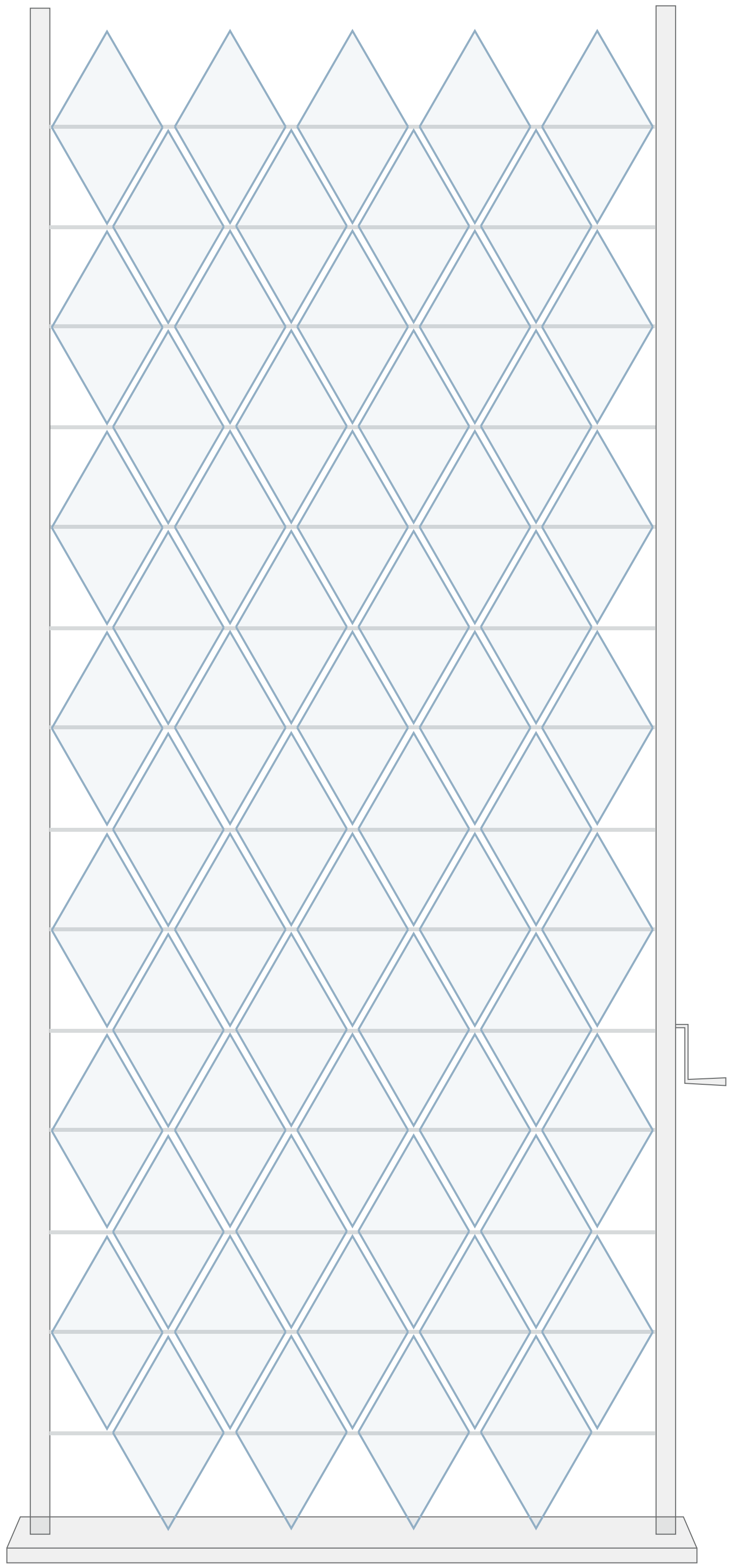
3.



Attach the wires in the holes of the two vertical elements

4.

INSTRUCTIONS FOR THE ROTATION



The PCMs trombe wall is ready to be used

Heating system

8:00 - 18:00

18:00 - 8:00

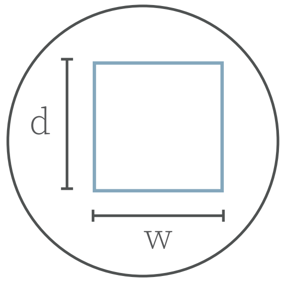
Cooling system

! Activate the ventilation system

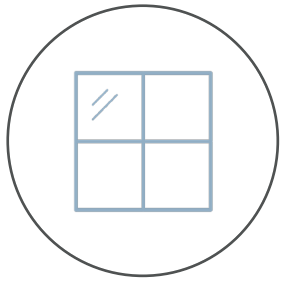
8:00 - 18:00

18:00 - 8:00

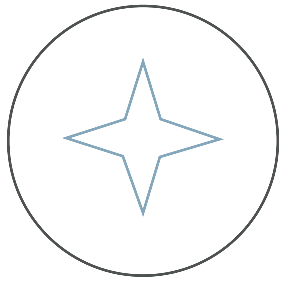
PCMs TROMBE WALL BEHAVIOUR



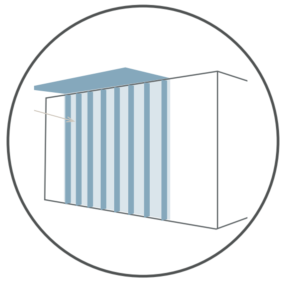
It is advised a room area with a ratio of 1:1 or 3:2 (width : depth)



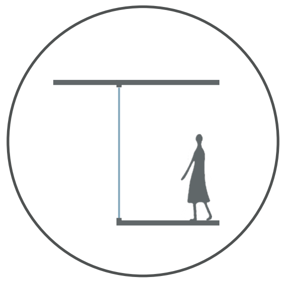
The glazed façade should have a window-to-wall of 80 or 60%



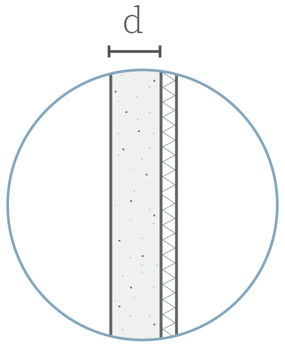
The building can be orientated east, south, or west. However, the south side is preferred.



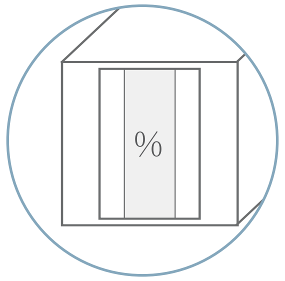
The east and west orientations should include an external fixed shading system, as vertical fins or the presence of biodiversity.



The overhang on the south orientation achieves great performance with any of the three ratio, 1:2, 1:1, and 3:2 (overhang length : room height).



A thickness of the PCMs layer of 1 cm is sufficient to achieve great thermal and daylight performance



If the room does not fulfil the above requirements but is still included in the simulated room configurations, the trombe wall may be still integrated. Indeed, all the designs investigated reach low thermal requirements. Therefore, it is assumed that a decrease in the surface area of the trombe wall could enhance the spatial Daylight Autonomy, while still fulfilling the thermal demand.

ADVICES

- If the room configuration reaches a spatial Daylight Autonomy minor of 50%, it is advised to reduce the surface area of the PCMs trombe wall by decreasing its width.
- The configuration of rhombuses does not impact the trombe wall performance. However, be aware that the product has a different width depending on the pattern.
- Make sure to use a shading system in the summer months to not overheat the PCMs.
- When in cooling mode, do not forget to activate the façade natural or mechanical ventilation system from 18:00 to 8:00. This ensures to refresh the air, heated from the heat released by the trombe wall.

6.3 Conclusion

The chapter illustrates the design of the PCMs trombe wall. By developing the building component at micro and macro scale, the product has achieved its final appearance. On the other hand, the generation of design guidelines simplifies the use of the trombe wall and the PCMs themselves, while ensuring an interaction with the customer.

The rhombuses have a small gap between them which resulted in a trombe wall with an opening percentage of 11.2. Both thermal and daylight simulations were iterated for the final design to verify its performance. The following table compares the wall without and with openings.

Openings (%)	Heating (kWh/m^2)	Cooling (kWh/m^2)	DA (%)	sDA (%)
0	1.45	3.96	60.15	74
11.2	1.55	4.08	62.61	88

The conclude, the design development has investigated the following sub research question: *what is the final appearance of the room and trombe wall if it is researched a balance between the best results of thermal and daylight simulations ?*

07. Conclusion

This chapter concludes the graduation report. The research outcomes are summarized by answering to the (sub) research questions. Subsequently, the further work that may be investigated on this research is described.

7.1 Research question

How can a **modular** and **translucent PCMs trombe wall** be integrated as a passive strategy in **existing** and **energy-optimized** buildings to work as **heating** during winter and **cooling** in summer?

The research has investigated the above research question by developing a workflow that guides the investigation of PCMs trombe walls (figure 7.1). The worflow is described as follows.

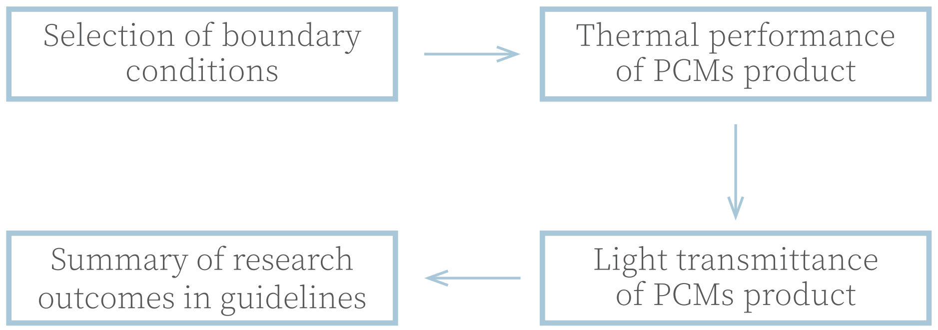


Figure 7.1: workflow for the investigation of translucent PCMs in building components

Firstly, it is necessary to select the boundary conditions that define the scenario where the trombe wall is integrated. For instance, the research requires a building whose shading system is optimized to block the solar radiation only during summer months. The definition of boundaries narrows the possible configurations that can integrate the trombe wall.

Once a specific scenario has been determined, the PCMs must be simulated on their thermal performance and light transmittance. Indeed, the trombe wall is a building component situated in front of the façade, thus it reduces the daylight admittance, which could not fulfil anymore its requirement. Therefore, it is advised to explore also this aspect. For instance, the research has identified only 12 suitable design configurations that meet the daylight building requirements.

During the simulation process, it is preferable to use only one software. This simplifies the definition of variables, which, otherwise, may be considered in two different ways. As an example, the use of two software in this research resulted in the shading effect estimated in Grasshopper by its geometry, but in the MatLab/Simulink by its SHGC.

Once the virtual models are developed and the variables selected, the simulations can be iterated. The results should be evaluated by using post-processing tools that facilitate the data management. Finally, the outcomes of the research should be summarized in guidelines that facilitate further researchers and ideal customers.

While developing a workflow suitable for further research, a PCMs trombe wall has been designed. In particular, the wall reaches great thermal performance for the majority of design configurations investigated. However, the panel has a high impact on the daylight admittance, which may be not able to fulfil its requirement.

Therefore, the following guidelines have been generated to describe how to integrate the trombe wall:

- It is advised a room area with a ratio of 1:1 or 3:2 (width : depth).
- The glazed façade should have a window-to-wall of 80 or 60%.
- The building can be orientated east, south, and west. However, the south side is preferred.
- The east and west orientations should include an external fixed shading system as vertical fins or the presence of biodiversity. However, it is advised to test their shading effect since they should block solar radiation only in the summer.
- The overhang integrated on the south orientation achieves great performance with any of the three ratio, 1:2, 1:1, and 3:2 (overhang length : room height).
- If the room does not fulfil the above requirements but is still included in the simulated room configurations, the trombe wall may be still integrated. Indeed, all the designs investigated reach low thermal requirements. Therefore, it is assumed that a decrease in the surface area of the trombe wall could enhance the spatial Daylight Autonomy, while still fulfilling the thermal demand.

7.1.1 Sub research questions

Which **passive design strategies** are applied in energy-optimized buildings and **how** do they **affect** their thermal inertia?

The analysis carried out in Chapter 2 on the reference case studies identified some common features belonging to the passive design principles. An investigation of them was performed to understand how they influence the thermal inertia of building envelopes. Specifically, the focus is on four strategies: building orientation, window-to-wall ratio, controlled ventilation, and sun-shading system.

The research explored each strategy to reach the following conclusions. The daylight and thermal requirements of buildings are influenced by the façade orientation. Indeed, solar gain reduces the heating demand on the winter, but could increase the cooling if a sun protection does not block the solar radiation in summer days.

Regarding the window-to-wall ratio of dwellings, it is commonly researched an intermediate value that ensures a balance between the thermal and daylight building requirements. As a whole, a smaller WWR enhances heating and cooling as the opaque surfaces have a higher insulation value than glazing systems.

The controlled natural ventilation is beneficial for the thermal demand of buildings in summer. Especially for heavyweight structures, night ventilation cools the indoor space from the heat absorbed during the day. Indeed, building envelopes with high thermal mass have a slow rise in temperature, thus reaching the maximum indoor temperature only in the evening, when the external temperature has already decreased.

Also sun protections have an impact on the trombe wall performance. Indeed, they block the solar radiation only during summer if properly designed. Considering the variety of sun-shading systems, the research classifies them into two categories. The adjustable devices are considered to be open in winter days and closed in summer months when the PCMs could overheat. Whereas, the permanent systems refer to optimized elements that act as a shading device only during the summer.

To conclude, the research assumed that the thermal building demands are affected by these strategies. Indeed, the simulations have investigated the application of certain passive strategies in relation with the PCMs trombe wall.

Which **room variables** are considered to achieve a **modular** PCMs trombe wall that could **adapt** to various buildings?

During the first stages, the research envisioned to test as many variables as possible to include all the differences between rooms. Ideally, the design of the PCMs trombe wall was going to adapt to a multitude of room configurations. However, the thermal requirements of a room are affected by a variety of factors, as the glazing system, the ventilation rate, the surroundings, etc.

As a result, the number of variables was reduced to four: building orientation, room area, window-to-wall ratio, and sun-shading system. The thermal and daylight performance of the trombe wall has been investigated in relation with the room configurations achieved by the aforementioned variables. However, rather than an adaptable design to all configurations, the results have been converted into guidelines that describe the behaviour of the trombe wall to the customer. As a result, the final design is theoretically adaptable to a restricted number of configurations that fulfil the thermal and daylight requirements (page 62).

How are the **thermal performance** and **daylight admittance** affected by the room variables and the PCMs trombe wall?

In Chapter 5, the results of the simulations were analysed to explore how each parameter affects the thermal and daylight building requirements.

The results demonstrate that the heating demand is improved by the thermal insulation value of the building envelope. Thereby, a deeper room and a smaller WWR reach low heating demands. When the façade is mainly glazed, the presence of direct sunlight can enhance the heating as well. Indeed, an ideal glazed façade is wide and faces south or east. Particularly for the south, it is advisable an overhang with a small to medium length as it blocks less solar radiation. Finally, the heating benefits from a thicker trombe wall since it requires more time to heat up.

The cooling demand is improved by either a high thermal mass or a sun shading system that limits the direct solar radiation. As a result, a deeper room, and a smaller WWR are preferred. The most beneficial façade is oriented east/west or even south if integrated with a long overhang. Moreover, a wider façade can reduce the cooling demand if it enhances the ventilation. Finally, a thinner PCMs layer is recommended as it requires less heat to melt, which may otherwise not be entirely fulfilled during the summer months.

To conclude, the daylight is improved by a larger glazed surface area. Therefore, the preferred variables are a wider façade, higher WWR, and a south orientation with a short or medium overhang. The room should have a limited depth, otherwise the daylight may not reach the entire indoor space. Moreover, the PCMs trombe wall slightly influences the light transmission as the material is translucent. Hence, a thinner PCMs layer is advised.

What is the **final appearance** of the room and trombe wall if it is researched a **balance** between the **best results** of thermal and daylight simulations?

The evaluation of the results has lead to the definition of the final room configuration. In particular, the room has an area of 9x6 m (width x depth) with a 80% glazed façade. The room is oriented south and the shading system consists of an overhang with medium length, thus achieving a SHGC of 0.28.

The PCMs trombe wall has a thickness of 1 cm since it ensures higher light transmittance while reducing the cooling demand. The simulations were performed for a trombe wall whose surface area equals the 50% of the glazed façade. Since the results have demonstrated that the minimum sDA value of 50% is frequently not fulfilled, it is advised to not design a trombe wall with a greater area.

The trombe wall has been investigated only on its macro scale. Therefore, the design consists of a flat panel composed of multiple and modular pieces. Specifically, the pieces are rhombuses, which enable to achieve different patterns and widths depending on how they are assembled.

As a whole, the selected design reaches a reduction on the heating demand of 1.74 kWh/ m^2, and on the cooling requirement of 10.28 kWh/ m^2. On the other hand, the sDA reaches a decrease of 26 %.

Which **strategies** could in the future be developed to bridge the **gap** between a **customized** and **unique** PCMs product and a **standardized** and modular component?

As described in the problem statement, the market on the built environment offers already some PCMs products. However, these products are designed only on request, thus being unique and customized. The lack of modular and standardized PCMs products is due to their limited knowledge. For this reason, the research has investigated strategies that can expand their application in the built environment.

The strategies have been classified into two objectives by the research. Indeed, the expansion of the material requires a progress on research about PCMs, and a development of principles that can facilitate the customer.

Being PCMs still experimental materials, the information on them must be enlarged by researching unexplored aspects. Indeed, a complete overview on the material would simplify the integration of PCMs in building components. Moreover, once a research has reached its outcomes, it is advised to convert them in guidelines that summarize the results. This highlights the main discoveries, while preparing a theoretical basis for further research. An example of this criteria is visible in Chapter 6.
Considering the limited software to properly simulate the thermal performance on PCMs, the creation of a platform to share the virtual models developed by each research could reach great results. Indeed, it requires much time to understand where PCMs can be investigated, and in case, to develop virtual models.

Finally, the research outcomes must be developed with thinking on the customer. As an example, the user should become aware on what PCMs are. Indeed, during the research, it was discovered that the material is not easily visualized without detailed explanations on their colour, shape, and functioning.

7.2 Further work

The research focused on the integration of PCMs trombe walls in existing and energy optimized buildings to work as heating and cooling systems. The thermal performance of the building component was compared with its light transmittance to find a balance between them.

The development of the research outlined some aspects that could be explored in more detail. They are described as follows:

- Investigation of a stepped calculation suitable to convert the shading effect given by a geometry to its Solar Heat Gain Coefficient.
- Further analysis on the room and trombe wall parameters necessary to achieve a higher spatial Daylight Autonomy in more design configurations. Indeed, the research outlined only 12 configurations with a sDA equal or higher 50%. An example could be the investigation of a PCMs trombe wall with a lower surface area than 50%, as the research took into account.
- Research on the thermal and daylight performance of the PCMs trombe wall for other properties that differ in rooms, such as the ventilation system, building function, etc.
- Analysis on how the micro scale of the PCMs trombe wall can affect its thermal and light performance in relation with the room variables. Indeed, the research focused only on the macro scale since it simulated a flat panel. Therefore, it is lacking on research on how 3D protrusions can influence the outcomes estimated.
- Refinement of the building component design and development of a prototype.
- Real life measurements on the prototype. For instance, the translucency value could be explored for both phases of the PCMs (liquid and frozen).

7.3 Conclusion

The aim of this study was the development of strategies that can expand the use of PCMs products in the built environment. This was achieved by exploring how a modular and energy-efficient PCMs trombe wall can be integrated in existing residential buildings in the Netherlands. In particular, the research demonstrated the potential of PCMs in terms of thermal energy storage systems by designing a PCMs trombe wall. The building component was analysed not only on its thermal performance, but also on its daylight transmittance because of the translucency of PCMs.

As a whole, this illustrated how a PCMs trombe wall can act as an intermediary element to reach a balance between the thermal and daylight requirements of residential buildings. Indeed, the trombe wall ensures a greater area of glazed façade while enhancing the thermal inertia of the building envelope. Moreover, it limits the building energy demand by passively heating/cooling the indoor space and guaranteeing a higher surface area of glazing, which reduces the need for artificial lighting.

The research topic was explored by digitally simulating the thermal performance and light transmittance of the PCMs trombe wall, which required the use of two different software. This resulted limiting since each software works and requires data differently, as for the shading effect considered in Grasshopper by the geometry and in MatLab/Simulink by the SHGC. Moreover, the use of software requires a proper knowledge on their functioning and should not be substituted by real-life measurements. Indeed, virtual models cannot fully reproduce the variety of factors that influence the buildings in real life.

Despite the limitations encountered, the research was able to demonstrate the potential of PCMs trombe walls, and more generally of PCMs. This was achieved by estimating the reduction in thermal demand of room configurations with the PCMs trombe wall. If the building component has a positive thermal reduction, it also impacts negatively the daylight admittance by reducing the percentage of spatial Daylight Autonomy. However, the reduction is about 10 - 20 % and still ensures the transmittance of light, in contrast to the higher presence of opaque walls that would required for the thermal inertia of the building envelope. Therefore, the research on the PCMs trombe wall is considered to be beneficial for the potential reduction of building energy demands. Moreover, the generation of design guidelines in Chapter 6 aims to leave the main outcomes of this research by trends that are easy to read and understand also for people who do not have knowledge in PCMs and building requirements.

Reflection

This chapter reflects on the research topic explored for the Master's thesis. The theme belongs to the Building Technology Graduation Studio of TU Delft. The focus is on two subjects of the Building Technology Master's track: Building Physics and Design Informatics. The topic, methodology, and relevance of the thesis are discussed in the following paragraphs.

Graduation topic

In the last decades, the Earth has been showing the impact of human activities by an increase in temperature that is leading to catastrophic events. Climate change is caused by the combustion of fossil fuels, where housing and tertiary buildings are responsible for the consumption of 46% of energy. It is, therefore, necessary to identify strategies to minimize or eliminate the reliance on buildings in mechanical systems for heating, cooling, and lighting. For this reason, the research explores the application of Phase Change Materials (PCMs) in the built environment. Indeed, these materials absorb a great amount of energy during their phase transition to release it later. In other words, they can passively heat or cool indoor spaces, thus replacing mechanical systems. Although there is a consistent number of research papers on PCMs, their application is still very limited. Moreover, the most common incorporation process consists of the encapsulation of PCMs in containers made of another material. The capsules have a variable dimension (macro, micro, and nano-encapsulation) and, commonly, are mixed with construction materials.

By mixing the PCMs with construction material, the achieved building component is opaque. A few researches have demonstrated that PCMs can be encapsulated in transparent plastics to benefit from their translucency. Indeed, if some PCMs as salt hydrates are semitransparent also in the solid phase, they are all translucent when liquid. This confers great potentiality to the PCMs, which could be applied for the design of a translucent building component that acts as an intermediary between the glazed façade and the opaque walls of the indoor space. Examples are PCMs curtains, shutters, and trombe walls. In particular, this research focuses on the integration of PCMs in trombe walls, whose traditional design consists of a massive, thick, and opaque wall placed in front of a glazed façade. Indeed, the classical trombe wall benefits from its high thermal mass to act as a passive storage system that can heat up or cool down an environment. Alternatively, PCMs trombe walls profit from the thermal properties of PCMs to constitute a thin, lightweight, and translucent building component that has equal outcomes to traditional trombe walls.

The thesis starts from the knowledge gained by previous research. Particular attention is given to Double Face 2.0, a project developed on a PCMs trombe wall by Martin Tenpierik and Michela Turrin, professors at TU Delft. At the same time, the MSc thesis developed by Eve G. Farruggia investigated some aspects of Double Face 2.0 in further detail. Indeed, the emphasis was on the impact of geometry on the thermal performance of a PCMs trombe wall in two different climate zones. Similarly, the aim of this research is to explore other fields of PCMs that have not previously been investigated.

The thesis has two main focuses. Firstly, the PCMs trombe wall is simulated to research a balance between the high thermal mass required by buildings and the large glazed area necessary for the daylight admittance. Ideally, the PCMs trombe wall can act as an intermediary element. Indeed, it enhances the thermal inertia of the building envelope while diffusing the daylight in the indoor space. The second focus of the research is on the development of a modular design that could adapt to multiple scenarios. However, since the thermal and light requirements of rooms are affected by a variety of factors, the research envisions to only provide an overview on the PCMs behaviour in relation with the building requirements. This is achieved by iterating multiple simulations in which the room variables are tested for each of their values. Specifically, the room variables correspond to aspects that vary by room, such as the room volume, orientation, and window-to-wall ratio.

As a whole, the research is looking for strategies that can expand the use of PCMs trombe walls in the built environment. This is accomplished by demonstrating the great potentiality of the building component. Being lightweight and modular, the user has great control of it while the building's thermal demand is reduced. It is, therefore, necessary to diffuse the knowledge of the product by showing its suitability to balance the thermal and daylight building requirements.

Graduation process

The research is organised into four phases, where the first consists of a theoretical framework. The framework is divided into four topics that deepen the level of detail. Indeed, the literature research begins with an explanation of computational design, where, after a brief description, the focus is on buildings designed parametrically. The second group analyses one building layer: the building envelope and its functions. Particular attention is given to its thermal mass and role in daylight admittance. The level of detail is then further increased to focus on a specific building component, the trombe wall. Finally, attention is directed towards the material used in the trombe wall: phase change materials. A number of research papers on PCMs were read about their functioning, classification, and location, while certain case studies were used as base for this research.

Once the theoretical framework phase is completed, all the necessary factors for the simulations are defined. The simulations test the thermal performance and light transmittance of the trombe wall. Whereas, the factors consist on the definition of a climate zone, building function and typology, room variables, and materials for the PCMs trombe wall. Subsequently, a case study is selected to set an environment for all the constant aspects of the simulations. Lastly, the previous outcomes on PCMs trombe walls are translated into design guidelines for this research.

The next step consists of digital research through a design framework. Once the variables of the room and the trombe wall are defined, the thermal energy simulations are iterated in MatLab/Simulink. The performance of the trombe wall is tested as a heating system during the winter and a cooling device on summer days. The simulations are at room level and, therefore, test the energy efficiency of the entire panel. While the thermal simulations are performed in MatLab/Simulink, daylight simulations are carried out in Grasshopper. The daylight admittance is investigated by calculating the spatial Daylight Autonomy (sDA) of each design configuration. In particular, the research analyses the impact that each variables combination has on the building demand. This is accomplished by automating the simulation process.

Once the simulations are concluded, the results are evaluated. Focus is given to the values that fulfil both thermal and daylight building demands. The software ModeFrontier enables to read from a multitude of results by using post-processing tools. Moreover, the results of the simulations are translated into a workflow, which illustrates the thermal and daylight performance of the trombe wall for the selected design configuration. The workflow is developed as a strategy to expand the application of PCMs trombe walls by creating an interaction between the customer and the product. As last step, the most performing design configuration is selected as scenario for the placement of the PCMs trombe wall. On the other hand, the product is developed at macro and micro scale to assume its final design.

As a whole, the methodology was slightly modified during the research process. Indeed, the aim to link the MatLab/Simulink model to ModeFrontier resulted in the need of changes, which required the knowledge in programming language. The application of ModeFrontier was going to optimize the simulation process by automatically performing multiple simulations. In conclusion, the same objective has been achieved by using a Master file developed by the previous researcher Jeroen van Unen. The file can be, indeed, connected to the MatLab model to automatize the simulation process.

The difficulty encountered with the MatLab/Simulink model was managed by looking for a better approach for the purpose of this research. The desire to work constantly on the thesis, and the awareness that research is an evolving study in which changes are inevitable, led to finding another solution. If the methodology was slightly modified, the new approach is more realistic and does not expect a design that is adaptable to a large range of scenarios, which could have been limiting. Moreover, the research still requires the use of the same software, but the level of challenge was decreased to be fully explored and achieved by the researcher.

Research and design

The methodology of this study considers research and design as two interrelated components. Firstly, the outcomes of previous projects are translated into design guidelines to set a base design for the PCMs trombe wall. Subsequently, the research performed by the simulations demonstrates how the design of the room and trombe wall affects the building requirements. Finally, the outcomes of the simulations are analysed to determine which room configuration and trombe wall design provides the best performance.

Social impact

Even though PCMs are experimental materials, a few PCMs products are already for sale in the built environment. For instance, the company GlassX offers two typologies of windows with a cavity filled with PCMs. However, these products are designed only on request, thus being unique and customized. This limits the range of clients that can afford it in terms of cost and time of production. The lack of modular and standardized PCMs products is due to their limited knowledge. For this reason, it is essential to keep researching this material and finding strategies to expand its application in the built environment.

PCMs have great potential when integrated with various building components. For instance, a PCMs trombe wall is a passive heating system, whose thermal performance is achieved with a wall of 2 cm rather than 15 cm. Moreover, being the PCMs trombe wall lightweight, it can be movable, while requiring a small amount of materials. Conversely to the traditional trombe wall, the innovative building component enables also natural light to enter the building. As a whole, the integration of PCMs in the building component solves many downsides of the classical trombe wall and confers a new potentiality to the wall. Therefore, the component could act as a passive strategy to increase the thermal mass of contemporary buildings, which frequently have a lightweight construction.

The great potentiality of this material is also appreciated by society. Indeed, the thesis was developed by contacting researchers of previous projects, which explained the downsides they encountered while experimenting with PCMs. This has demonstrated that the material still needs to be investigated before being applicable in standardized building components.

This research is developed to enlarge the information in PCMs by analysing unexplored aspects of the material. In particular, the trombe wall of the project has been, ideally, developed as a product that will be on the market. Therefore, the research and analysis that have characterized the thesis will be converted into guidelines for customers. This will enable the users interested in the product to easily gain an understanding on how the PCMs trombe wall could perform in their house.

Even if the product is only theoretically developed to be on the market, the thesis envisions to leave its workflow as the basis for further research. The workflow consists of the research methodology and the description on how the tested parameters affect the building performance. For instance, a further researcher could investigate other room variables, and then, combine the results to gain a wider overview.

Bibliography

Literature reference list

Ghosh, I. (2021, February 9). Since 1850, these historical events have accelerated climate change. *World Economic Forum*. https://bit.ly/3jYMwHl

United Nations. (n.d.). *What is climate change?* https://bit.ly/3jwKBtD

Larsson, S. (n.d.). *Modular Construction in Architecture: The Future of Flexible Design*. UnStudio. https://bit.ly/3ZgBy0d

Jabi, W. (2013). *Parametric design for architecture.* Laurence King Publishing.

Tedeschi, A. (2014). *Algorithms-Aided design: Parametric Strategies using Grasshopper*. Le Penseur Publisher.

Ramage, M. (2022, April 21). *What is Computational Design?* Trimble Construction. https://bit.ly/3H06B9D

Glassman, E., & Reinhart, C. F. (2013, August 26-28). *Facade Optimization Using Parametric Design and Future Climate Scenarios* [Paper presentation]. 13th Conference of International Building Performance Simulation Association., Chambery, France. http://dx.doi.org/10.26868/25222708.2013.974

Rocha, R. (2021). *Switching the Parametric Design Approach* [Architectural History Thesis, TU Delft]. TU Delft Repository. http://resolver.tudelft.nl/uuid:b76a48d5-2150-4f3b-af77-45fed329cf9b

Menges, A., Sheil, B., Glynn, R., & Skavara, M. (2017). *Fabricate: Rethinking design and construction*. UCL Press. https://doi.org/10.14324/111. 9781787350014

Serpentine Pavilion. (2016). *Serpentine Pavilion and Summer Houses 2016*. http://bit.ly/3XD2uW9

Aectual. (n.d.). *Soundwave . Horizontal*. http://bit.ly/41c0LJe

Ching, F. D. K., & Shapiro, I. M. (2014). *Green building illustrated*. Wiley.

Altan, H., & Aoul, K. T. (2016). Passive Design. In Noguchi, M., *ZEMCH: Toward the Delivery of Zero Energy Mass Custom Homes* (pp. 209 - 236). Springer International Publishing. https://doi.org/10.1007/978-3-319-31967-4_8

Knaack, U., Klein, T., Bilow, M., & Auer, T. (2007). *Façades: Principles of construction*. Birkhäuser Verlag AG.

Kalkhoven, P., & Verkuijlen, S. (2019). *Technical Design Guide: Façades*. Publisher. Delft University of Technology.

Murray, S. (2013). *Translucent Building Skins: Material in Modern and Contemporary Architecture*. Taylor & Francis Group.

Van der Linden, A. C., Kuijpers-Va Gaalen, I. M, & Zeegers, A. (2018). *Building Physics* (2nd ed.). ThiemeMeulenhoff

Wiedenhoff, J., & de Vaan, C. (2010). Thermal mass; about the myth. *TVVL Magazine, 39*(7-8), 28 - 31.

Tilmann, E. K. (2017). State of the art of advanced solar control devices for buildings. *Solar Energy, 154*(2017), 112 - 133. https://doi.org/10.1016/j.solener.2016.12.044

Overbey, D. (2015, May 18). *Comparing Solar Heat Gain Coefficients (SHGC) and Shading Coefficients (SC)*. Building Enclosure. http://bit.ly/3Etet1s

First Green Consulting. (2023, February 26). *Understanding the SHGC*. https://bit.ly/3MkvX50

Bureau of Energy Efficiency. (2017). *Energy Conservation Building Code 2017*. https://bit.ly/3qip7nw

Netherlands Enterprise Agency. (n.d.). *Building regulations*. Business.gov.nl. https://bit.ly/3UEHAFT

Rijksdienst voor Ondernemend Nederland. (2017, July 12). *Energieprestatie indicatoren - BENG* [Energy performance indicators - BENG]. https://bit.ly/43BEB5j

Zhou, D., Zhao, C. Y., & Tian, Y. (2012). Review on thermal energy storage with phase change materials (PCMs) in building applications. *Applied Energy, 92*(2012), 593-605. https://doi.org/10.1016/j.apenergy.2011.08.025

Xiong, Q., Alshehri, H. M, Monfaredi, R., Tayebi, T., Majdoub, F., Hajjar, A., Delpisheh, M., & Izadi, M. (2021). Application of phase change material in improving trombe wall efficiency: An up-to-date and comprehensive overview. *Energy and Buildings, 258*(2022). https://doi.org/10.1016/j.enbuild.2021.111824

Mehling, H., Brütting, M., & Haussmann, T. (2022). PCM products and their field of application - An overview of the state in 2020/2021. *Journal of Energy Storage, 51*. https://doi.org/10.1016/j.est.2022.104354

Baetens, R., Jelle, B. P., & Gustavsen, A. (2010). Phase change materials for building applications: A state-of-the-art review. *Energy and Buildings, 42*(2010), 1361 - 1368. https://doi.org/10.1016/j.enbuild.2010.03.026

Cui, Y., Xie, J., Liu, J., Wang, J., & Chen, S. (2017). A review in phase change material application in building. *Advances in Mechanical Engineering, 9*(6), 1-15. https://doi.org/10.1177/ 167814017700828

Kuznik, F., David, D., Johannes, K., & Roux, J.-J. (2011). A review on phase change materials integrated in building walls. *Renewable and Sustainable Energy Reviews, 15*(1)*, 379-391*. https://doi.org/10.1016/j.rser.2010.08.019

Vigna, I., Bianco, L., Goia, F., & Serra, V. (2018). Phase Change Materials in Transparent Building Envelopes: A Strengths, Weakness, Opportunities and Threats (SWOT) Analysis. *Energies, 11*(2018). https://doi.org/10.3390/en11010111

Omara, A. A. M., & Albenuor, A. A. A. (2020). Trombe wall with phase change materials: A review. *Energy Storage, 2*(6). https://doi.org/10.1002/est.2.123

Meteoblue. (n.d.). *Climate zones*. http://bit.ly/3iMZMyf

GlassX. *Products*. https://www.glassx.ch/en/products/glassx-crystal/

Tenpierik, M.J., Turrin, M., Wattez, Y.C.M., Cosmatu, T., & Tsafou, S.E. (2018). *Double Face 2.0: A lightweight, adjustable, translucent Trombe wall*. TU Delft Repositories. http://resolver.tudelft.nl/uuid:01e9d1d2-80a3-4974-a463-8c0d2b20b78d

Farruggia, E. G. (2018). *Thermal Morphology: A Geometrically Optimized Trombe Wall* [Master's thesis, TU Delft]. TU Delft Repository. http://resolver.tudelft.nl/uuid:0ad5f3cc-a5e9-45c0-a37e-75e139713409

Royal Danish Academy. (2018). *Phase Change Material (PCM) Facade*. https://bit.ly/3Vn4WiY

Van Unen, J. (2019). *The Energy and Comfort Performance of a Lightweight Translucent Adaptable Trombe Wall in Different Buildings and Climates: A Numerical study* [Master's thesis, TU Delft]. TU Delft Repository. http://resolver.tudelft.nl/uuid:2f619b08-4bd4-4d20-98ef-091f2bd1e136

Wikipedia. (2023, January 29). *Amsterdam*. http://bit.ly/3wCZbD2

Energy Design Tools. (2023). *Climate Consultant 6.0*

Donner, J. P. H. (2012). *Draft Building Decree [Bouwbesluit] 2012*. European Commission. http://bit.ly/3JmPoIZ

AL Windows. (n.d.). *Which type of glass is best for energy efficiency?* http://bit.ly/3EbjzPM

Guerra-Santin, O., & Silvester, S. (2016). Development of Dutch occupancy and heating profiles for building simulation. *Building Research & Information, 45*(4), 396-413. https://doi.org/10.1080/09613218.2016.1160563

Worldometer. (2023). *Netherlands Population*. http://bit.ly/3JY0aFY

Van Mameren, A. (2022, October 3). *The education system in the Netherlands*. Expatica. http://bit.ly/3loWse3

Weessies, R. (2022, December 14). *Team met Mecanoo en BOOM Landscape ontwerpt woongebouw aan Beatrixpark Zuidas* [Team with Mecanoo and BOOM Landscape designs residential building at Beatrixpark Zuidas]. Architectenweb. http://bit.ly/3DEPV5k

Mecanoo. (2022, December 14). [Mecanoo wins tender for nature-inclusive residential building at Amsterdam Zuidas]. https://bit.ly/3ksMmrX

KondorWessels. (n.d.). *Habitat Royale: Beatrixpark.*

Rubitherm. (n.d.). *SP25E2*. Rubitherm. http://bit.ly/3wQiNDW

Cabot. (n.d.) *Lumira translucent aerogel LA1000; LA2000*. http://bit.ly/3IbbnAt

Ladybug Tools. (n.d.). *Ladybug Tools*. food4Rhino. https://bit.ly/444wWgb

EnergyPlus. (n.d.). *Weather data*. https://bit.ly/3HdKVGF
TOI-Pedia. (2021, December 19). *Honeybee Tutorial 1: Creating the HB model*. https://bit.ly/3oJOxJS

Image reference list

1.1 - Ghosh, I. (2021, February 9). Since 1850, these historical events have accelerated climate change. *World Economic Forum*. https://bit.ly/3jYMwHl

2.1 - Serpentine Pavilion. (2016). *Serpentine Pavilion and Summer Houses 2016*. http://bit.ly/3XD2uW9

2.2 - Aectual. (n.d.). *Soundwave . Horizontal*. http://bit.ly/41c0LJe

2.3 - ArchDaily. (2016, April 8). *Citylife Apartments / Zaha Hadid Architects*. http://bit.ly/3J3pAS5

2.4 - Koschuch. (n.d.). *Elements*. http://bit.ly/3XjZ62J

2.5 - Mecanoo. (2022, December 14). *Mecanoo wins tender for nature-inclusive residential building at Amsterdam Zuidas*. http://bit.ly/3ksMmrX

2.6 - MVRDV. (n.d.). La Vallée Verte. https://bit.ly/3CYenhv

2.7 - Smakkelaarspark. (n.d.). About Spark. http://bit.ly/3CVWKik

2.8 - ARUP. (n.d.). *How do you use parametric design to push the boundaries of what is possible?* http://bit.ly/3IYK2Dj

2.13 - Knaack, U., Klein, T., Bilow, M., & Auer, T. (2007). *Facades: Principles of construction*. Birkhäuser Verlag AG.

2.14 - Murray, S. (2013). *Translucent Building Skins: Material in Modern and Contemporary Architecture*. Taylor & Francis Group.

2.15/ 2.16 - Omara, A. A. M., & Albenuor, A. A. A. (2020). Trombe wall with phase change materials: A review. *Energy Storage, 2*(6). https://doi.org/10.1002/est.2.123

2.17 - Vicente, R., & Silva, T. (2014). Brick masonry walls with PCM macrocapsules: An experimental approach. *Applied Thermal Engineering, 67*(1-2), 24 - 34. https://doi.org/10.1016/j.applthermaleng.2014.02.069y

2.18 - Baetens, R., Jelle, B. P., & Gustavsen, A. (2010). Phase change materials for building applications: A state-of-the-art review. *Energy and Buildings, 42*(2010), 1361 - 1368. https://doi.org/10.1016/j.enbuild.2010.03.026

2.19/ 3. 1- VectorStock. (n.d). *Map with world climate zones vector image*. http://bit.ly/3Xh36Be

2.20 - Zhou, D., Zhao, C. Y., & Tian, Y. (2012). Review on thermal energy storage with phase change materials (PCMs) in building applications. *Applied Energy, 92*(2012), 593-605. https://doi.org/10.1016/j.apenergy.2011.08.025

2.21 - Cui, Y., Xie, J., Liu, J., Wang, J., & Chen, S. (2017). A review in phase change material application in building. *Advances in Mechanical Engineering, 9*(6), 1-15. https://doi.org/10.1177/ 167814017700828

2.22 - Vigna, I., Bianco, L., Goia, F., & Serra, V. (2018). Phase Change Materials in Transparent Building Envelopes: A Strengths, Weakness, Opportunities and Threats (SWOT) Analysis. *Energies, 11*(2018). https://doi.org/10.3390/en11010111

2.23 - Tenpierik, M.J., Turrin, M., Wattez, Y.C.M., Cosmatu, T., & Tsafou, S.E. (2018). *Double Face 2.0: A lightweight, adjustable, translucent Trombe wall*. TU Delft Repositories. http://resolver.tudelft.nl/uuid:01e9d1d2-80a3-4974-a463-8c0d2b20b78d

2.24 - Farruggia, E. G. (2018). *Thermal Morphology: A Geometrically Optimized Trombe Wall* [Master's thesis, TU Delft]. TU Delft Repository. http://resolver.tudelft.nl/uuid:0ad5f3cc-a5e9-45c0-a37e-75e139713409

2.25 - Royal Danish Academy. (2018). *Phase Change Material (PCM) Facade*. https://bit.ly/3Vn4WiY

3.2 - Energy Design Tools. (2023). *Climate Consultant 6.0*

3.3 - Guerra-Santin, O., & Silvester, S. (2016). Development of Dutch occupancy and heating profiles for building simulation. *Building Research & Information, 45*(4), 396-413. https://doi.org/10.1080/09613218.2016.1160563

3.4 - Weessies, R. (2022, December 14). *Team with Mecanoo and BOOM Landscape designs residential building at Beatrixpark Zuidas*. Architectenweb. http://bit.ly/3DEPV5k

3.8 - Zhou, D., Zhao, C. Y., & Tian, Y. (2012). Review on thermal energy storage with phase change materials (PCMs) in building applications. *Applied Energy, 92*(2012), 593-605. https://doi.org/10.1016/j.apenergy.2011.08.025

3.9 - Rubitherm. (n.d.). *SP25E2*. Rubitherm. http://bit.ly/3wQiNDW

Appendix

	Composite	Hot and dry	Warm and humid	Temperate	Cold
Maximum U-factor ($W/m^2 \cdot K$)	2.20	2.20	2.20	3.00	1.80
Maximum SHGC non-north	0.25	0.25	0.25	0.25	0.62
Maximum SHGC north for latitude ≥ 15° N	0.50	0.50	0.50	0.50	0.62
Maximum SHGC north for latitude < 15° N	0.25	0.25	0.25	0.25	0.62

Table I: vertical fenestration U-factor and SHGC requirements
Source: edited from *Energy Conservation Building Code 2017*, by Bureau of Energy Efficiency, 2017, https://bit.ly/3qip7nw

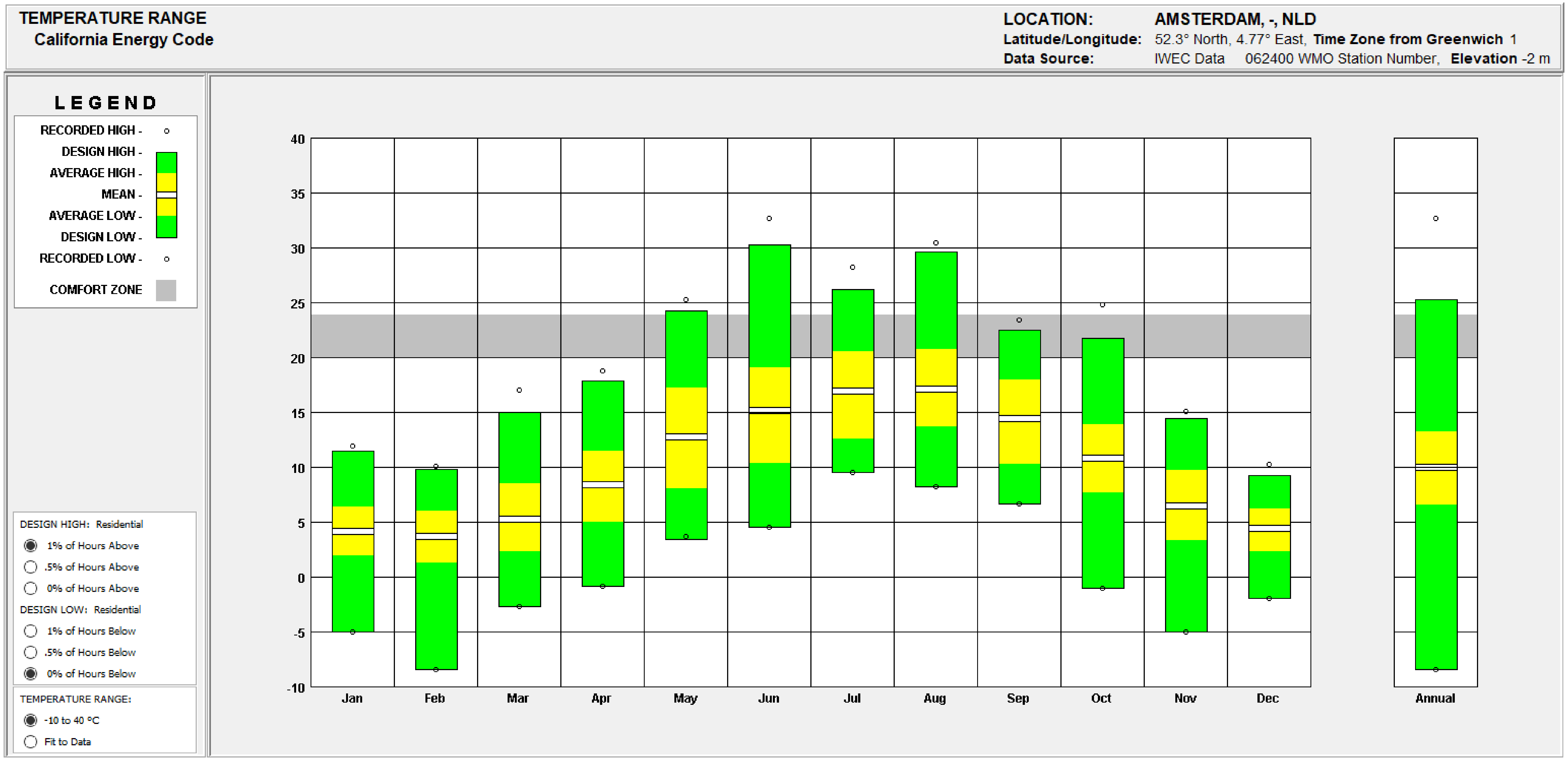


Table II: temperature range of Amsterdam
Source: from *Climate Consultant 6.0*, by Energy Design Tools, 2023

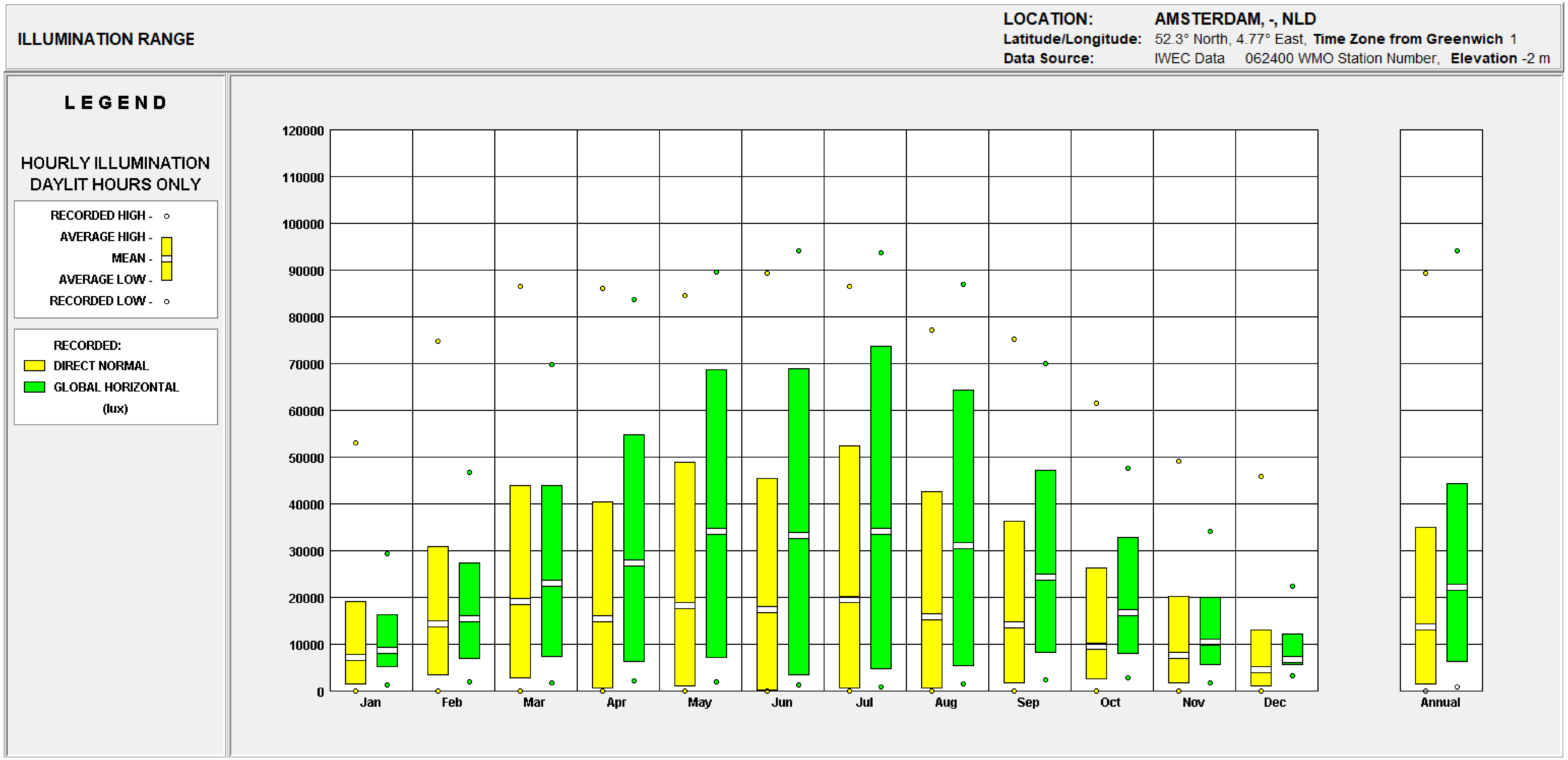


Table III: illumination range of Amsterdam
Source: from *Climate Consultant 6.0*, by Energy Design Tools, 2023

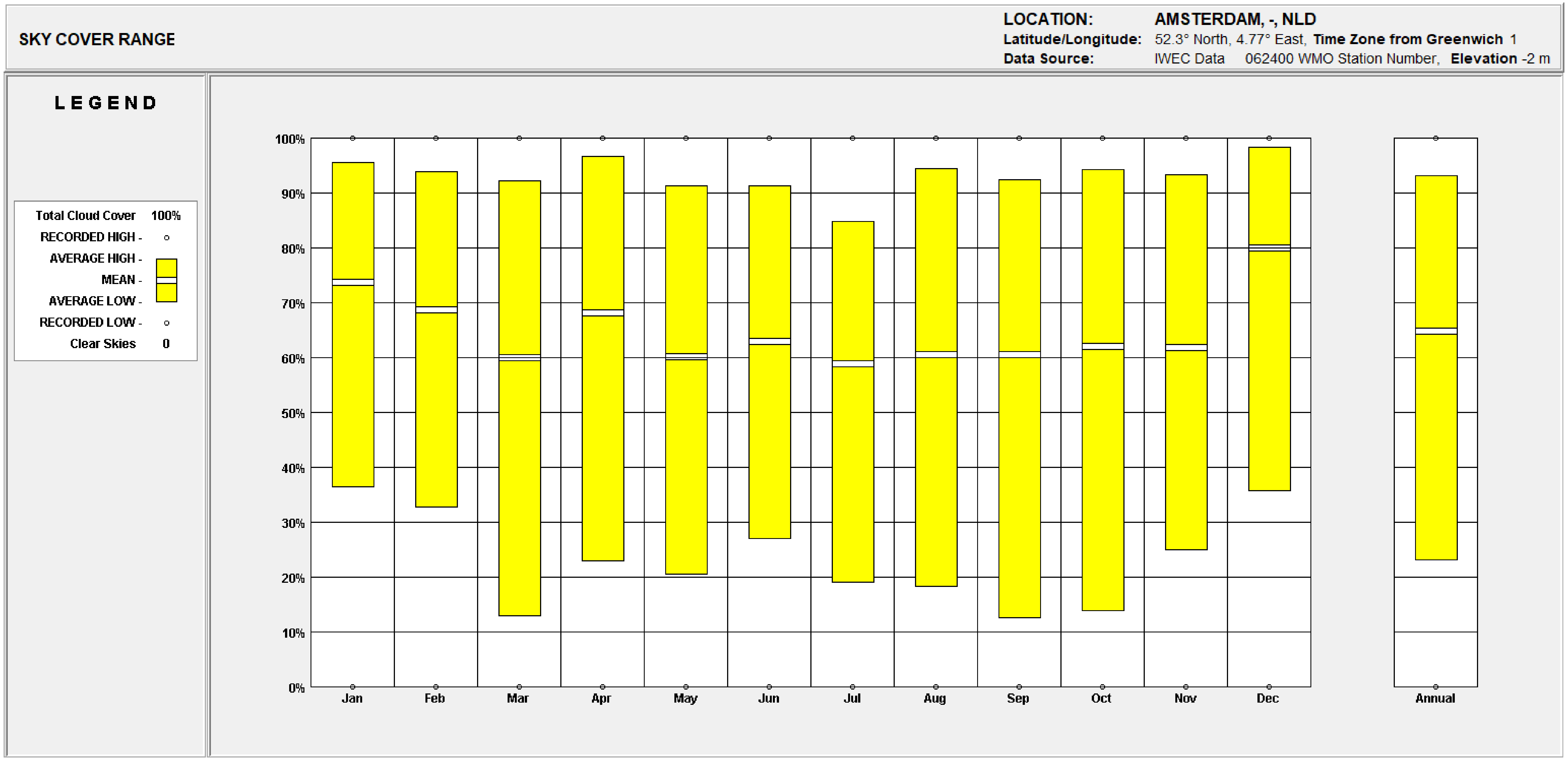


Table IV: range of sky cover in Amsterdam
Source: from *Climate Consultant 6.0*, by Energy Design Tools, 2023

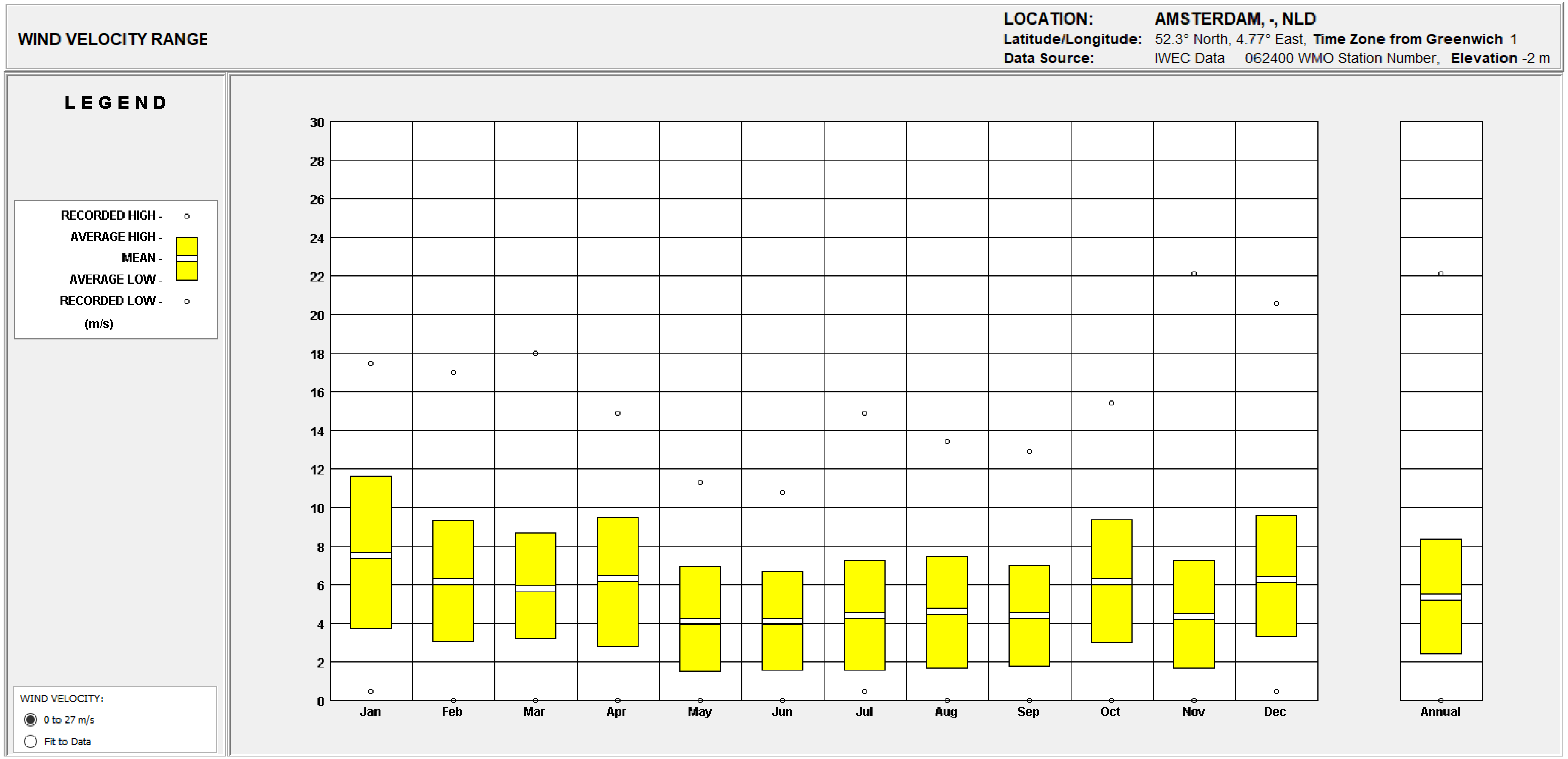


Table V: yearly wind velocity of Amsterdam
Source: from *Climate Consultant 6.0,* by Energy Design Tools, 2023

SP25E2

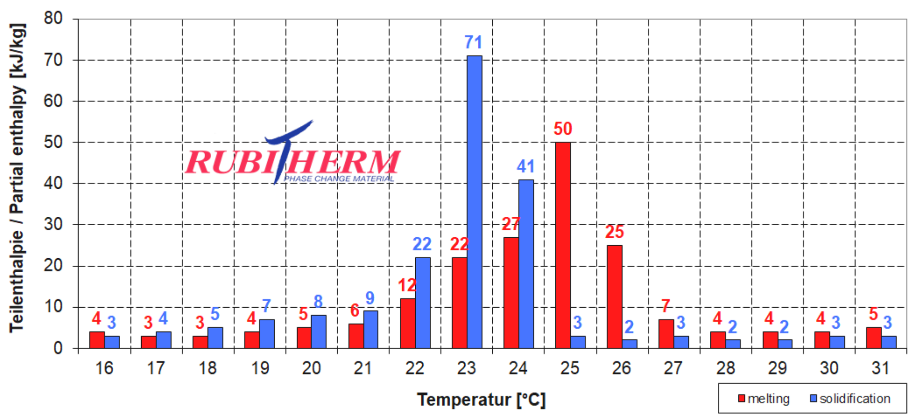
The creation of the latent heat material RUBITHERM® SP has led to a new and innovative class of low flammability PCM. RUBITHERM® SP consists of a unique composition of inorganic components.
RUBITHERM® SP is used as macroencapsulated material. Densities of 1,0 kg/l and more can be achieved. This and all properties mentioned below make RUBITHERM® SP to the preferred PCM used in the construction industry. Both passive and active cooling can easily be realized e.g. air conditioners.
We look forward to discussing your particular questions, needs and interests with you.

Properties:
- stable performance throughout the phase change cycles
- high thermal storage capacity per volume
- limited supercooling (2-3K dependdig on volume and cooling rate),
- low flammability, non toxic
- different melting temperatures between -50°C und 70°C are available
- encapsulation necessary, minimum volume: 50ml

The most important data:	Typical Values	
Melting area	**24-26** main peak: 25	[°C]
Congealing area	**24-23** main peak: 24	[°C]
Heat storage capacity ± 7,5% Combination of sensible and latent heat in a temperatur range of 17 °C to 32°C.	**180**	[kJ/kg]
	50	[Wh/kg]*
Specific heat capacity	**2**	[kJ/kg·K]*
Density solid at 15°C	**~1,6**	[kg/l]
Density liquid at 35°C	**~1,5**	[kg/l]
Volume expansion	**~6**	[%]
Heat conductivity	**~0,5**	[W/(m·K)]
Max. operation temperature	**45**	[°C]
Corrosion	corrosive effect on metals	

The product must be initialized (melt, homogenize and cool to 0 ° C) once before use to achieve the specified properties.
SP-products may absorb release water if stored improperly. This can result in a change of the physical properties given. Storing in closed containers mandatory.

Beispiel / example: SP25E2 Teilenthalpie / Partial enthalpy distribution*



*Measured with 3-layer-calorimeter.

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The product information given is a non-binding planning aid, subject to technical changes without notice. Version: 12.07.2022

Table VI: technical data sheet of salt hydrates SP25E2
Source: from *SP25E2*, by Rubitherm, n.d., http://bit.ly/3wQiNDW

S-POLYTEC POLYMERTECHNOLOGIE

Technical Data Sheet
PETG sheets (transparent)

Polyethylene terephthalate glycol (PETG) is a thermoplastic copolyester with a very high surface gloss and good transparency. This plastic is extremely impact resistant (also at minus temperatures), has very good thermoforming properties and is resistant to chemicals.

Mechanical properties:		
Yield stress	DIN EN ISO 527	52 MPa
Elongation at yield	DIN EN ISO 527	4.5%
Tensile modulus of elasticity	ISO 527-2	1900 MPa
Impact strength	ISO 179-1	without break
Notched impact strength	ISO 179-1	10 kJ/m²
Ball indentation hardness	ISO 2039-1	97 MPa
Shore hardness D (15 s)	DIN EN ISO 868	78

Thermal properties:		
Vicat B	ISO 306	77°C
Processing temperature		200-215°C
Temperature heat bed		80-100°C

Electrical properties:		
Surface resistivity	IEC 60093	10^{14}
Dielectric strength	DIN IEC 60243-1	16 kV/mm

Typical properties:		
Fire behaviour	DIN 4102 B1	low flammability 1 to 8 mm
Density	ISO1183	1.27 g/cm³
Temperature range		-40 to +65°C
Light transmission (3 mm)		90%
Physiological safety	BfR	✓
Food compliance	EU	✓
Food compliance	FDA	✓

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The figures shown are the data of the sheet manufacturers. Values may differ depending on the production batch. This data sheet is not a guarantee for exact compliance with the values!

Table VII: technical data sheet of the encapsulation material PETG
Source: from *PETG sheets (transparent)*, by S-Polytec, n.d. (http://bit.ly/3YVCwOq)

AEROGEL

LUMIRA® TRANSLUCENT AEROGEL LA1000; LA2000

Product highlights

The superior properties of translucent Lumira aerogel, make it the obvious choice for insulating a wide variety of daylighting systems from glass to polycarbonate. Its light transmitting nature and superior thermal performance result in enhanced energy efficiency while enabling a wide range of commercial and residential building design choices.

Performance benefits:

- Hydrophobic/water repellant
- UV stability
- Sound absorption
- Thermal insulation
- High light transmission
- Lightweight
- Non-combustible
- Inert

For information on product-specific storage conditions, please refer to the applicable Safety Data Sheet (SDS) available from your Cabot representative or at cabotcorp.com.
Enova is a trademark of Cabot Corporation.

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LUMIRA® TRANSLUCENT AEROGEL LA1000; LA2000

PRODUCT FEATURES		
PROPERTY	**LA1000**	**LA2000**
Particle size range	1.2 – 4.0 mm	0.7 – 1.2 mm
Pore diameter	~20nm	~20nm
Porosity	>90%	>90%
Particle density	120 – 150 kg/m^3	120 – 150 kg/m^3
Bulk density	68 kg/m^3	75 kg/m^3
Surface chemistry	Hydrophobic	Hydrophobic
Surface area	600 – 800 m^2/g	600 – 800 m^2/g
Light Transmission per cm thickness	93%	89%
Thermal conductivity - particle	12 mW/m-K	12 mW/m-K
Thermal conductivity - bulk	17 -22 mW/m-K (depending on density)	17 -22 mW/m-K (depending on density)
CAS RN	102262-30-6	102262-30-6

The data in the table above are typical test values intended as guidance only; they are not product specifications. Product specifications are available upon request from your Cabot representative.

For information on product-specific storage conditions, please refer to the applicable Safety Data Sheet (SDS) available from your Cabot representative or at cabotcorp.com.
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Table VIII: technical data sheet of Aerogel Lumira LA1000 (insulating material)
Source: from *Lumira translucent aerogel LA1000; LA2000*, by Cabot, n.d. (http://bit.ly/3IbbnAt)

```
% m-file for simulation of a room with a revolving translucent PCM panel behind the
window at orientation 1
% FINAL VALIDATED AND VERIFIED ROOM MODEL
% Version: 9 October 2018
%Heating demand


% ----------- VARIABLES -------------

building_function_type = 2; % 1 = office, 2 = residence
building_age_type = 1;      % 1 = new, 2 = old
panel_present = 1;          % 0 = no, 1 = yes

% ------------- SCRIPT ---------------

start_time = 273*86400; % start time of the simulation (days * seconds in a day)
stop_time  = 485*86400; % stop time of the simulation

% Glazing data for calculation of transmission of direct solar as function of
incidence angle. See report 'Modeling Windows in Energy Plus with Simple
Performance Indices', LBNL report 2804E, October 2009
glazing_transmission_data = [
1.470E-02    1.486E+00  -3.852E+00  3.355E+00   -1.474E-03
5.546E-01    3.563E-02  -2.416E+00  2.831E+00   -2.037E-03
7.709E-01   -6.383E-01  -1.576E+00  2.448E+00   -2.042E-03
3.462E-01    3.963E-01  -2.582E+00  2.845E+00   -2.804E-04
2.883E+00   -5.873E+00  2.489E+00   1.510E+00   -2.577E-03
3.025E+00   -6.366E+00  3.137E+00   1.213E+00   -1.367E-03
3.229E+00   -6.844E+00  3.535E+00   1.088E+00   -2.891E-03
3.334E+00   -7.131E+00  3.829E+00   9.766E-01   -2.952E-03
3.146E+00   -6.855E+00  3.931E+00   7.860E-01   -2.934E-03
3.744E+00   -8.836E+00  6.018E+00   8.407E-02    4.825E-04];

glazing_values = [
1.6  0.7  5
1.6  0.2  6
0.7  0.5  5
0.7  0.1  10          % All values for U, SHGC and transmission type
1    0.5  5];         % type 5 corresponds to triple glazing of case study

WWR_values = [
0.2
0.4
0.6
0.8];                 % WWR values

SHGC_values = [
0.35
0.28
0.23];                % values for SHGC glass with a sun-shading system for South
orientation

PCM_values = [
0.01
0.03
0.05];                % thickness values of PCM layer

A_wall_values = 0.5;  % values for area of PCM trombe wall

TinIC = 23;           % initial temperature in all nodes (23 is average of heating
and cooling setpoint)

room.volume = room.depth*room.width*room.height;    % air volume room, depth x
width x height [m3]
room.area   = room.depth*room.width;
orien1.area = room.height*room.width;

WWR_properties = WWR_values(WWR_type,:);
WWR_area = WWR_properties(1) * orien1.area;         % the surface area of glazed
facade depends on the WWR

A_wall_properties = A_wall_values(A_wall_type,:);

A_gl_orien1 = WWR_area*A_wall_properties;           % surface area glass with PCM
panel behind glass orien1 facade (m^2).
A_gl_orien2 = 0;                                    % surface area glass orien2
facade (m^2)
A_gl_orien3 = 0;                                    % surface area glass orien3
facade (m^2)
A_gl_orien4 = 0;                                    % surface area glass orien4
facade (m^2)

glazing_properties = glazing_values(glazing_type,:);

% window U values (glazing + frame)
U_gl = glazing_properties(1);

U_gl_orien1 = U_gl; % don't change this
U_gl_orien2 = U_gl; % don't change this
U_gl_orien3 = U_gl; % don't change this
U_gl_orien4 = U_gl; % don't change this

% Solar heat gain coefficient glass without a sun-shading system
SHGC_orien1 = glazing_properties(2);
SHGC_orien2 = SHGC_orien1;
SHGC_orien3 = SHGC_orien1;
SHGC_orien4 = SHGC_orien1;

% Solar heat gain coefficient glass with a sun-shading system
SHGC_shading = SHGC_values(SHGC_type,:);

if orientation == 180
    SHGC_orien1_SB = SHGC_shading;
else
    SHGC_orien1_SB = 0.30;
end
```

```
SHGC_orien2_SB = SHGC_orien1_SB;
SHGC_orien3_SB = SHGC_orien1_SB;
SHGC_orien4_SB = SHGC_orien1_SB;

% Define glazing transmission type for calculation of transmission of direct solar↙
as
% function of incidence angle. See report 'Modeling Windows in Energy Plus
% with Simple Performance Indices', LBNL report 2804E, October 2009
glazing_transmission_type =  glazing_properties(3);
                                % 1 =   A- 3mm clear
                                % 2 =   B- 3mm bronze
                                % 3 =   C- 6mm bronze
                                % 4 =   D-Single Coated
                                % 5 =   E-Double clear 3mm
                                % 6 =   F-Double coated 3mm clear
                                % 7 =   G-Double 3mm tinted 3 mm clear
                                % 8 =   H-Double glazing: coated - 6mm clear
                                % 9 =   I-Double Glazing:6mm tinted - 6mm clear
                                % 10=   J-Triple-Coated-3mm clear- coated

glazing_transmission_coef = glazing_transmission_data(glazing_transmission_type,:);

ThresholdSBoff  = 99;          % Operative room temperature below which the↙
sunblinds are never used
ThresholdSBon   = 100;          % Operative room temperature above which the↙
sunblinds are in use, provided that Isol > ThresholdSBIsol
ThresholdSBIsol= 1000;          % incoming solar radiative power below which the↙
sunblinds are never used (per orientation)

CFsol  = 0.2;                  % convection factor solar radiation entering the↙
room. The fraction CFSol is given off to the room air node, the remainder is given↙
off at the floor surface

working_days = 7;              % number of (consecutive) 'working days' in a week,↙
must be >=0 and <=7. The remaining days of the week are designated 'non-working↙
days'.

building_function_values = [
25 8   18 0 0  2.0/3600 8  18 0 0
6  18  8  0 24 0.7/3600 18 8  0 24]; % All values for corresponding building↙
function

building_function_properties = building_function_values(building_function_type,:);

p_i_wd =  building_function_properties(1); % total sensible internal heat↙
production in W/m2, only applies on working days AND when people are present.
                                           % options: 6 W/m2 (residences), 25 W/m2↙
(offices)
p_i_nwd = 6;                               % total sensible internal heat↙
production in W/m2, only applies on non-working days AND when people are present.
                                           % on non-working days: no office↙
situation, so always 6 W/m2 (residences)
```

Table IX: first part of code of the MatLab file that highlights the main modifications carried out in light blue

```
% MASTER FILE -- SIMULATION OF PART X OF COMPUTER X

clear;
clc;
close all;

% Y variabelen
A_matrix = [6;9];        % room width (6;9)
B_matrix = [6;9];        % room depth (6;9)
C_matrix = [3];          % room height
D_matrix = [1;2;3;4];         % window-to-wall ratio (from 20% to 80%). (1;2;3;4)
E_matrix = [5];         % type of glazing. It is considered always the type 5.
F_matrix = [90;180;270];       % orientation of glazed facade (orien1). (90;180;
270)
G_matrix = [5];         % climate zone. In this case, it is considered only the
Temperate climate of the Netherlands.
H_matrix = [1];         % building method (1: lightweight; 2: heavyweight)
I_matrix = [1;2;3];         % SHGC of glass with sun-shading system. In report you
can find the SHGC for each shading system (1;2;3)

% X variabelen
M_matrix = [1;2;3];       % thickness of PCM layer (1;2;3)
N_matrix = [1];       % PCM trombe wall surface area (1)

L_A = length(A_matrix);
L_B = length(B_matrix);
L_C = length(C_matrix);
L_D = length(D_matrix);
L_E = length(E_matrix);
L_F = length(F_matrix);
L_G = length(G_matrix);
L_H = length(H_matrix);
L_I = length(I_matrix);
L_M = length(M_matrix);
L_N = length(N_matrix);

size_x = L_M*L_N;
size_y = L_A*L_B*L_C*L_D*L_E*L_F*L_G*L_H*L_I;

Results_heating = zeros(size_y,size_x);
Results_cooling = zeros(size_y,size_x);

% matlab file to run
init_file = 'MATLAB_MODEL_v20181010_simulations.m';
% simulink file to run
file_to_run = 'SIMULINK_MODEL_v20181010_simulations.slx';

%run each room width
for A = 1:L_A
    room.width = A_matrix(A);
    %run each room depth
    for B = 1:L_B
        room.depth = B_matrix(B);
        for C = 1:L_C
            room.height = C_matrix(C);
            %run each window size
            for D = 1:L_D
                WWR_type = D_matrix(D);
                %run type of glazing
                for E = 1:L_E
                    glazing_type = E_matrix(E);
                    %run each orientation
                    for F = 1:L_F
                        orientation = F_matrix(F);
                        %run climate zone
                        for G = 1:L_G
                            climate_type = G_matrix(G);
                            % run building method
                            for H = 1:L_H
                                building_method_type = H_matrix(H);
                                % run each shading coefficient
                                for I = 1:L_I
                                    SHGC_type = I_matrix(I);
                                    % run each surface area of PCM trombe wall
                                    for M = 1:L_M
                                        PCM_type = M_matrix(M);
                                        % run each surface area of PCM trombe wall
                                        for N = 1:L_N
                                            A_wall_type = N_matrix(N);
                                            % run matlab file and simulink file
                                            run(init_file);
                                            sim(file_to_run);

                                            index_x = size_x*( (M-1)/L_M + N/size_x
);
                                            index_y = size_y*( (A-1)/L_A + (B-1)/
(L_A*L_B) + (C-1)/(L_A*L_B*L_C) + (D-1)/(L_A*L_B*L_C*L_D) + (E-1)/
(L_A*L_B*L_C*L_D*L_E) + (F-1)/(L_A*L_B*L_C*L_D*L_E*L_F) + (G-1)/
(L_A*L_B*L_C*L_D*L_E*L_F*L_G) + (H-1)/(L_A*L_B*L_C*L_D*L_E*L_F*L_G*L_H) + I/size_y
);
                                            round_index_y = round(index_y);
                                            round_index_x = round(index_x);

                                            result_heating = sim_output_heating
(end);
                                            result_cooling = sim_output_cooling
(end);

                                            Results_heating(round_index_y,
round_index_x) = result_heating;
                                            Results_cooling(round_index_y,
round_index_x) = result_cooling;
                                        end
```

Table X: Master file of MatLab

Source: edited from *The Energy and Comfort Performance of a Lightweight Translucent Adaptable Trombe Wall in Different Buildings and Climates: A Numerical study*, by Jeoren Van Unen, 2019. http://resolver.tudelft.nl/uuid:2f619b08-4bd4-4d20-98ef-091f2bd1e136

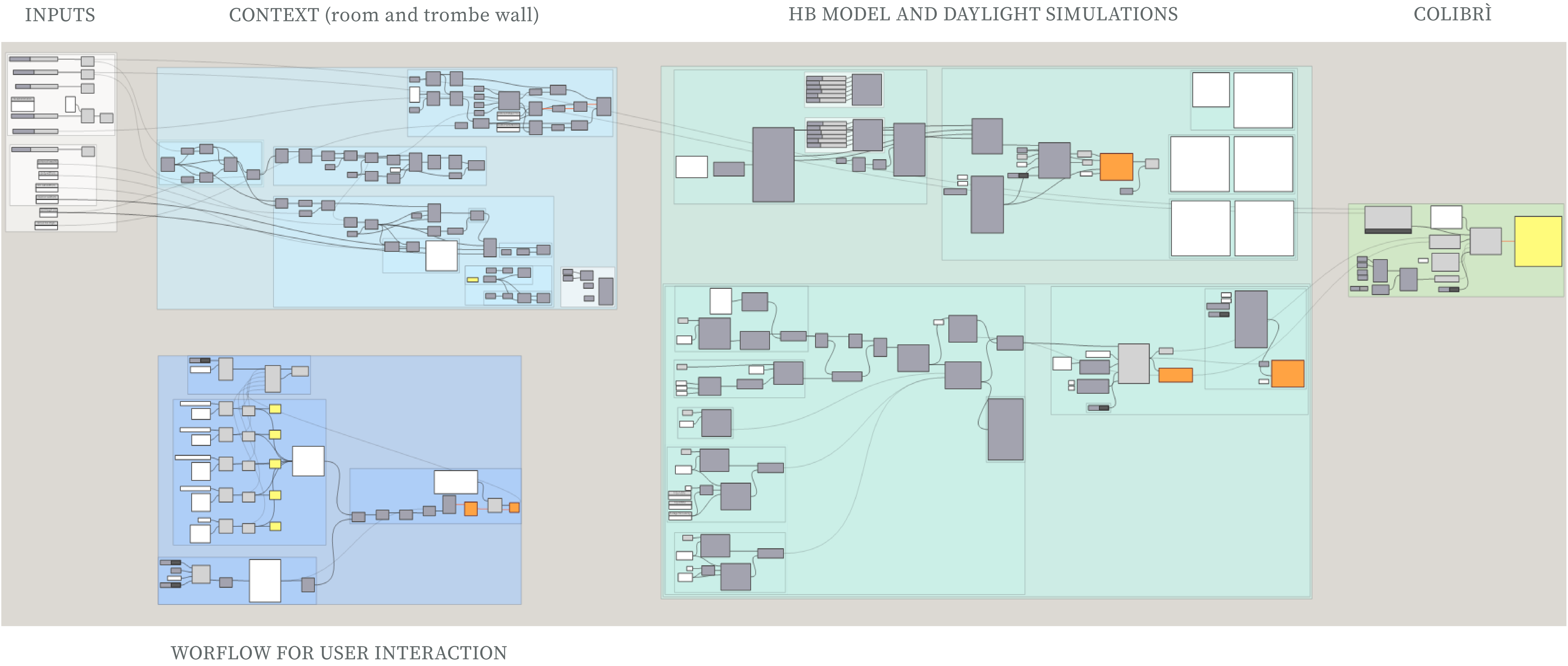
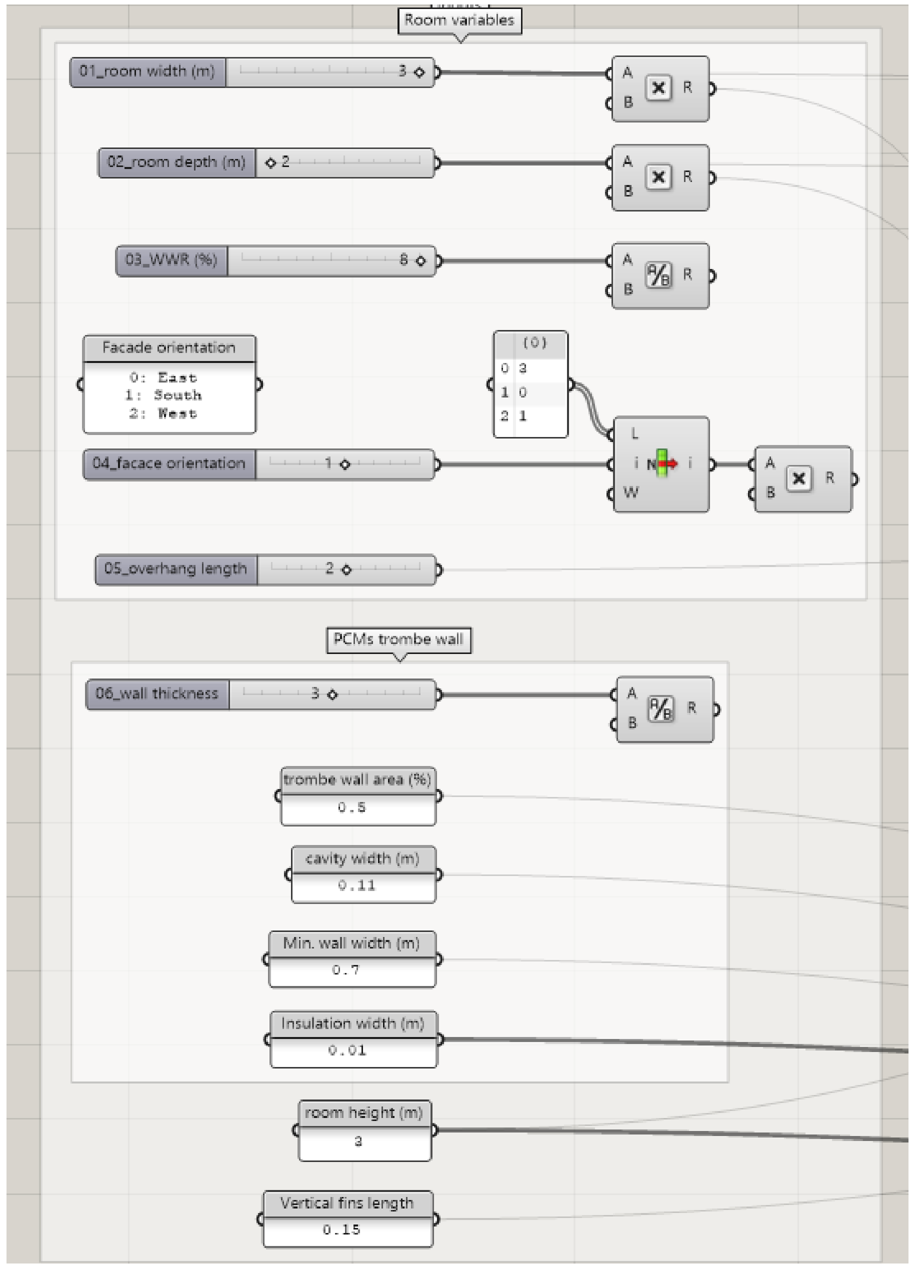
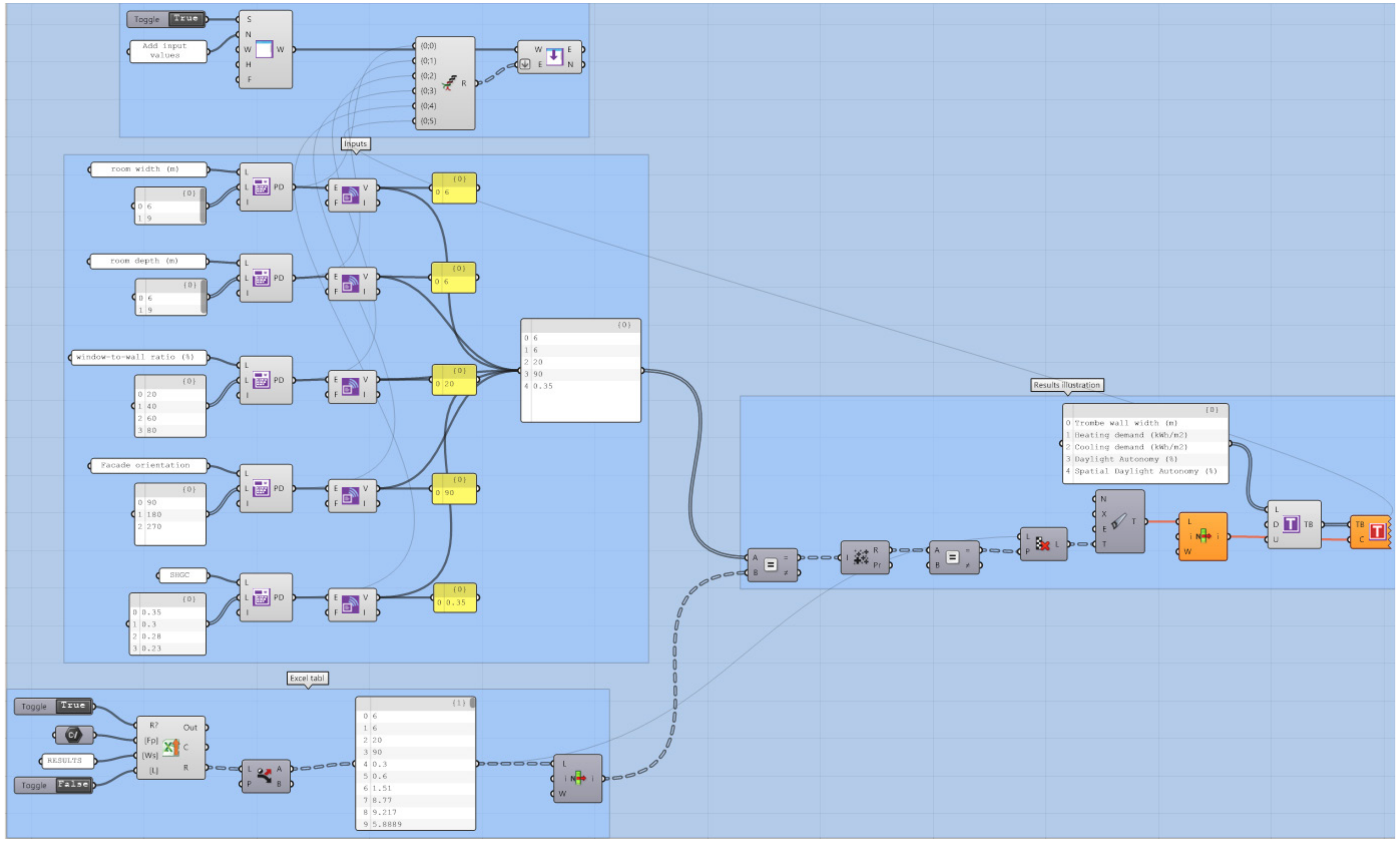


Table XI: overview of Grasshopper script used for the daylight simulations and the workflow development



HUMAN UI (creation of window and inputs)

RESULTS TO SHOW IN THE WINDOW



TT TOOLBOX (Excel table)

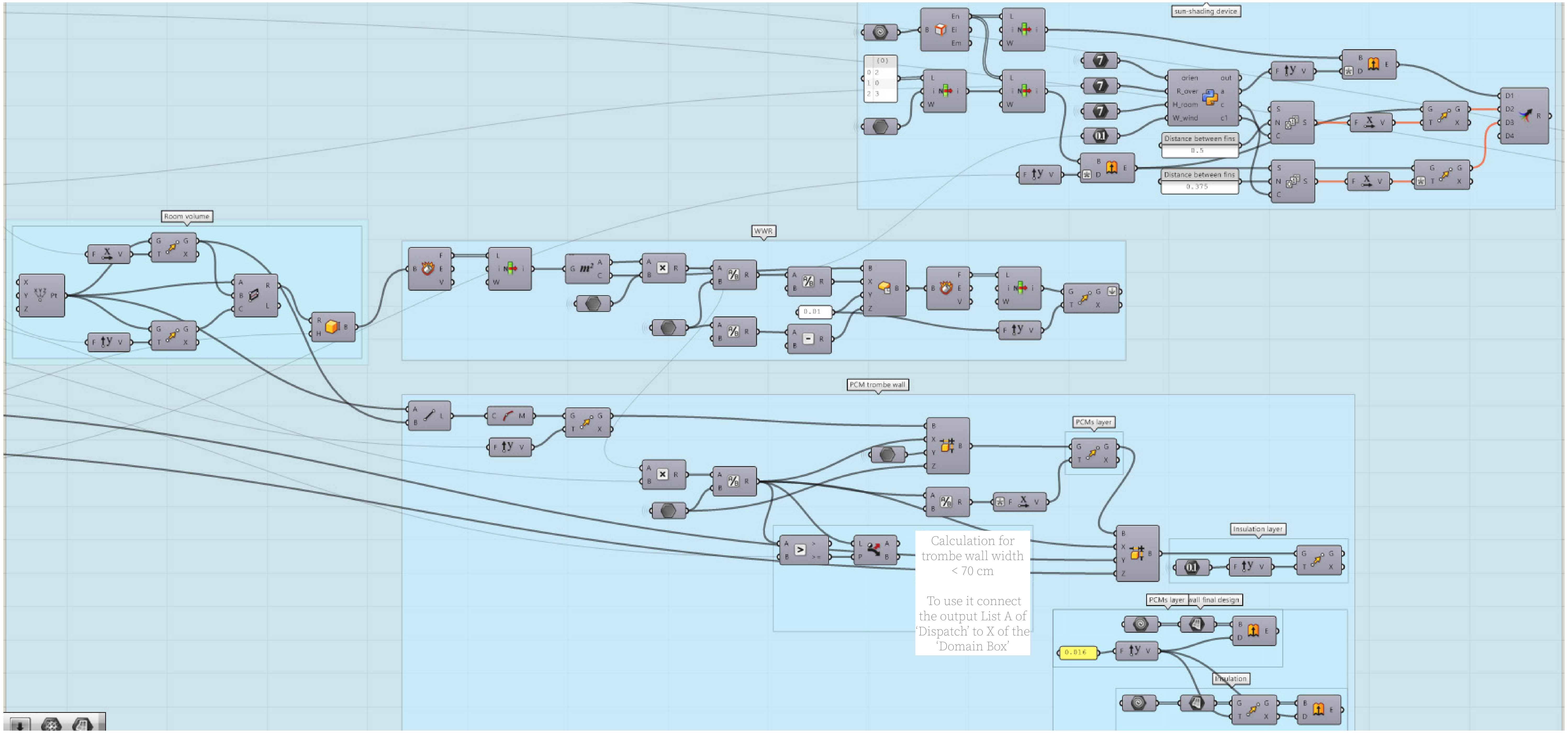
Table XII: inputs of the GH model

Table XIII: development of workflow for user interaction

ROOM VOLUME

WWR

SHADING SYSTEM



PCMs TROMBE WALL

Table XIV: script for the development of room and PCMs trombe wall

WEATHER DATA

CALCULATION OF DIRECT SUN HOURS

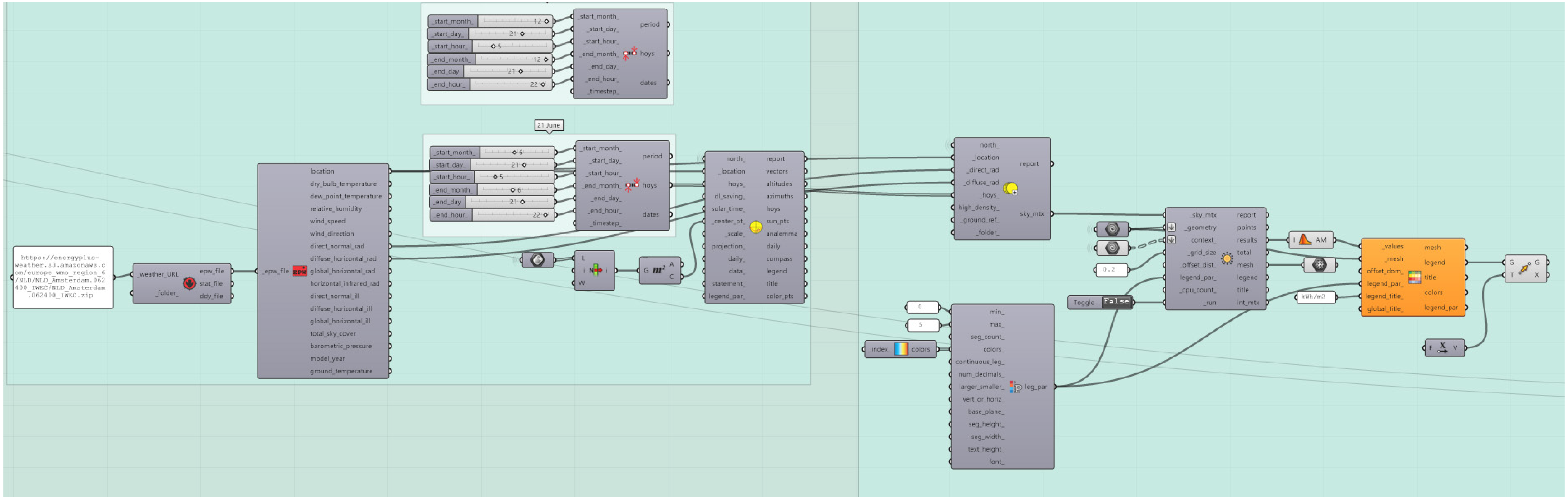


Table XV: use of Ladybug components for the climate conditions of Amsterdam and the calculation of the direct sun hours

OPAQUE PARTS (walls, floor, ceiling)

GLAZED FAÇADE

SHADING SYSTEM

PCMs LAYER

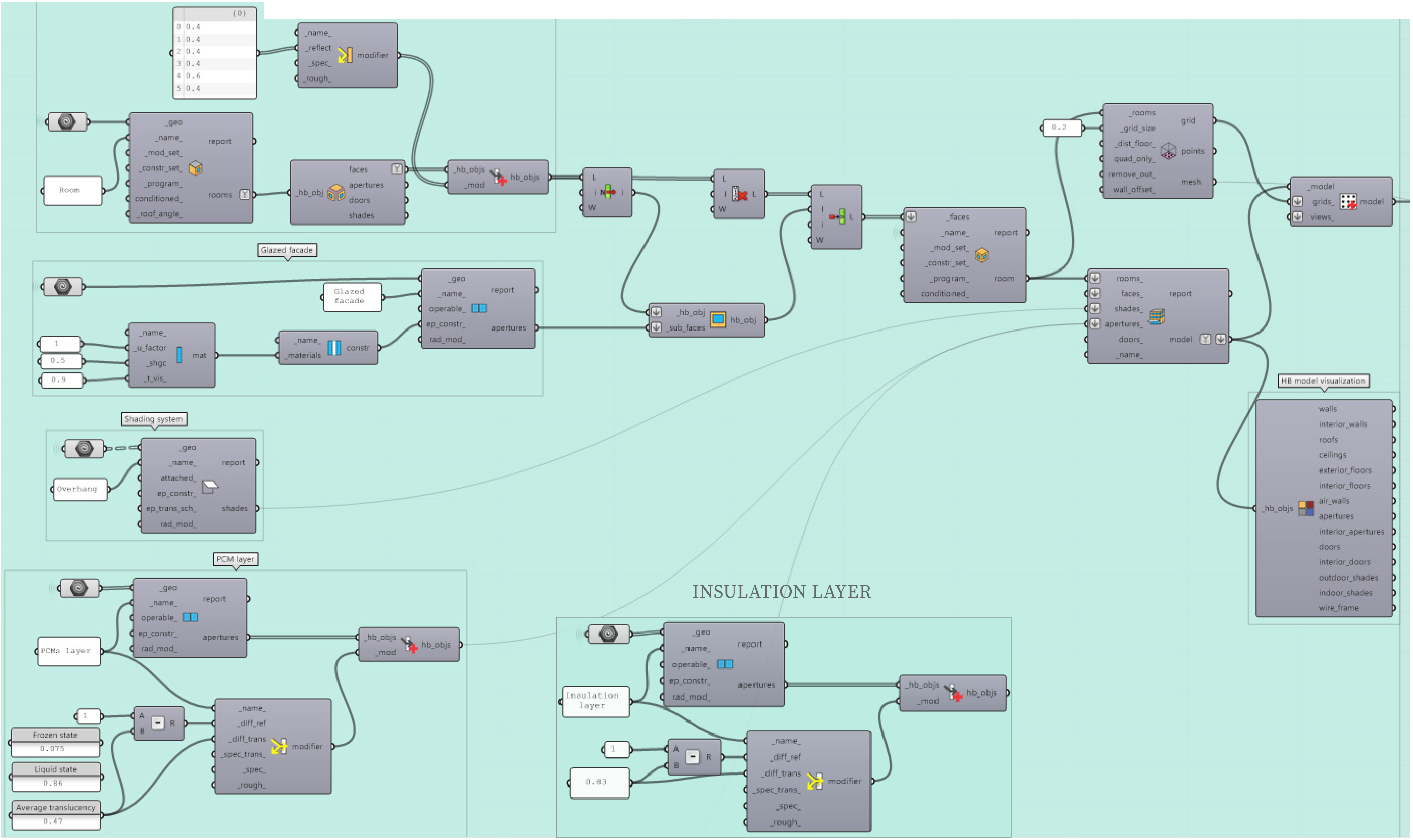
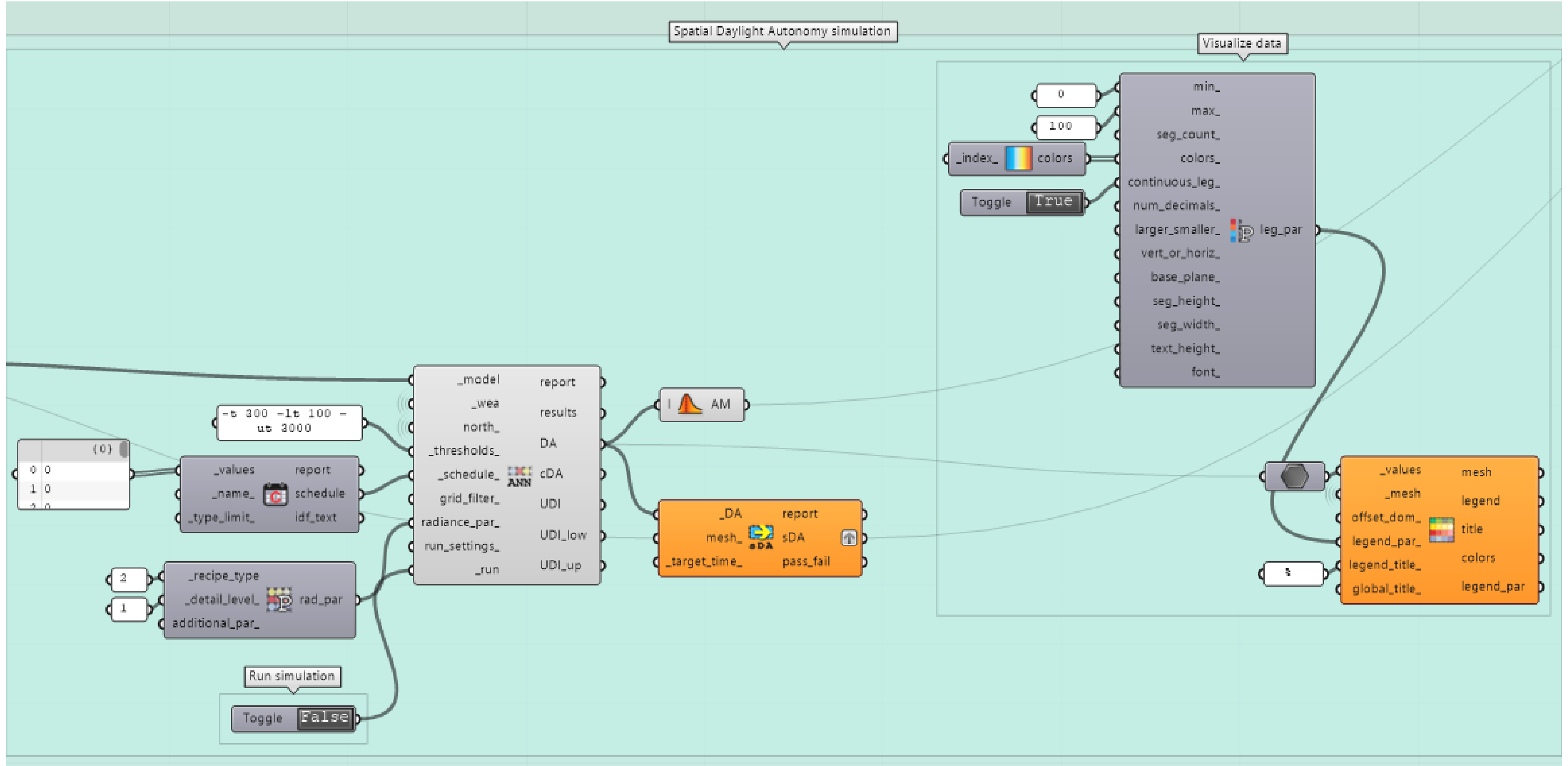


Table XVI: development of the HB model



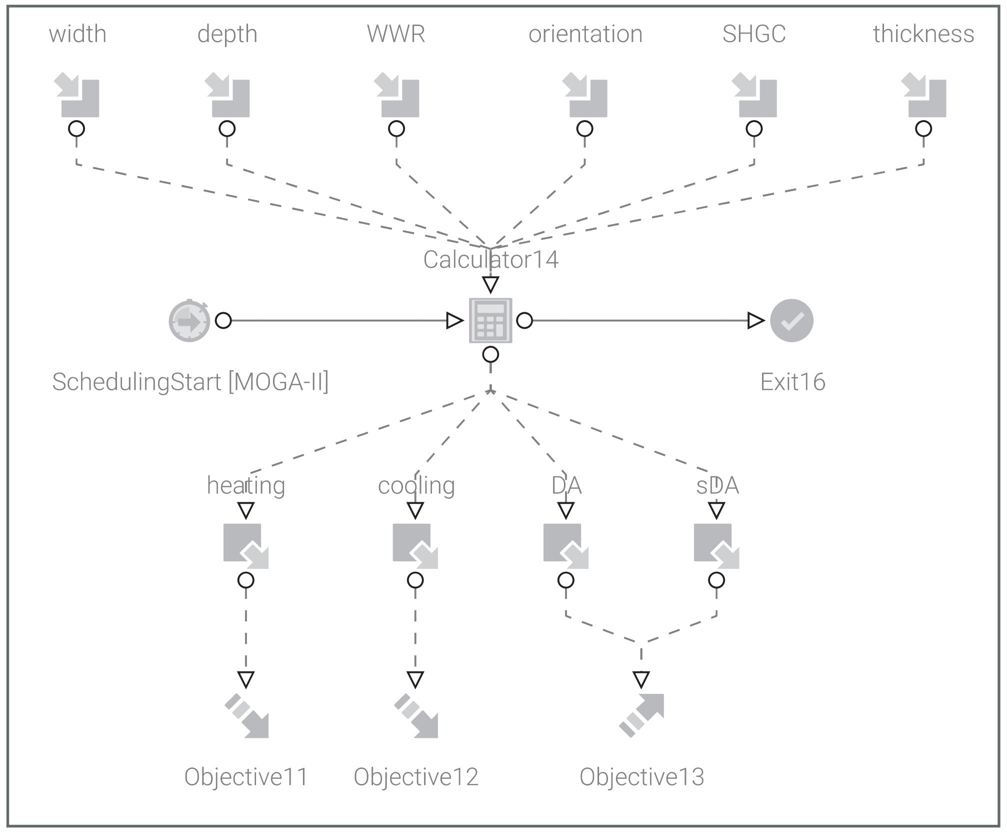


Table XVII: tools to estimate the spatial Daylight Autonomy and visualize it in the virtual model

Table XIX: workflow developed in ModeFrontier to manage the data of the simulations and plot graphs

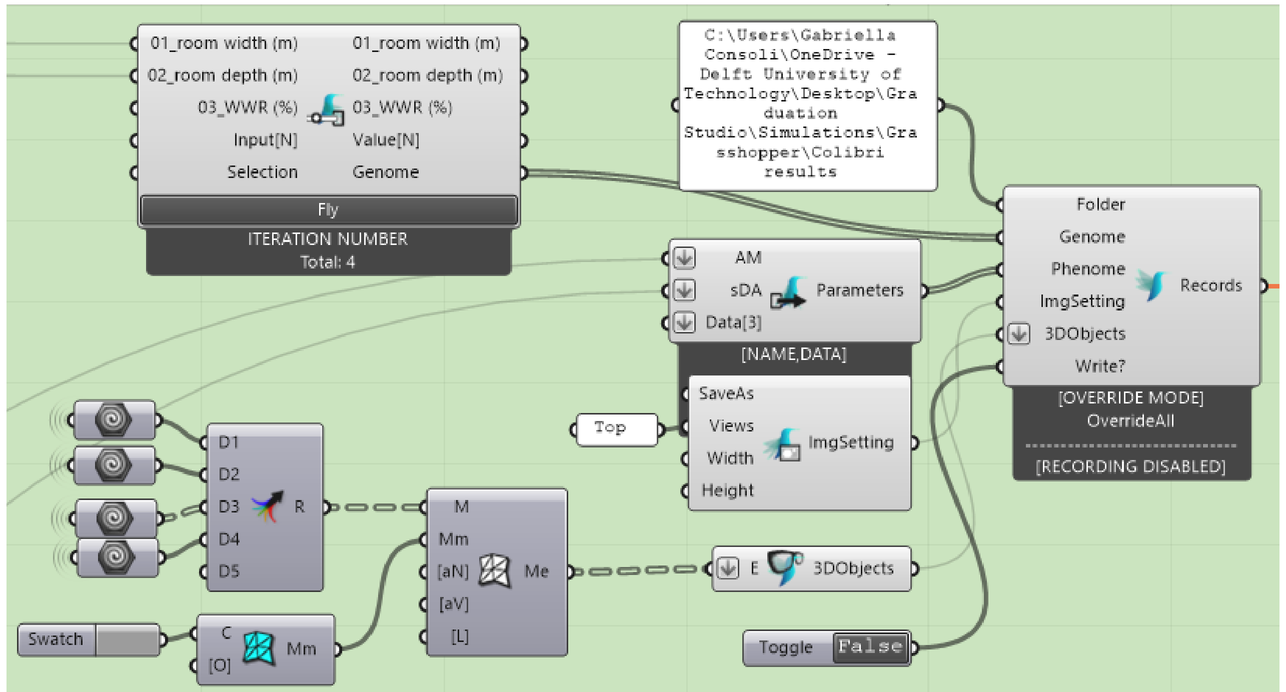


Table XVIII: use of Colibrì to automate the simulation process

The following Excel table contains all the data from the thermal and daylight simulations. The ID indicates the design configurations and is coloured in red when the trombe wall has a width minor of 70 cm. The subsequent columns illustrate the values of each input, whereas the last four columns show the results. Specifically, the heating and cooling demand is in kWh/ m². DA states for Daylight Autonomy, while sDA for spatial Daylight Autonomy.

ID	width	depth	WWR	orientation	SHGC	thickness	heating	cooling	DA	sDA
0	6	6	20	90	0.3	0.01	1.51	8.77	9.22	0.059
1	9	6	20	90	0.3	0.01	1.01	5.85	10.33	0.072
2	6	9	20	90	0.3	0.01	1.01	5.85	5.88	0.039
3	9	9	20	90	0.3	0.01	0.60	3.61	6.38	0.047
4	6	6	40	90	0.3	0.01	1.35	6.22	25.88	0.173
5	9	6	40	90	0.3	0.01	0.90	3.34	26.39	0.193
6	6	9	40	90	0.3	0.01	1.61	19.36	15.90	0.113
7	9	9	40	90	0.3	0.01	1.07	12.91	15.83	0.121
8	6	6	60	90	0.3	0.01	2.42	29.04	40.08	0.316
9	9	6	60	90	0.3	0.01	1.28	13.13	43.14	0.346
10	6	9	60	90	0.3	0.01	1.39	10.34	24.76	0.203
11	9	9	60	90	0.3	0.01	0.93	5.11	26.98	0.215
12	6	6	80	90	0.3	0.01	1.66	16.28	50.32	0.506
13	9	6	80	90	0.3	0.01	1.11	7.67	53.19	0.544
14	6	9	80	90	0.3	0.01	1.11	5.58	32.01	0.317
15	9	9	80	90	0.3	0.01	1.23	4.86	35.24	0.335
16	6	6	20	180	0.35	0.01	2.90	3.73	22.22	0.122
17	9	6	20	180	0.35	0.01	1.94	3.68	21.46	0.130
18	6	9	20	180	0.35	0.01	1.65	5.41	13.74	0.079
19	9	9	20	180	0.35	0.01	1.10	4.77	12.81	0.083
20	6	6	40	180	0.35	0.01	2.48	4.19	44.63	0.316
21	9	6	40	180	0.35	0.01	1.33	3.29	45.13	0.324
22	6	9	40	180	0.35	0.01	1.33	4.70	27.94	0.203
23	9	9	40	180	0.35	0.01	0.88	4.02	29.23	0.202
24	6	6	60	180	0.35	0.01	3.85	5.88	56.08	0.588
25	9	6	60	180	0.35	0.01	2.57	5.75	57.47	0.626
26	6	9	60	180	0.35	0.01	2.57	8.41	38.31	0.364
27	9	9	60	180	0.35	0.01	1.33	7.26	42.25	0.366
28	6	6	80	180	0.35	0.01	3.00	6.64	62.27	0.746
29	9	6	80	180	0.35	0.01	2.00	5.19	64.30	0.927
30	6	9	80	180	0.35	0.01	1.43	7.29	45.74	0.451
31	9	9	80	180	0.35	0.01	0.95	6.21	50.77	0.492
32	6	6	20	270	0.3	0.01	2.14	19.58	9.64	0.056
33	9	6	20	270	0.3	0.01	1.99	19.36	11.09	0.075
34	6	9	20	270	0.3	0.01	1.99	19.36	6.05	0.038
35	9	9	20	270	0.3	0.01	1.33	12.91	6.77	0.049
36	6	6	40	270	0.3	0.01	1.88	7.20	26.39	0.173
37	9	6	40	270	0.3	0.01	1.25	4.80	27.41	0.195
38	6	9	40	270	0.3	0.01	1.25	4.80	16.17	0.113
39	9	9	40	270	0.3	0.01	0.76	3.13	16.68	0.123
40	6	6	60	270	0.3	0.01	1.70	5.29	41.14	0.324
41	9	6	60	270	0.3	0.01	1.14	2.85	43.32	0.347
42	6	9	60	270	0.3	0.01	2.51	31.00	26.00	0.207
43	9	9	60	270	0.3	0.01	1.67	20.66	27.89	0.218
44	6	6	80	270	0.3	0.01	3.37	25.03	50.75	0.507
45	9	6	80	270	0.3	0.01	1.36	11.86	53.17	0.540
46	6	9	80	270	0.3	0.01	1.36	11.86	33.33	0.320
47	9	9	80	270	0.3	0.01	0.90	7.90	36.24	0.331
48	6	6	20	180	0.28	0.01	3.05	2.87	19.87	0.104
49	9	6	20	180	0.28	0.01	2.03	2.80	18.43	0.107
50	6	9	20	180	0.28	0.01	1.50	4.15	12.26	0.070
51	9	9	20	180	0.28	0.01	1.00	3.72	11.01	0.070
52	6	6	40	180	0.28	0.01	2.26	3.27	40.67	0.261
53	9	6	40	180	0.28	0.01	3.19	2.48	40.29	0.261
54	6	9	40	180	0.28	0.01	3.19	3.53	24.72	0.167
55	9	9	40	180	0.28	0.01	2.13	3.15	24.63	0.161
56	6	6	60	180	0.28	0.01	2.46	4.54	52.30	0.492
57	9	6	60	180	0.28	0.01	1.64	4.47	53.20	0.473
58	6	9	60	180	0.28	0.01	1.64	6.66	34.15	0.306
59	9	9	60	180	0.28	0.01	0.97	5.77	36.82	0.283
60	6	6	80	180	0.28	0.01	2.18	5.21	58.83	0.649
61	9	6	80	180	0.28	0.01	1.45	3.96	60.15	0.738
62	6	9	80	180	0.28	0.01	2.17	5.65	41.14	0.400
63	9	9	80	180	0.28	0.01	1.45	4.96	45.75	0.429
64	6	6	20	180	0.23	0.01	2.76	2.28	19.02	0.101
65	9	6	20	180	0.23	0.01	1.84	2.23	17.33	0.099
66	6	9	20	180	0.23	0.01	2.52	3.34	11.80	0.066
67	9	9	20	180	0.23	0.01	1.68	3.02	10.40	0.065
68	6	6	40	180	0.23	0.01	3.79	2.64	38.82	0.241
69	9	6	40	180	0.23	0.01	2.20	1.96	37.78	0.230
70	6	9	40	180	0.23	0.01	2.20	2.85	23.42	0.152
71	9	9	40	180	0.23	0.01	1.47	2.49	22.47	0.146
72	6	6	60	180	0.23	0.01	2.82	3.67	50.42	0.439
73	9	6	60	180	0.23	0.01	1.88	3.59	50.87	0.407
74	6	9	60	180	0.23	0.01	1.88	5.40	32.10	0.269
75	9	9	60	180	0.23	0.01	2.09	4.78	33.95	0.249
76	6	6	80	180	0.23	0.01	4.70	4.24	56.95	0.602
77	9	6	80	180	0.23	0.01	3.13	3.12	57.81	0.659
78	6	9	80	180	0.23	0.01	2.62	4.71	38.85	0.372
79	9	9	80	180	0.23	0.01	1.75	4.18	42.71	0.389
80	6	6	20	90	0.3	0.03	1.47	8.71	8.03	0.050
81	9	6	20	90	0.3	0.03	0.98	5.81	9.09	0.064
82	6	9	20	90	0.3	0.03	0.96	4.75	5.15	0.033
83	9	9	20	90	0.3	0.03	0.54	3.69	5.67	0.043
84	6	6	40	90	0.3	0.03	1.22	6.26	23.33	0.159
85	9	6	40	90	0.3	0.03	0.82	3.34	23.71	0.173
86	6	9	40	90	0.3	0.03	1.48	19.45	14.30	0.103
87	9	9	40	90	0.3	0.03	0.99	12.96	14.11	0.111
88	6	6	60	90	0.3	0.03	2.22	29.17	37.13	0.286
89	9	6	60	90	0.3	0.03	1.14	13.13	40.18	0.312
90	6	9	60	90	0.3	0.03	1.14	13.13	22.68	0.184
91	9	9	60	90	0.3	0.03	0.76	8.76	24.50	0.195

92	6	6	80	90	0.3	0.03	1.35	16.91	47.58	0.462
93	9	6	80	90	0.3	0.03	0.90	7.89	50.38	0.468
94	6	9	80	90	0.3	0.03	0.90	5.71	29.64	0.292
95	9	9	80	90	0.3	0.03	1.19	18.32	32.39	0.279
96	6	6	20	180	0.35	0.03	2.73	3.66	19.04	0.109
97	9	6	20	180	0.35	0.03	1.82	3.69	18.46	0.115
98	6	9	20	180	0.35	0.03	1.46	5.53	11.79	0.070
99	9	9	20	180	0.35	0.03	0.98	4.85	11.11	0.075
100	6	6	40	180	0.35	0.03	2.19	4.09	41.26	0.283
101	9	6	40	180	0.35	0.03	1.09	3.25	41.96	0.290
102	6	9	40	180	0.35	0.03	1.09	4.73	25.41	0.180
103	9	9	40	180	0.35	0.03	0.73	4.11	26.18	0.182
104	6	6	60	180	0.35	0.03	3.62	5.86	53.81	0.533
105	9	6	60	180	0.35	0.03	2.41	5.81	55.33	0.543
106	6	9	60	180	0.35	0.03	2.41	8.57	35.56	0.333
107	9	9	60	180	0.35	0.03	1.23	7.48	38.99	0.325
108	6	6	80	180	0.35	0.03	2.78	6.61	60.43	0.682
109	9	6	80	180	0.35	0.03	1.85	5.26	62.22	0.802
110	6	9	80	180	0.35	0.03	1.23	7.44	42.89	0.420
111	9	9	80	180	0.35	0.03	0.82	6.40	47.78	0.455
112	6	6	20	270	0.3	0.03	1.84	20.28	8.37	0.052
113	9	6	20	270	0.3	0.03	1.72	19.31	9.80	0.065
114	6	9	20	270	0.3	0.03	1.72	19.31	5.31	0.035
115	9	9	20	270	0.3	0.03	1.15	12.87	6.02	0.043
116	6	6	40	270	0.3	0.03	1.79	7.30	23.80	0.158
117	9	6	40	270	0.3	0.03	1.19	4.86	24.76	0.176
118	6	9	40	270	0.3	0.03	1.19	4.86	14.46	0.104
119	9	9	40	270	0.3	0.01	0.76	3.13	14.77	0.113
120	6	6	60	270	0.3	0.01	1.70	5.29	38.40	0.298
121	9	6	60	270	0.3	0.01	1.14	2.85	40.42	0.307
122	6	9	60	270	0.3	0.03	2.26	30.98	23.86	0.187
123	9	9	60	270	0.3	0.03	1.51	20.65	25.31	0.190
124	6	6	80	270	0.3	0.03	3.40	46.47	48.25	0.467
125	9	6	80	270	0.3	0.03	1.29	11.73	50.33	0.444
126	6	9	80	270	0.3	0.03	1.29	11.73	31.00	0.291
127	9	9	80	270	0.3	0.03	0.86	7.82	33.39	0.267
128	6	6	20	180	0.28	0.03	2.68	2.79	16.93	0.096
129	9	6	20	180	0.28	0.03	1.78	2.81	15.81	0.096
130	6	9	20	180	0.28	0.03	1.28	4.18	10.54	0.061
131	9	9	20	180	0.28	0.03	0.86	3.76	9.57	0.064
132	6	6	40	180	0.28	0.03	1.93	3.15	37.02	0.229
133	9	6	40	180	0.28	0.03	3.13	2.46	36.94	0.232
134	6	9	40	180	0.28	0.03	3.13	3.53	22.37	0.147
135	9	9	40	180	0.28	0.03	2.09	3.15	21.87	0.147
136	6	6	60	180	0.28	0.03	2.37	4.51	49.85	0.428
137	9	6	60	180	0.28	0.03	1.58	4.45	50.96	0.419
138	6	9	60	180	0.28	0.03	1.58	6.66	31.63	0.266
139	9	9	60	180	0.28	0.03	0.89	5.94	33.94	0.257
140	6	6	80	180	0.28	0.03	2.00	5.12	56.94	0.600
141	9	6	80	180	0.28	0.03	1.33	4.01	58.23	0.663
142	6	9	80	180	0.28	0.03	2.12	5.75	38.62	0.370
143	9	9	80	180	0.28	0.03	1.41	5.04	42.80	0.394
144	6	6	20	180	0.23	0.03	2.45	2.16	16.28	0.090
145	9	6	20	180	0.23	0.03	1.63	2.23	14.90	0.090
146	6	9	20	180	0.23	0.03	2.47	3.34	10.16	0.058
147	9	9	20	180	0.23	0.03	1.65	3.05	9.04	0.059
148	6	6	40	180	0.23	0.03	3.71	2.52	34.99	0.212
149	9	6	40	180	0.23	0.03	1.95	1.97	34.28	0.208
150	6	9	40	180	0.23	0.03	1.95	2.85	20.98	0.133
151	9	9	40	180	0.23	0.03	1.30	2.46	19.91	0.131
152	6	6	60	180	0.23	0.03	2.21	3.58	47.77	0.376
153	9	6	60	180	0.23	0.03	1.48	3.61	48.55	0.371
154	6	9	60	180	0.23	0.03	1.48	5.45	29.67	0.235
155	9	9	60	180	0.23	0.03	2.07	4.85	31.23	0.225
156	6	6	80	180	0.23	0.03	4.66	4.18	55.00	0.552
157	9	6	80	180	0.23	0.03	3.10	3.07	55.95	0.595
158	6	9	80	180	0.23	0.03	2.25	4.69	36.38	0.344
159	9	9	80	180	0.23	0.03	1.50	4.13	39.88	0.358
160	6	6	20	90	0.3	0.05	1.42	8.61	8.04	0.051
161	9	6	20	90	0.3	0.05	0.95	5.74	9.09	0.064
162	6	9	20	90	0.3	0.05	0.95	5.74	5.15	0.034
163	9	9	20	90	0.3	0.05	0.50	3.67	5.67	0.042
164	6	6	40	90	0.3	0.05	1.13	6.33	23.35	0.161
165	9	6	40	90	0.3	0.05	0.75	3.37	23.74	0.173
166	6	9	40	90	0.3	0.05	1.35	18.92	14.32	0.103
167	9	9	40	90	0.3	0.05	0.90	12.62	14.12	0.110
168	6	6	60	90	0.3	0.05	2.03	28.38	37.11	0.287
169	9	6	60	90	0.3	0.05	1.07	12.87	40.19	0.310
170	6	9	60	90	0.3	0.05	1.07	12.87	22.69	0.186
171	9	9	60	90	0.3	0.05	0.71	8.58	24.52	0.194
172	6	6	80	90	0.3	0.05	1.10	16.61	47.59	0.461
173	9	6	80	90	0.3	0.05	0.74	7.84	50.38	0.465
174	6	9	80	90	0.3	0.05	0.74	5.60	29.65	0.291
175	9	9	80	90	0.3	0.05	1.00	17.93	32.38	0.277
176	6	6	20	180	0.35	0.05	2.77	3.64	18.82	0.107
177	9	6	20	180	0.35	0.05	1.85	3.74	18.38	0.113
178	6	9	20	180	0.35	0.05	1.30	5.51	11.66	0.071
179	9	9	20	180	0.35	0.05	0.87	4.83	11.06	0.076
180	6	6	40	180	0.35	0.05	1.95	4.02	41.17	0.284
181	9	6	40	180	0.35	0.05	0.87	3.25	41.89	0.290
182	6	9	40	180	0.35	0.05	0.87	4.71	25.37	0.178
183	9	9	40	180	0.35	0.05	0.58	4.12	26.14	0.182
184	6	6	60	180	0.35	0.05	3.56	5.79	53.71	0.533
185	9	6	60	180	0.35	0.05	2.37	5.79	55.28	0.543
186	6	9	60	180	0.35	0.05	2.37	8.56	35.46	0.333
187	9	9	60	180	0.35	0.05	1.02	7.44	38.87	0.324
188	6	6	80	180	0.35	0.05	2.29	6.47	60.33	0.676
189	9	6	80	180	0.35	0.05	1.53	5.24	62.17	0.796
190	6	9	80	180	0.35	0.05	0.98	7.41	42.71	0.421
191	9	9	80	180	0.35	0.05	0.66	6.36	47.72	0.454
192	6	6	20	270	0.3	0.05	1.48	19.74	8.39	0.052
193	9	6	20	270	0.3	0.05	1.68	18.93	9.79	0.065

194	6	9	20	270	0.3	0.05	1.68	18.93	5.34	0.034
195	9	9	20	270	0.3	0.05	1.12	12.62	6.05	0.043
196	6	6	40	270	0.3	0.05	1.71	7.40	23.85	0.158
197	9	6	40	270	0.3	0.05	1.14	4.93	24.76	0.177
198	6	9	40	270	0.3	0.05	1.14	4.93	14.42	0.102
199	9	9	40	270	0.3	0.05	0.62	3.14	14.76	0.112
200	6	6	60	270	0.3	0.05	1.40	5.46	38.38	0.292
201	9	6	60	270	0.3	0.05	0.94	2.86	40.40	0.305
202	6	9	60	270	0.3	0.05	1.97	30.35	23.82	0.188
203	9	9	60	270	0.3	0.05	1.31	20.23	25.31	0.190
204	6	6	80	270	0.3	0.05	2.95	45.53	48.20	0.464
205	9	6	80	270	0.3	0.05	1.21	11.57	50.35	0.444
206	6	9	80	270	0.3	0.05	1.21	11.57	30.99	0.294
207	9	9	80	270	0.3	0.05	0.81	7.72	33.33	0.262
208	6	6	20	180	0.28	0.05	2.25	2.76	16.96	0.094
209	9	6	20	180	0.28	0.05	1.50	2.81	15.84	0.097
210	6	9	20	180	0.28	0.05	0.99	4.22	10.54	0.061
211	9	9	20	180	0.28	0.05	0.66	3.82	9.58	0.063
212	6	6	40	180	0.28	0.05	1.49	3.10	37.02	0.229
213	9	6	40	180	0.28	0.05	3.04	2.45	36.90	0.231
214	6	9	40	180	0.28	0.05	3.04	3.64	22.31	0.147
215	9	9	40	180	0.28	0.05	2.03	3.21	21.87	0.147
216	6	6	60	180	0.28	0.05	2.32	4.49	49.83	0.428
217	9	6	60	180	0.28	0.05	1.55	4.44	50.95	0.421
218	6	9	60	180	0.28	0.05	1.55	6.72	31.63	0.266
219	9	9	60	180	0.28	0.05	0.81	5.91	33.94	0.256
220	6	6	80	180	0.28	0.05	1.82	5.04	56.92	0.594
221	9	6	80	180	0.28	0.05	1.21	3.95	58.22	0.662
222	6	9	80	180	0.28	0.05	2.14	5.75	38.60	0.373
223	9	9	80	180	0.28	0.05	1.42	5.16	42.76	0.395
224	6	6	20	180	0.23	0.05	2.29	2.12	16.25	0.089
225	9	6	20	180	0.23	0.05	1.53	2.22	14.86	0.090
226	6	9	20	180	0.23	0.05	2.43	3.37	10.17	0.059
227	9	9	20	180	0.23	0.05	1.62	3.04	9.01	0.060
228	6	6	40	180	0.23	0.05	3.64	2.48	34.86	0.208
229	9	6	40	180	0.23	0.05	1.88	1.96	34.19	0.209
230	6	9	40	180	0.23	0.05	1.88	2.86	20.91	0.134
231	9	9	40	180	0.23	0.05	1.25	2.48	19.85	0.132
232	6	6	60	180	0.23	0.05	2.06	3.54	47.69	0.370
233	9	6	60	180	0.23	0.05	1.37	3.60	48.46	0.364
234	6	9	60	180	0.23	0.05	1.37	5.48	29.60	0.236
235	9	9	60	180	0.23	0.05	1.99	4.84	31.15	0.224
236	6	6	80	180	0.23	0.05	4.48	4.09	54.90	0.553
237	9	6	80	180	0.23	0.05	2.99	3.12	55.90	0.592
238	6	9	80	180	0.23	0.05	2.12	4.68	36.28	0.345
239	9	9	80	180	0.23	0.05	1.42	4.22	39.75	0.354

Table XX: inputs and results of thermal and daylight simulations

ID	width	depth	WWR	orientation	SHGC	thickness	heating/m2	cooling/m2	DA	sDA
12	6	6	80	90	0.3	0.01	1.66	16.28	50.32	0.506
13	9	6	80	90	0.3	0.01	1.11	7.67	53.19	0.544
24	6	6	60	180	0.35	0.01	3.85	5.88	56.08	0.588
25	9	6	60	180	0.35	0.01	2.57	5.75	57.47	0.626
28	6	6	80	180	0.35	0.01	3.00	6.64	62.27	0.746
29	9	6	80	180	0.35	0.01	2.00	5.19	64.30	0.927
44	6	6	80	270	0.3	0.01	3.37	25.03	50.75	0.507
45	9	6	80	270	0.3	0.01	1.36	11.86	53.17	0.540
60	6	6	80	180	0.28	0.01	2.18	5.21	58.83	0.649
61	9	6	80	180	0.28	0.01	1.45	3.96	60.15	0.738
76	6	6	80	180	0.23	0.01	4.70	4.24	56.95	0.602
77	9	6	80	180	0.23	0.01	3.13	**3.12**	57.81	0.659

Table XXI: selected design configurations with a 1 cm PCMs layer thickness

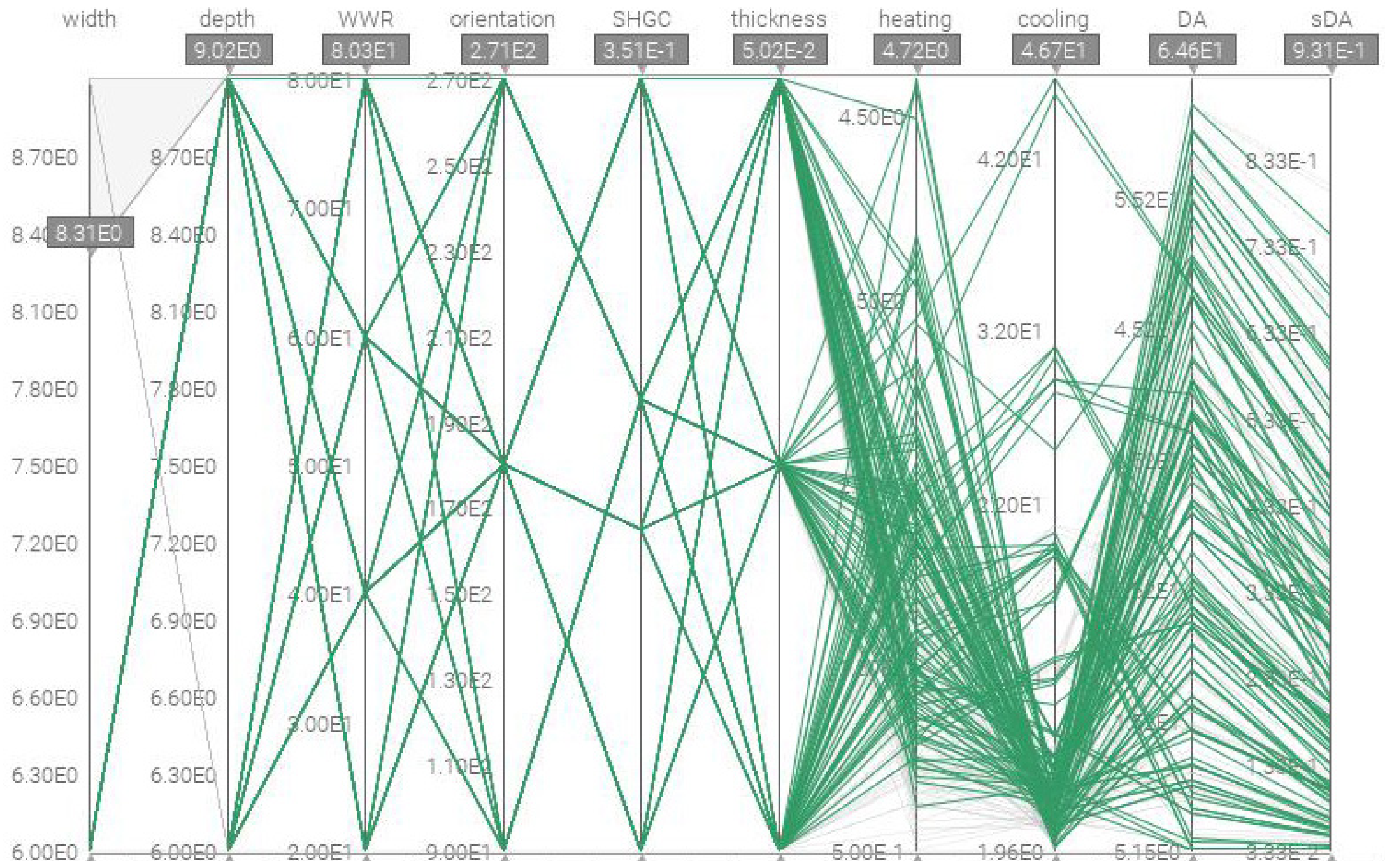


Table XXII: room width - 6 m

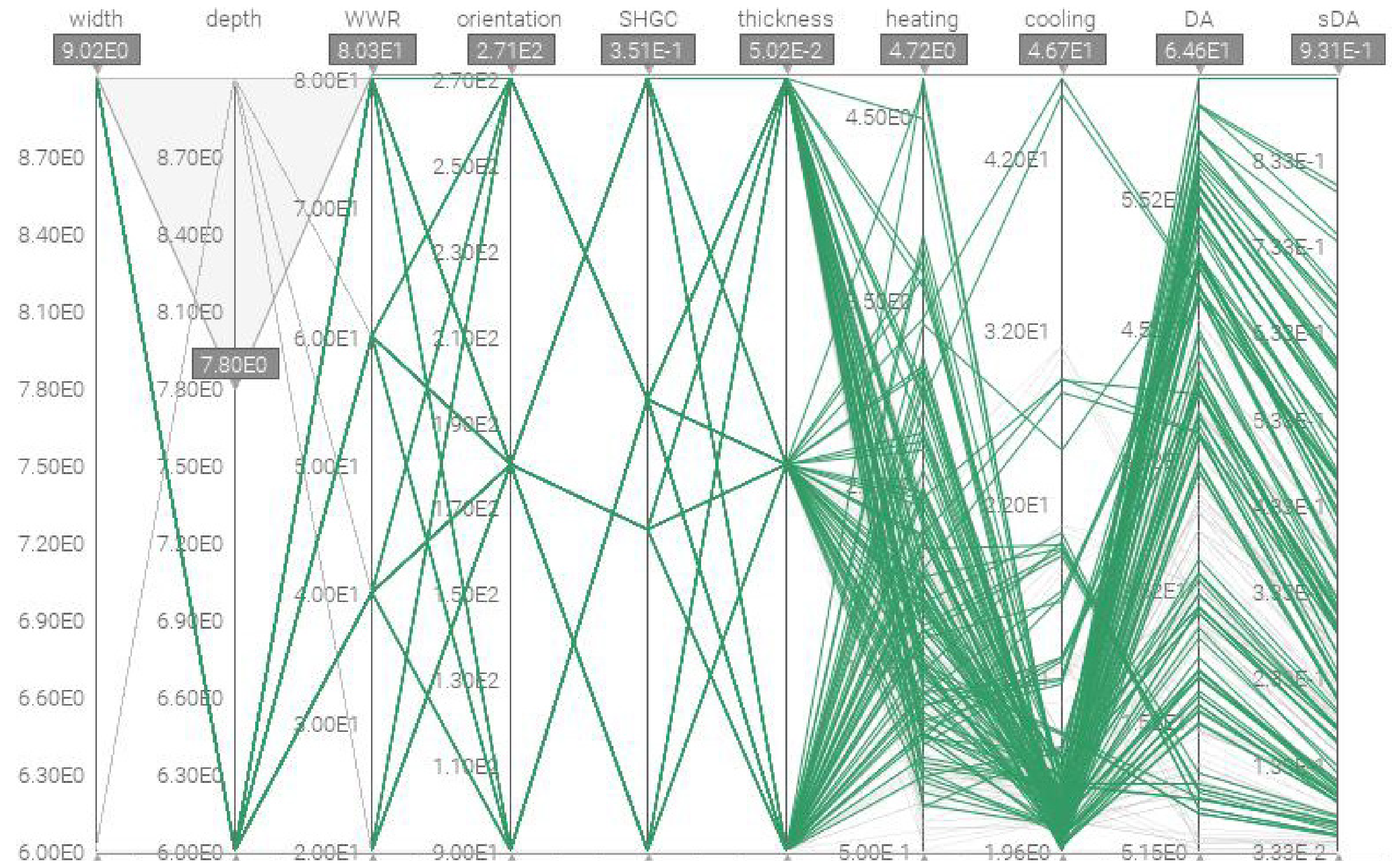


Table XXIV: room depth - 6 m

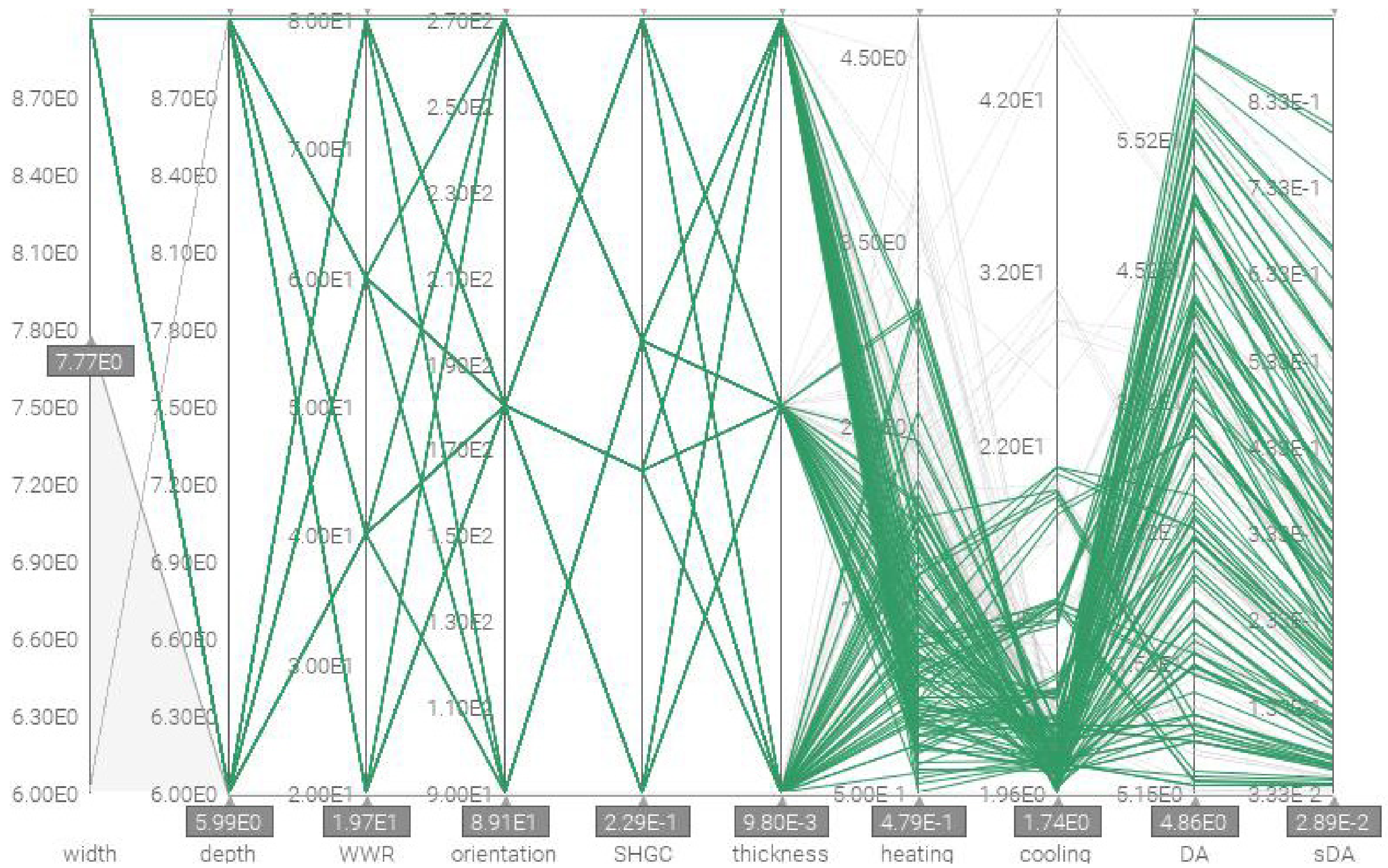


Table XXIII: room width - 9 m

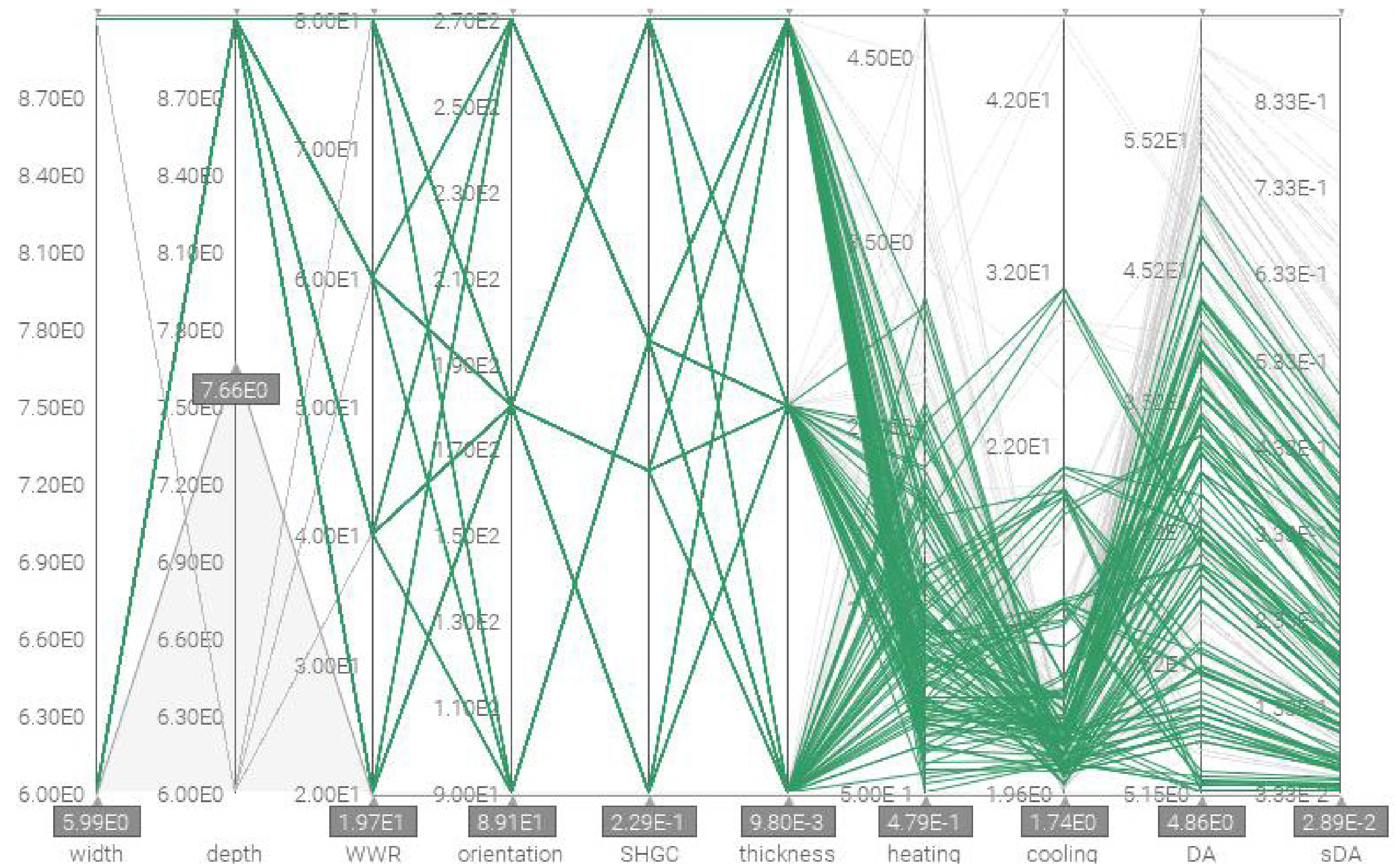


Table XXV: room depth - 9 m

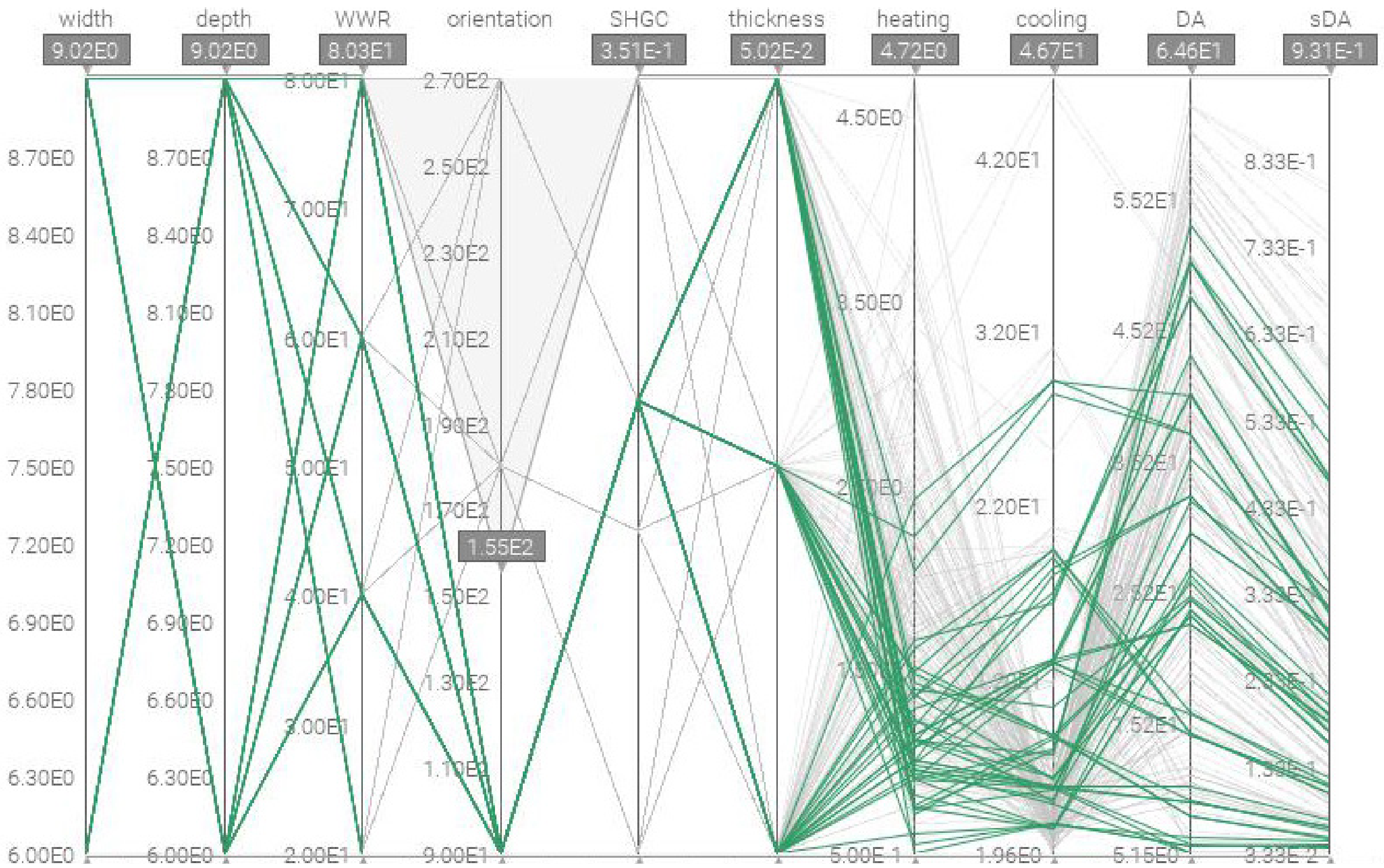


Table XXVI: east orientation

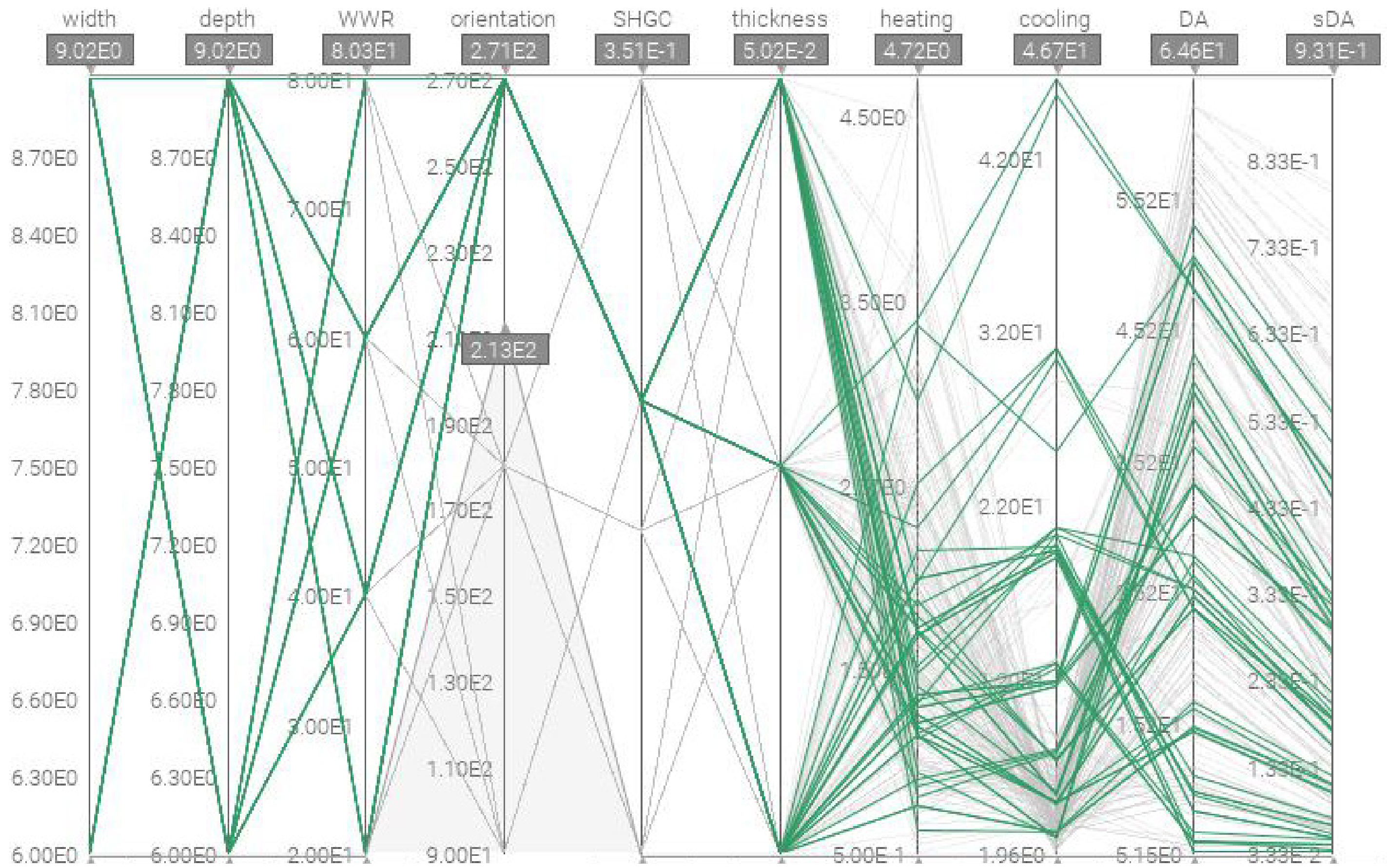


Table XXVIII: west orientation

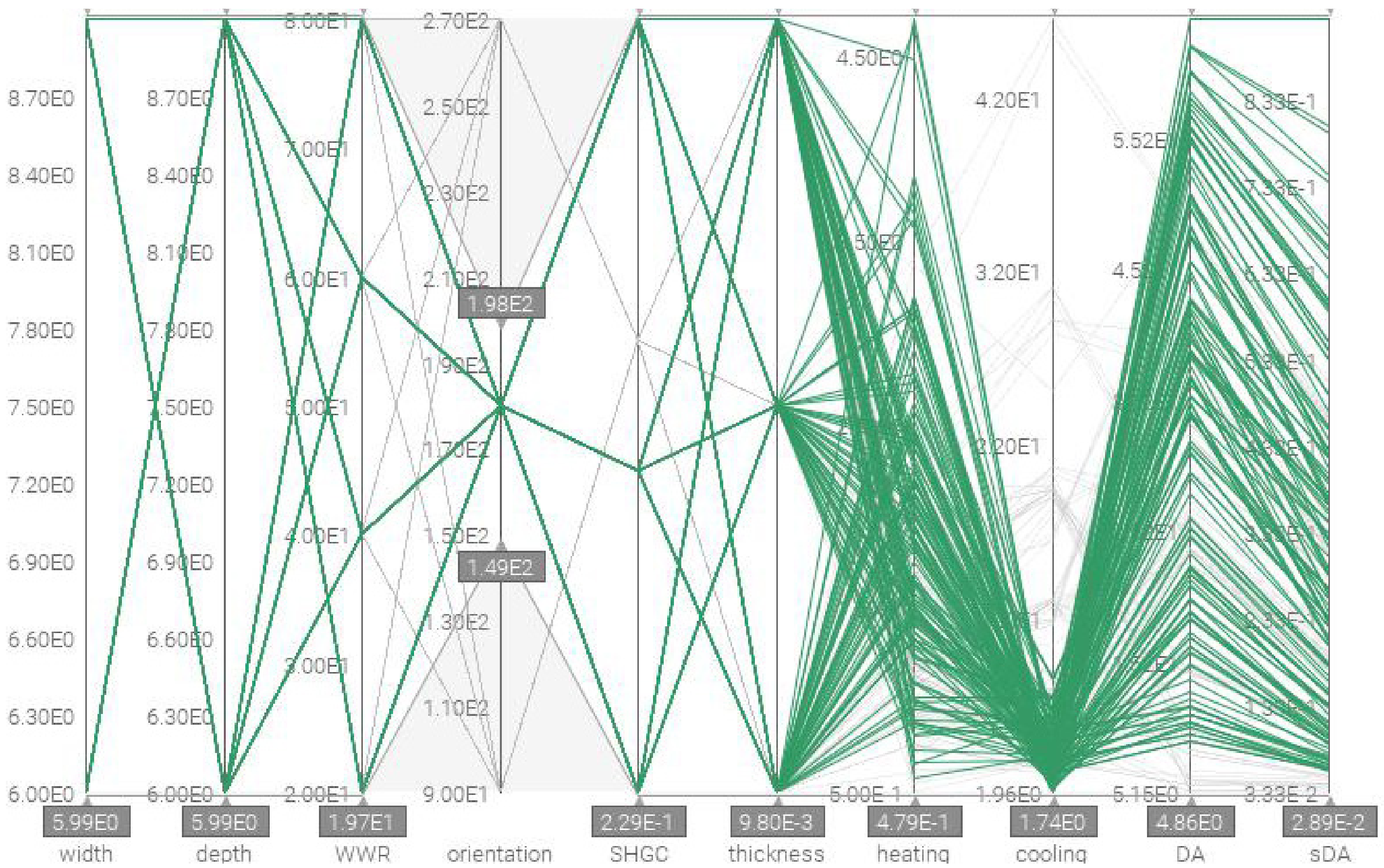


Table XXVII: south orientation

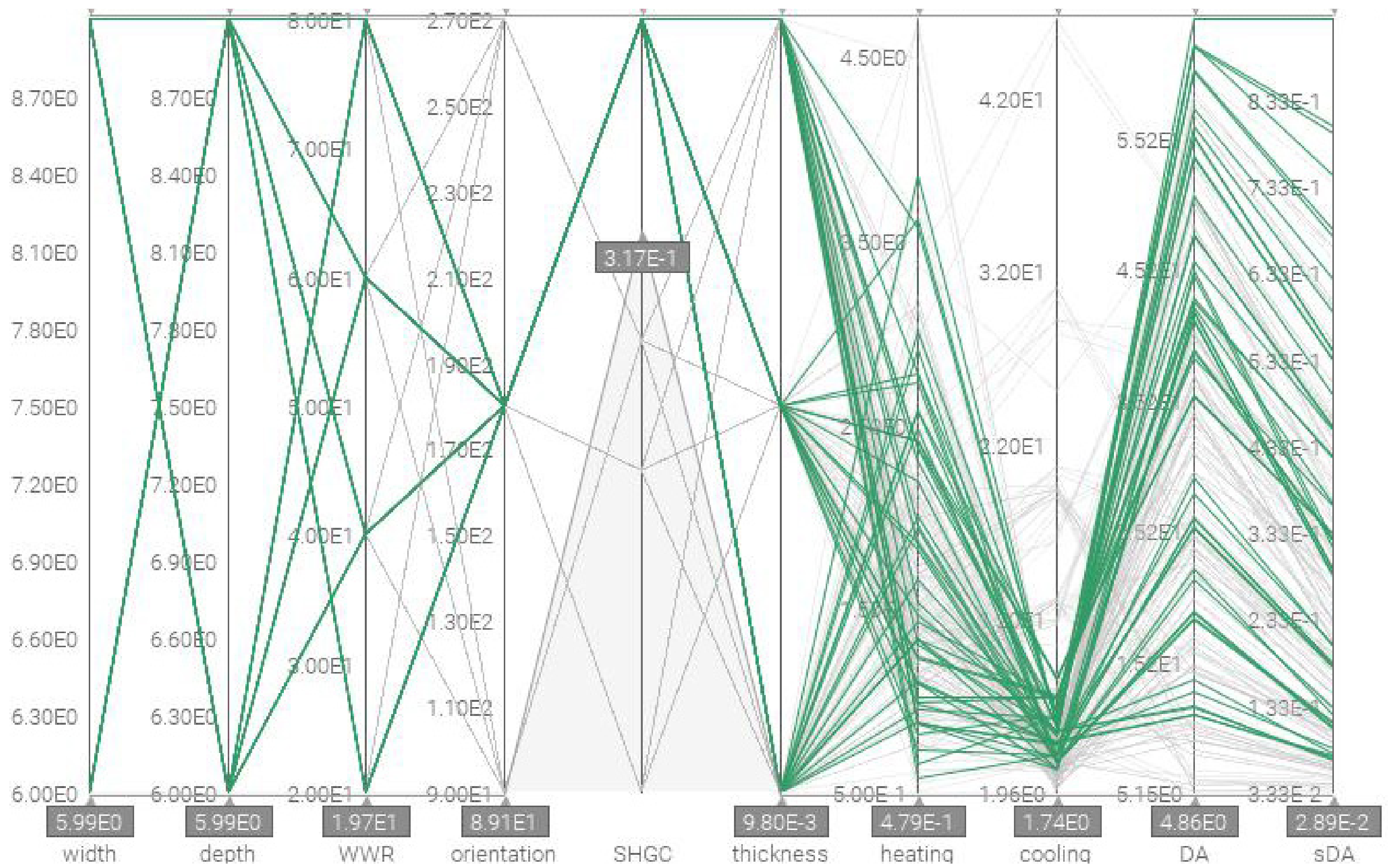


Table XXIX: south orientation - SHGC 0.35

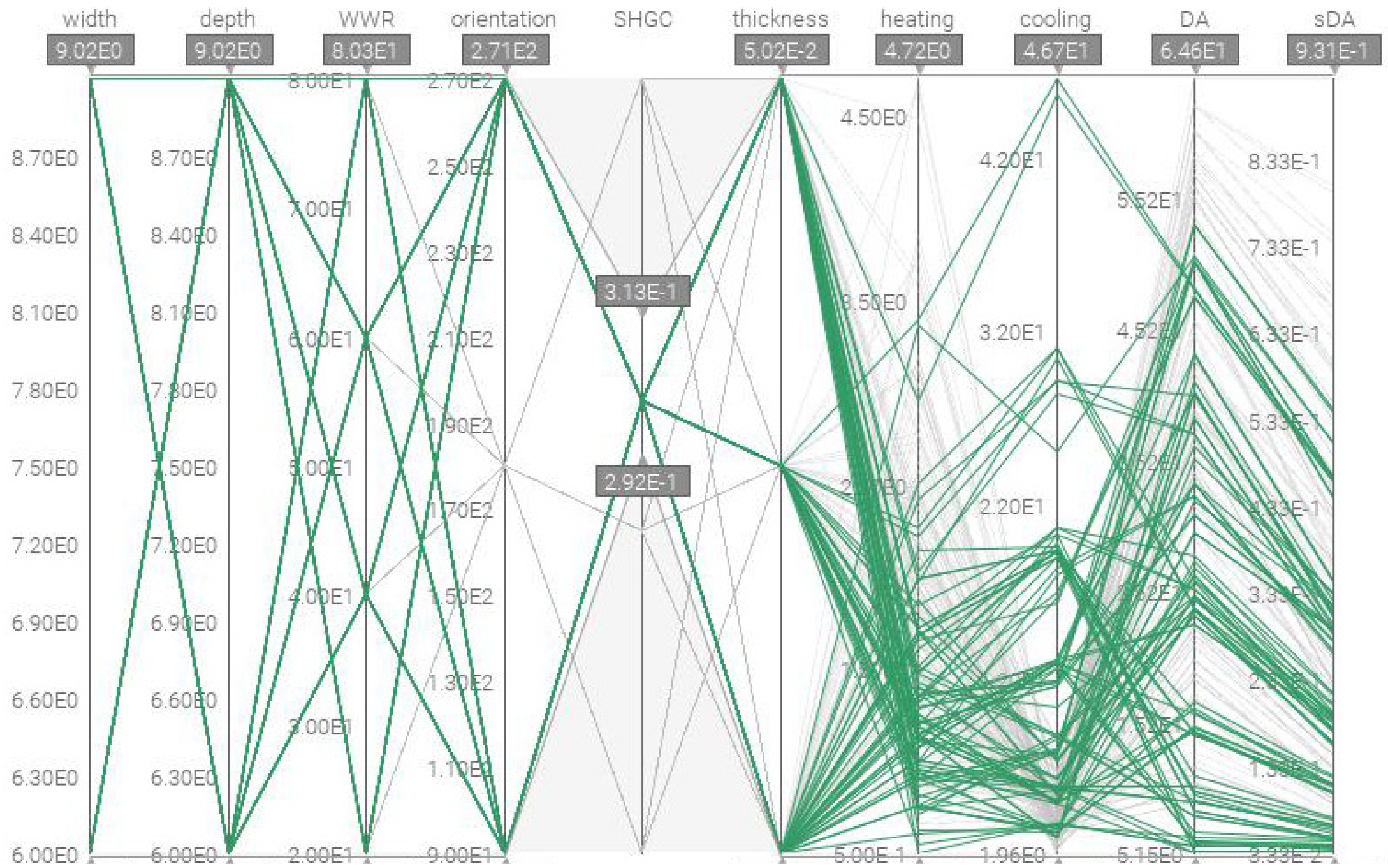


Table XXX: east/west orientation - SHGC 0.30

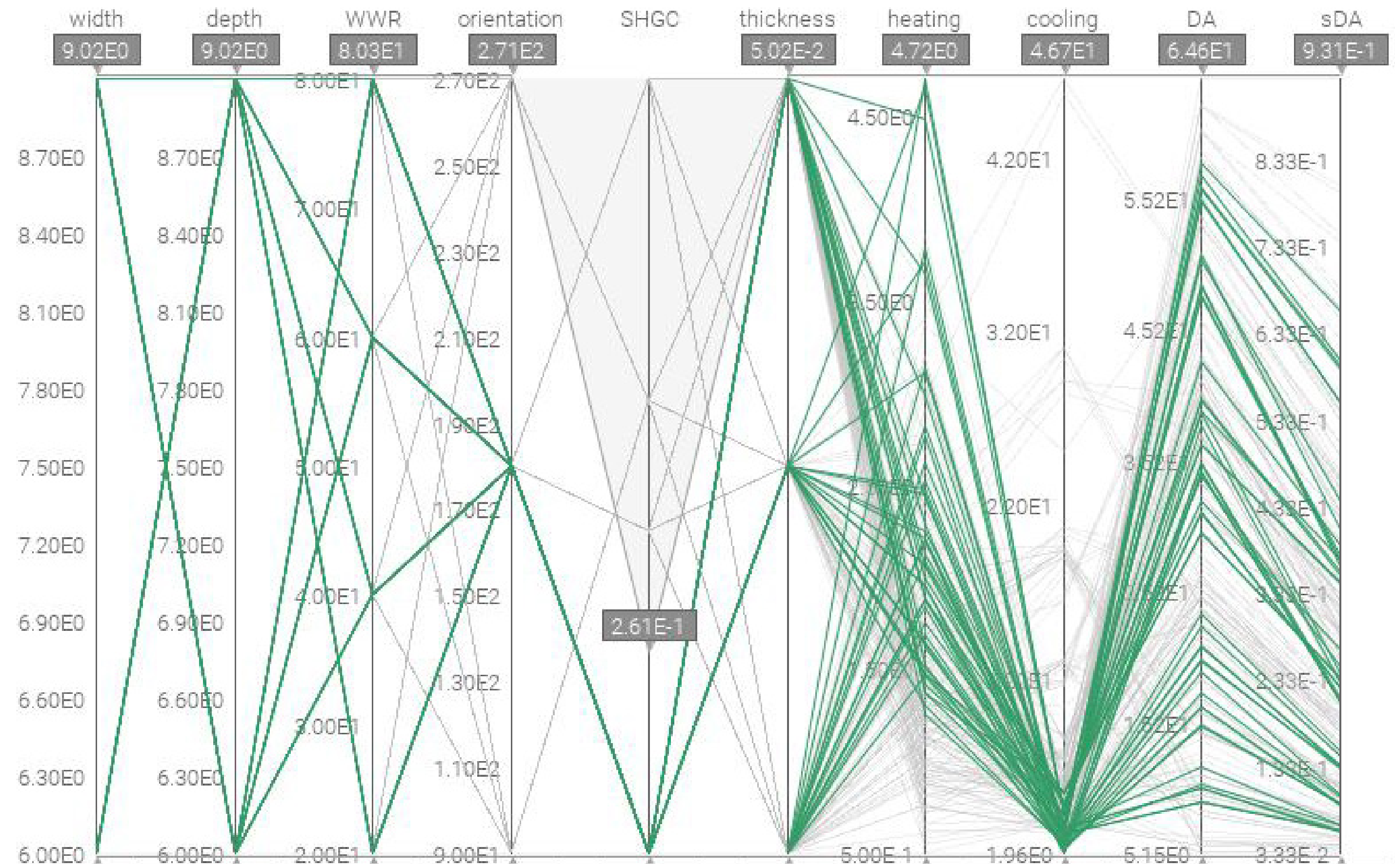


Table XXXII: south orientation - SHGC 0.23

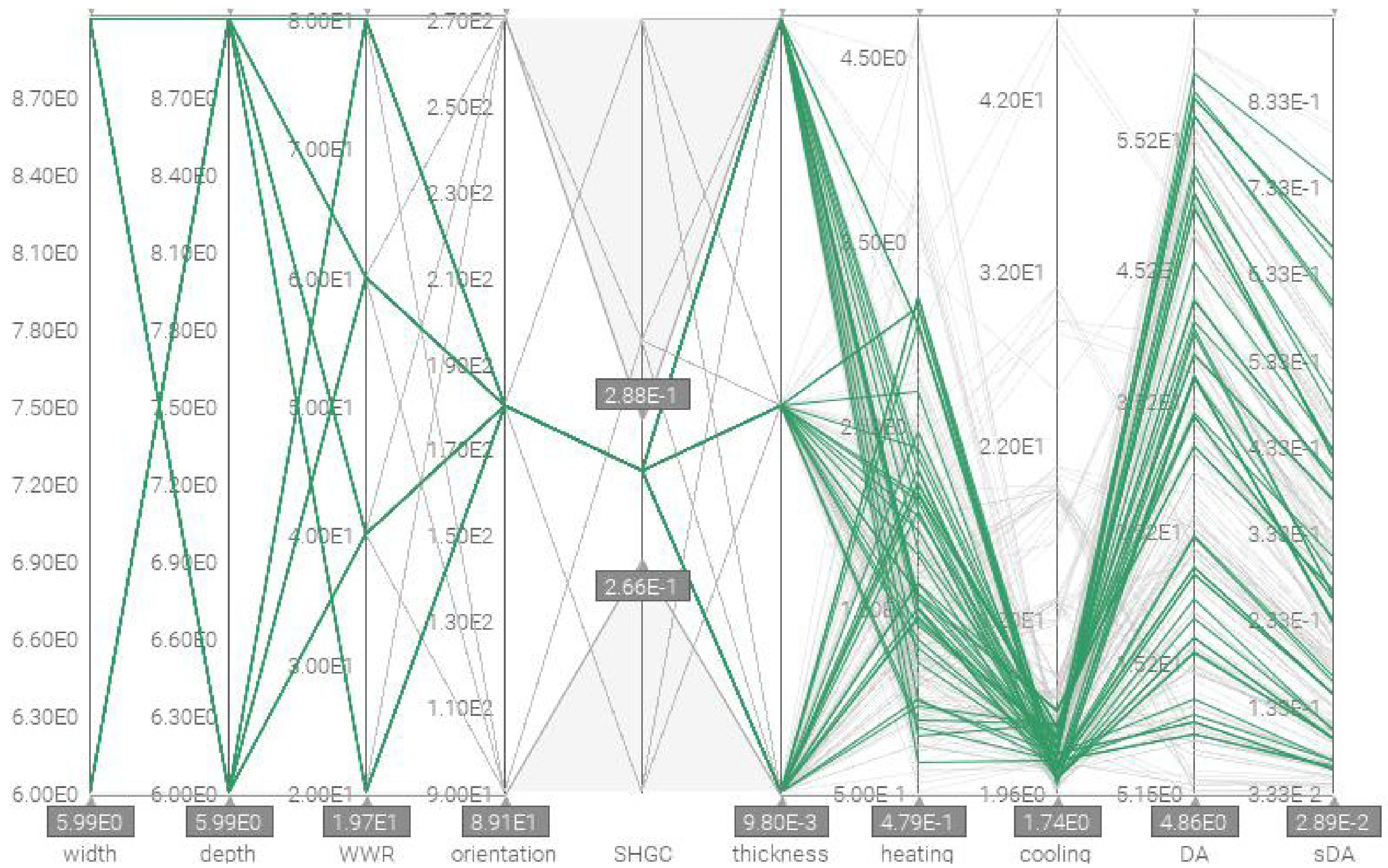


Table XXXI: south orientation - SHGC 0.28

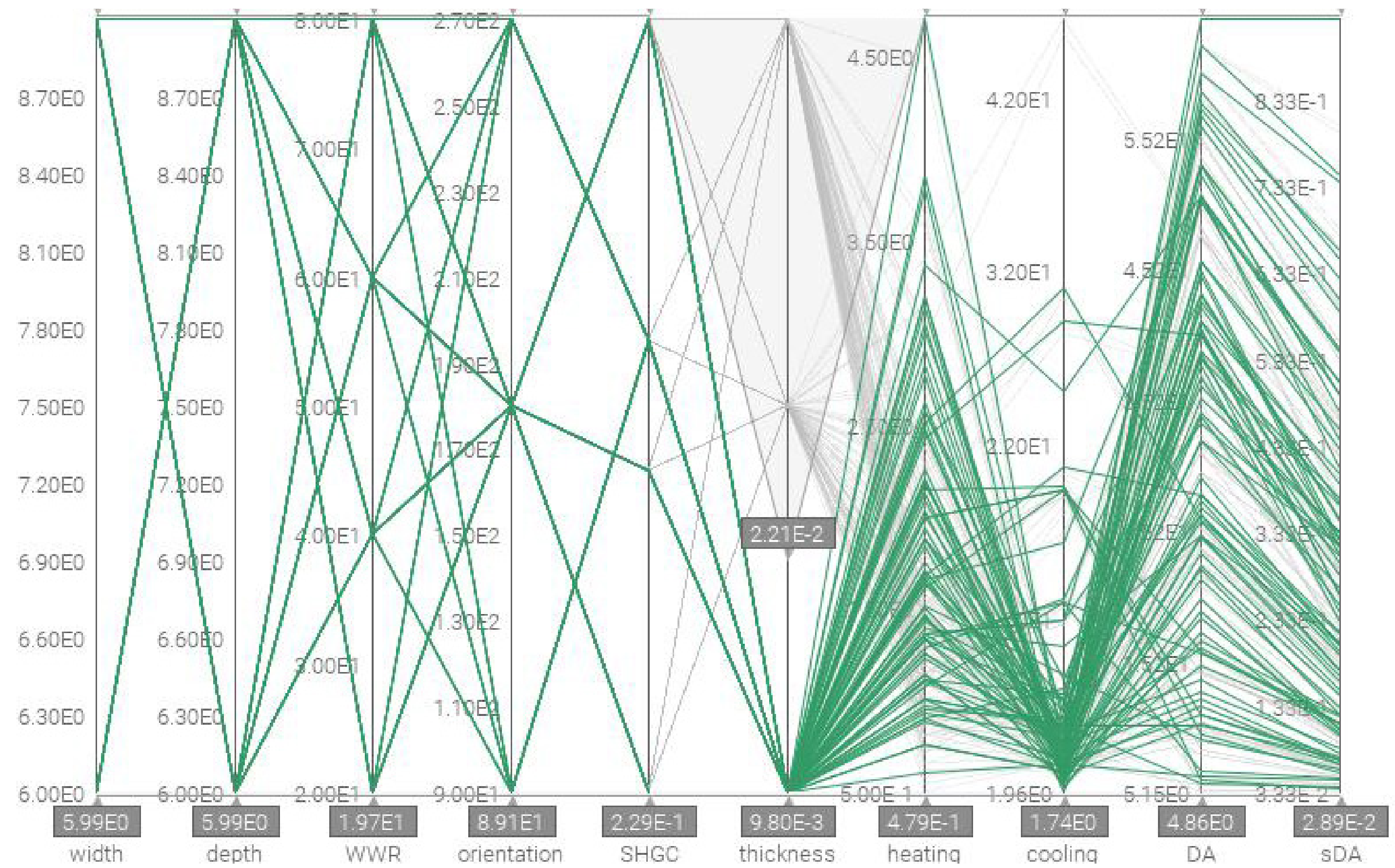


Table XXXIII: PCMs layer 1 cm thick

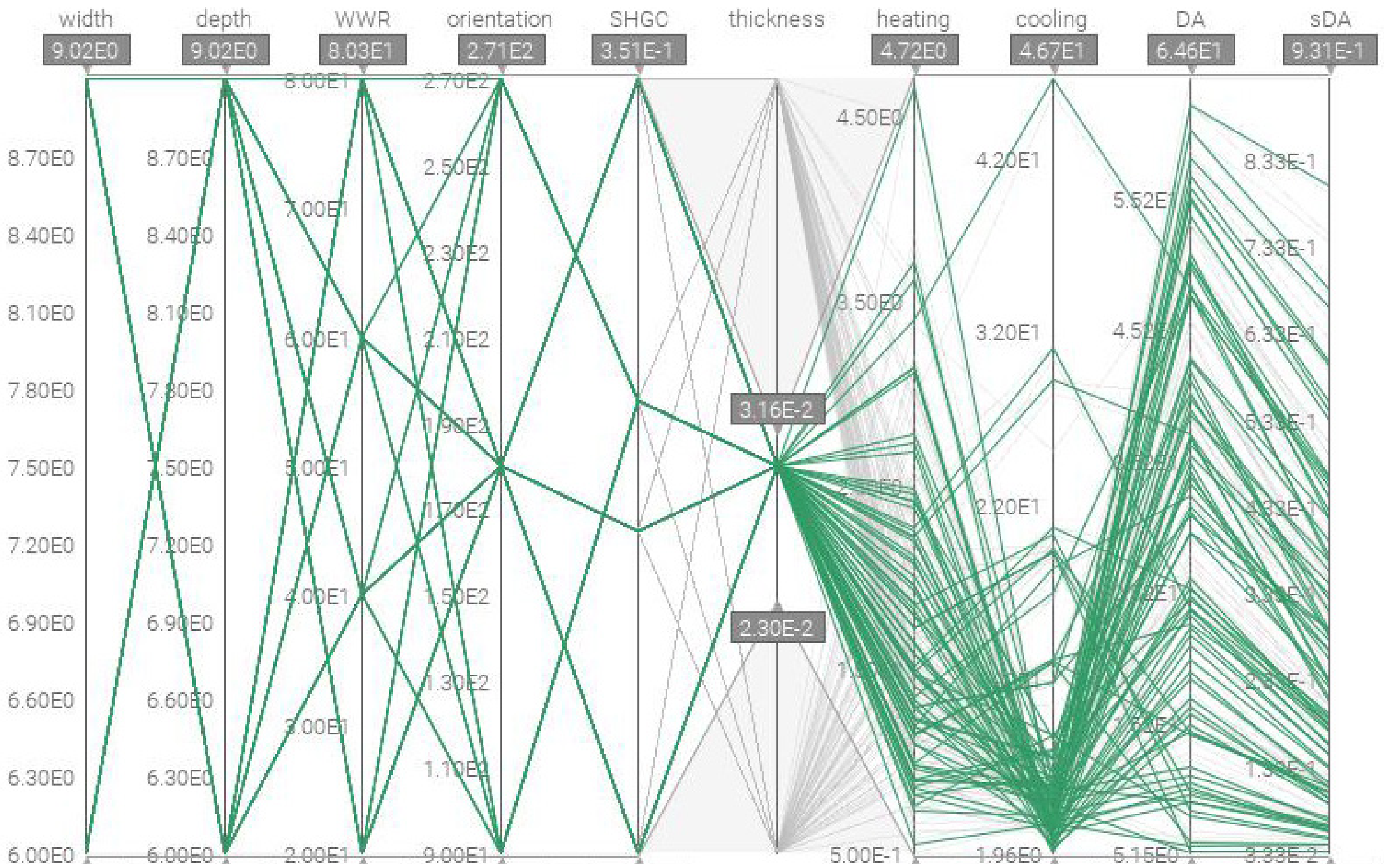


Table XXXIV: PCMs layer 3 cm thick

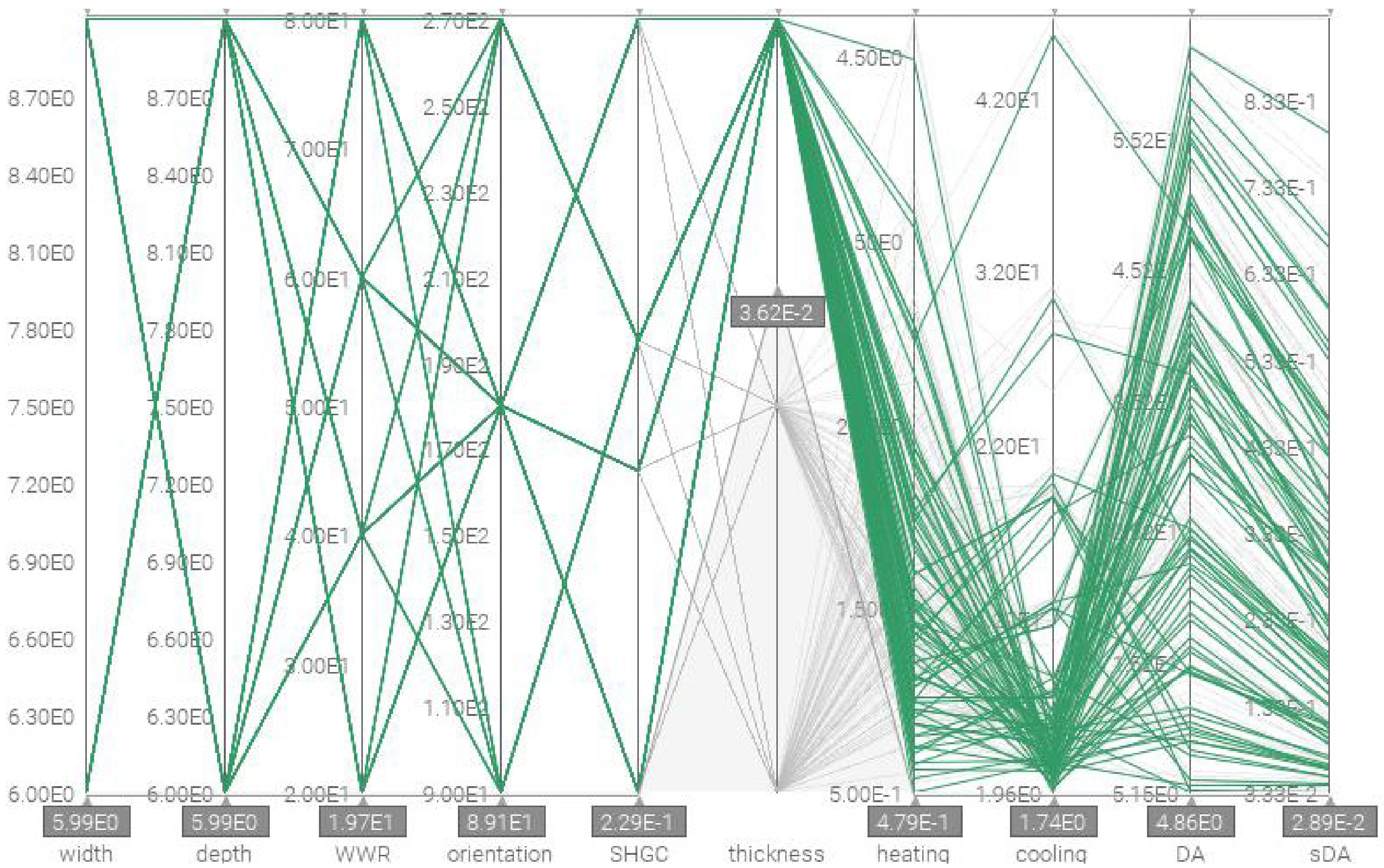


Table XXXV: PCMs layer 5 cm thick