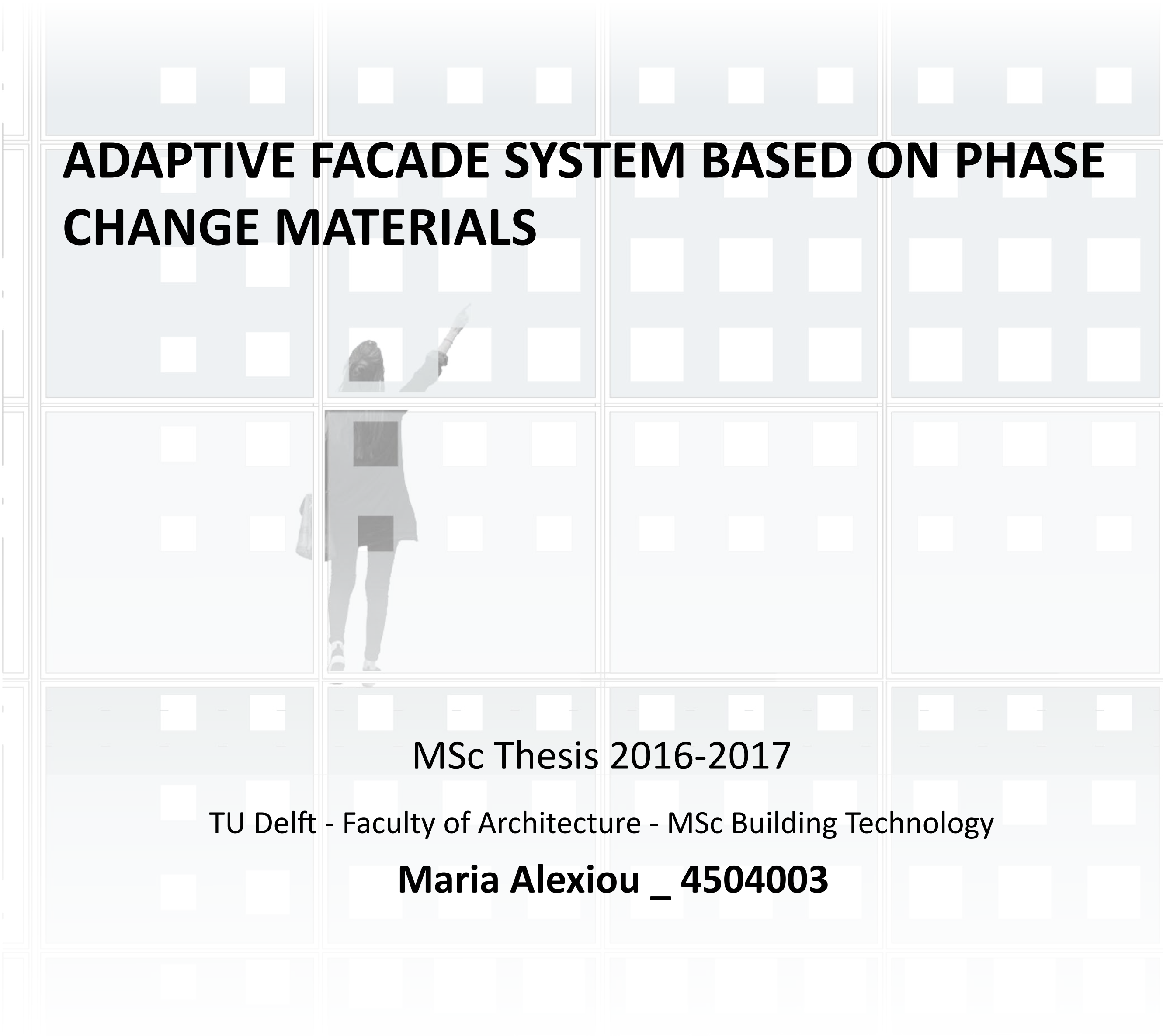

ADAPTIVE FACADE SYSTEM BASED ON PHASE CHANGE MATERIALS

MSc Thesis 2016-2017

TU Delft - Faculty of Architecture - MSc Building Technology

Maria Alexiou _ 4504003

Mentors:

Main supervisor: dr.ir. MSc.Arch Michela Turrin
dr.ir.arch. M.J. (Martin) Tenpierik
dr.ing. Marcel Bilow

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CONTENTS

ABSTRACT

In order to limit the exorbitant energy consumption by the use of mechanical heating and cooling systems, several buildings are trying to adopt a heat storage system as a part of the energy system of the building. However, there are also passive systems that perform independently from the building's energy system and store heat in alternative ways. More specifically, an efficient way to achieve thermal energy storage is the use of phase change materials (PCMs) in the building construction. PCMs offer a high thermal storage density with a moderate temperature variation, and have attracted growing attention due to their important role in achieving energy conservation in lightweight buildings while maintaining thermal comfort. Research in this area has resulted in findings, which depict a significant plummet in temperature variations whilst maintaining desirable thermal comfort. Despite these findings, only a few research projects deal with the implementation of PCMs in the façade system, as a method to enhance the visual and the thermal comfort of the indoor environment of the buildings. This paper summarises previous works on latent thermal energy storage in building applications, covering PCMs, the current building applications and their thermal performance. It also provides new innovative ideas on integrating PCM in the building envelope, as well as on their impact on the visual and the thermal quality of the indoor space.

INTRODUCTION

Façades constitute one of the fundamental systems of contemporary buildings. They serve multiple purposes; they create better indoor climatic conditions, provide sufficient daylight and create an aesthetic image. They are more than just mere skin that forms the exoskeleton of a building.
On the other hand, the indoor environment of a building and the amount of electricity consumed by the heating and the cooling systems can be influenced by several building envelope characteristics such as building shape, orientation, thermal insulation, thermal mass, wall colour, window size, glazing material, shading devices, green roof system, etc.
Technological advances in the building technology have led to the implementation of smart systems and materials in the building's envelope that reduce the building's energy consumption, giving it an adaptive character to respond to changing conditions.
The design and the construction of these intelligent façade systems aim to create a dialogue within the building, its exterior surroundings and the occupants. This is achieved either by transformative and mechanised structures or by smart materials that are able to change the behaviour of the outer skin so as to cover the users needs on the inside and adapt to the exterior climate conditions.

1

literature review

PHASE
A phase is a set of states of a macroscopic physical system that have relatively uniform chemical composition and physical properties (i.e. density, crystal structure, index of refraction, etc)
PHASE CHANGE
A phase change is the transformation of a thermodynamic system from one phase to another. The distinguishing characteristics of a phase transition are abrupt transitions in one or more physical properties, in particular the heat capacity, with a small shift in a thermodynamic variable such as the temperature.
PHASE CHANGE MATERIAL
A Phase Change Material (PCM) is a substance with a high heat of fusion such that it can melt and solidify at specific temperatures, giving it the ability to store and release significant amounts of energy.
Retrieved from https://www.researchgate.net/topic/Phase-Change-Materials

Transitions between solid, liquid, and gaseous phases typically involve large amounts of energy compared to the specific heat. If heat were added at a constant rate to a mass of ice to take it through its phase changes to liquid water and then to steam, the energies required to accomplish the phase changes (called the latent heat of fusion and latent heat of vaporization) would lead to plateaus in the temperature versus time graph. The graph below presumes that the pressure is one standard atmosphere **(Nave, 2015).**

PCMs are latent heat storage materials. The phase change is a heat-seeking (endothermic) process and therefore, the material absorbs or releases heat depending on the direction of the phase change. Phase change materials are organic compounds or inorganic salts and they both depend on molecular effects. Therefore it is not surprising that materials within one material class behave similar **(Mehling and Cabeza,2008).**

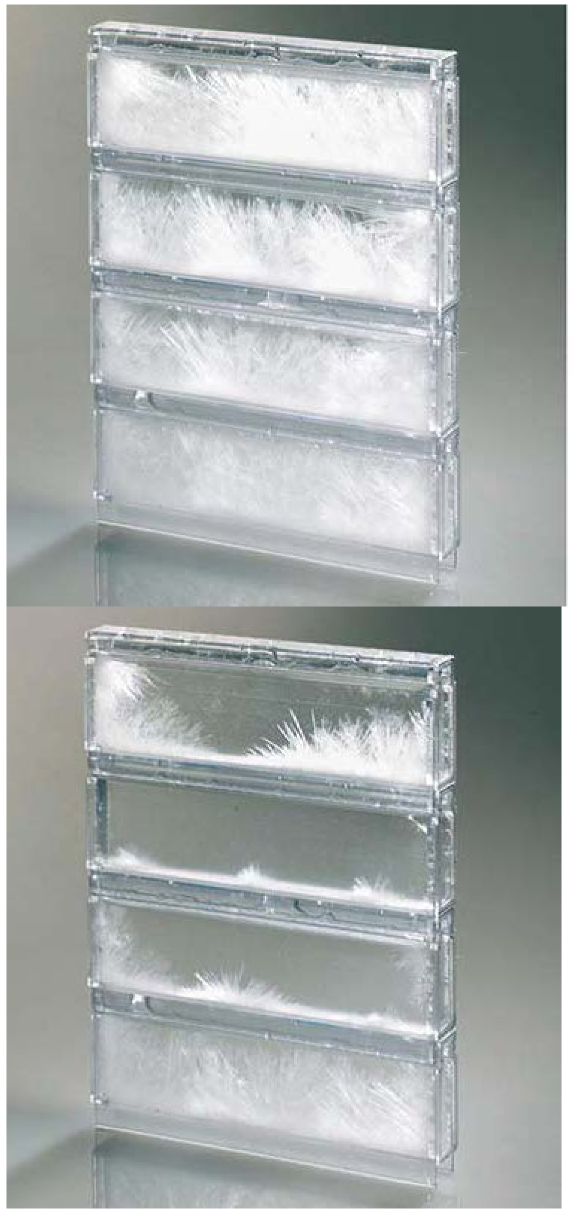


Figure 1.1:Calcium chloride hexahydrate contained in one of the cavities acts as a phase change material, absorbing energy as it melts. Retrieved from http://www.tectonica-online.com/products/2536/change_phase_glazing_crystal_glassx/

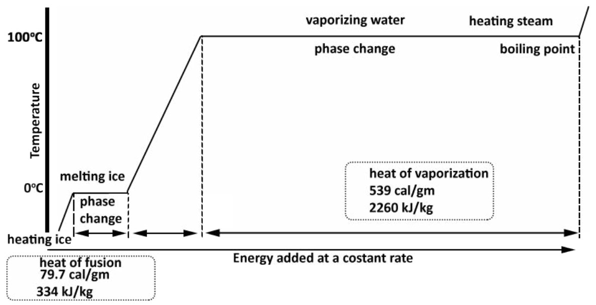


Figure 1.2: The phase change transitions of the water Redesigned by the author (initial source: Nave,2015)

Phase change materials can be divided in 3 different categories according to their chemical composition. Three groups are commonly made:(i) organic compounds, (ii) inorganic compounds and (iii) inorganic eutectics or eutectic mixtures. The group of organics can be divided in paraffins and non-paraffins. Each group has its typical range of melting temperature and its range of melting enthalpy (Fig 4). Moreover, an overview of common PCMs from each group is given in Table 1 **(Baetens et al.2010).** In 1983, Abhat gave a useful classification of the substances used for thermal energy storage shown in Fig 1.3.

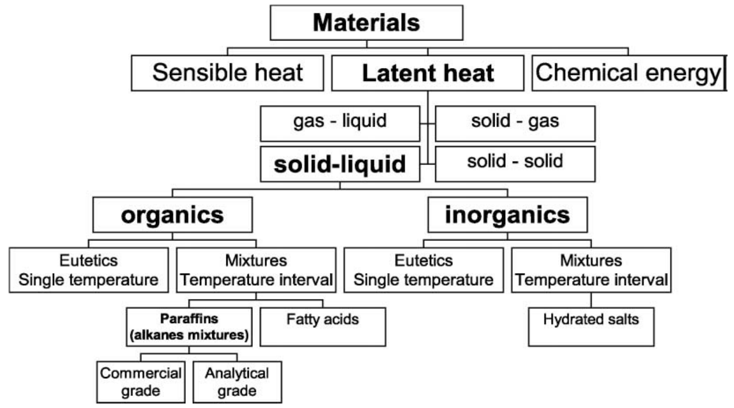


Figure 1.3:The classification of PCM (Abhat,1983)

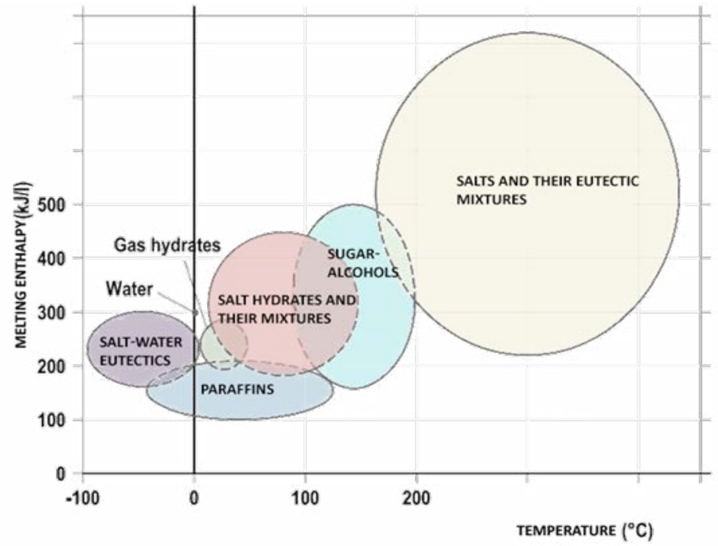


Figure 1.4: The melting enthalpy and melting temperature for the different groups of phase change materials redesigned by the author (intital source:Dieckmann,2008)

ORGANIC COMPOUNDS	PARAFFINS	INORGANIC COMPOUNDS	INORGANIC EUTECTICS
Polyglycol E 400	Paraffin C_{14}	H_2O	58.7% $Mg(NO)_3 \cdot 6H_2O$-
Polyglycol E 600	Paraffin C15–C16	$LiClO_3 \cdot 3H_2O$	41.3% $MgCl_2 \cdot 6H_2O$
Polyglycol E 6000	Paraffin C16–C18	$Mn(NO_3)2 \cdot 6H_2O$	
Dodecanol	Paraffin C13–C24	$LiNO_3 \cdot 3H_2O$	66.6% $CaCl_2 \cdot 6H_2O$+
Tetradodocanol	Paraffin C16–C28	$Zn(NO_3)2 \cdot 6H_2O$	33.3% $MgCl_2 \cdot 6H_2O$
Biphenyl	Paraffin C18	$Na_2CO_3 \cdot 10H_2O$	
HDPE	Paraffin C20–C33	$CaBr_2 \cdot 6H_2O$	48% $CaCl_2$ + 4.3% NaC
Trans-1,4-	Paraffin C22–C45	$Na_2HPO_4 \cdot 12H_2O$	+ 0.4% KCl + 47.3 H_2O
polybutadiene	Paraffin C23–C50	$Na_2S_2O_3 \cdot 5H_2O$	
Propianide Naphtalene	Paraffin wax	$Na(CH_3COO) \cdot 3H_2O$	47% $Ca(NO_3)2 \cdot 4H_2O$+
Erythitol	Octadecane	$Na_2P_2O_7 \cdot 10H_2O$	53% $Mg(NO_3)2 \cdot 6H_2O$
Dimethyl-sulfoxide		$Ba(OH)2 \cdot 8H_2O$	
Capric acid		$Mg(NO_3)2 \cdot 6H_2O$	60% $Na(CH_2COO)$
Capricinic acid		$MgCl_2 \cdot 6H_2O$	$\cdot 3H_2O$+ 40% $CO(NH_2)2$
Laurinic acid		$(NH_4)Al(SO_4) \cdot 6H_2O$	
Miristic acid		$NaNO_3$	66.6% Urea + 33.4%
Lakisol		KNO_3	NH_4Br
Palmitic acid		KOH	
Stearic acid		$MgCl_2$	
Acetamid Propionamid		NaCl	
		$Na2CO_3$	
		KF	
		K_2CO_3	

Table 1.1:Overview of the main phase change materials resigned by the author (initial source: Abhat,1983)

PHASE CHANGE MATERIALS|ORGANIC PHASE CHANGE COMPOUNDS

A)ORGANIC PHASE CHANGE COMPOUNDS

Organic phase change materials are in general chemically stable, do not suffer from supercooling, are non-corrosive, are non-toxic and have a high latent heat of fusion. Organic PCMs can be subdivided in two groups: paraffins and non-paraffins .

1)PARAFFINS

Paraffins are simple hydrocarbons with the formula C_xH_{2x+2} . They are the most applicable PCMs in the building industry as they are cost effective and have good latent heat from 120-266kJ /kg and melting temperatures fluctuating points from 20-112°C.However, they have low thermal conductivity (typically 0.2 W/mK) and they are prone to leaking as they have the characteristic of altering the volume during the solidification and melting process (Baetens, 2011). For example, when paraffins are directly combined with other materials such as plasterboard, the increase in volume on melting can damage the structure, leading to leakage. To get around this problem you can encapsulate the paraffin in small nodules with room inside for melting.

Paraffins and other organic PCMs are often flammable but fire retardant treatments can be applied to the material they are embedded in (Cabeza et al, 2010). They are usually derived from mineral oil and they are cost effective, although they do need to be refined to technical-grade.

2)NON PARAFFINS

The non-paraffin organics is composed by various organic materials like fatty acids, esters, alcohols and glycols. They have generally excellent melting and freezing properties, but are more expensive than paraffins .The most applicable materials in this category are the fatty acids or palmitoleic acids. This happens as they have melting points in a relatively low temperature range, have a high latent heat of fusion, undergo small volume changes during phase transition and do not undergo super cooling during freezing.(Hasnain,1998)

Fatty acids are commercially available but typically three times as expensive as paraffin. Latent heats are a little lower than for paraffins and there are available with a melting point in the comfort range between 19°C and 26°C.Fatty acids have very low volume change between the solid and liquid phase and this makes them easier to incorporate into porous materials without leakage.(Li et al,2011)

Figure1.5:Fully refined paraffin wax 0.5% oil content Retrieved from (https://atdmco.com/wax/fully-refined-paraffin-wax/0-5-oil-content.html)

Figure 1.6:The melting enthalpy and melting temperature for the different groups of phase change materials redesigned by the author (intital source:Dieckmann,2008)

PHASE CHANGE MATERIALS|INORGANIC PHASE CHANGE COMPOUNDS, EUTECTICS

B)INORGANIC PHASE CHANGE COMPOUNDS

Of inorganic PCMs, salt hydrates are the most widely studied. Most studies have shown that the thermal stability of salt hydrates is poor due to phase separation and supercooling that they undergo after many cycles of heating and cooling. However, the thermal stability may be improved to a certain extent by introducing gelled or thickened mixtures and suitable nucleating materials.

The phase change thermal capacity is typically between 200 and 400 kJ/kg but can be lower or higher **(Cabeza, 2011).** They are usually more dense than organic PCMs and also more conductive: typically 0.5 W/mK .The specific heat capacity of salt hydrates is in a similar range to that for organic PCMs, typically 1.5-2.5 J/kg/K **(Kuznik et al, 2010).**

C)EUTECTICS

A eutectic is a minimum melting composition of two or more components, each of which melts and freezes congruently, forming a mixture of the component crystals during crystallization. Therefore none of the phases can sink down due to a different density.

Eutectics nearly always melt and freeze without segregation because they freeze to an intimate mixture of crystals, leaving little opportunity for the components to separate. Eutectic compositions show a melting temperature and good storage density8. Eutectic water-salt solutions have melting temperatures below 0oC, because the addition of salt reduces the melting temperature and usually good storage density. The thermal conductivity of eutectic water-salt solutions is similar to that of water **(Mehling and Cabeza,2008).**

Based on the discussion so far on PCMs, a summary of the advantages and disadvantages can be deduced. Organic PCMs are available in a large temperature range, have a high heat of fusion, and are chemically stable and easily recyclable. In addition to this, they don't undergo supercooling. However, their thermal conductivity is low, they undergo large volume changes and they are also flammable. Inorganic PCMs on the other hand, have a high thermal conductivity and undergo low volume changes but are prone to supercooling and corrosion. On a positive note, they have a high heat of fusion and are available for relatively lower costs. Lastly, we have Eutectics, which have positive properties such as sharp melting temperature and a high volumetric thermal storage capacity but unfortunately, there isn't enough data available regarding its thermo-physical properties.

CLASSIFICATION	ADVANTAGES	DISADVANTAGES
• Organic PCMs	1)Availability in a large temperature range 2)High heat of fusion 3)No supercooling 4)Chemically stable and recyclable 5)Good compatibility with other materials	1)Low thermal conductivity 2)Relative large volume change 3)Flammability
• Inorganic PCMs	1)High heat of fusion 2)High thermal conductivity 3)Low volume range 4)Availability in low cost	1)Supercooling 2)Corrosion
• Eutectics	1)Sharp melting temperature 2)High volumetric thermal storage density	1)Lack of currently available test data of thermophysical properties

Table 1.2: Comparison of different kinds of PCMs,designed by the author.

Starting from the solid phase, if heat is added to the PCM, its temperature rises until melting starts. In this way the PCM stores heat in a sensible way. During melting, the addition of heat no longer leads to an increase in temperature. The added heat is responsible for the phase change to happen. The PCM thus stores heat in a latent way. After all material has molten, adding heat again leads to a temperature rise, at which point the material again stores heat in a sensible way. Upon freezing, the PCM solidifies at its freezing temperature and the energy (heat) that has been absorbed before for melting is now released. This can be explained by the fact that the liquid state has a higher energy state than the solid. Thus, there is more energy stored in the liquid which is fully dissipated during solidification.This principle can be also integrated in a façade system made of PCMs.More specifically, on sunny days, part of the incoming solar radiation is absorbed and stored in the PCM, the temperature of which begins to rise until melting starts. The melting process takes a few hours, during which the PCM remains at melting temperature.
With all material in liquid state, the PCM behaves like any other sensible heat storage material. When the temperature drops below the solidification temperature in the evening, the PCM starts to crystallise. The energy set free by the solidification process raises the temperature of the PCM again to melting temperature. It then takes several hours to discharge the PCM. During this time, the system not only compensates its heat losses, but in fact helps to reduce heating requirements. Thermal comfort will also improve due to the high surface temperatures of the facade panel.**(Weinläder, Beck and Fricke, 2004)**

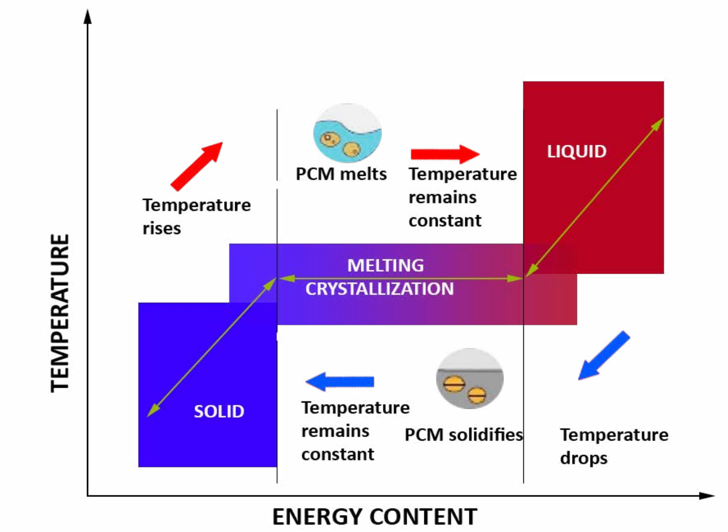


Figure 1.7: The working principle of PCM,designed by the author

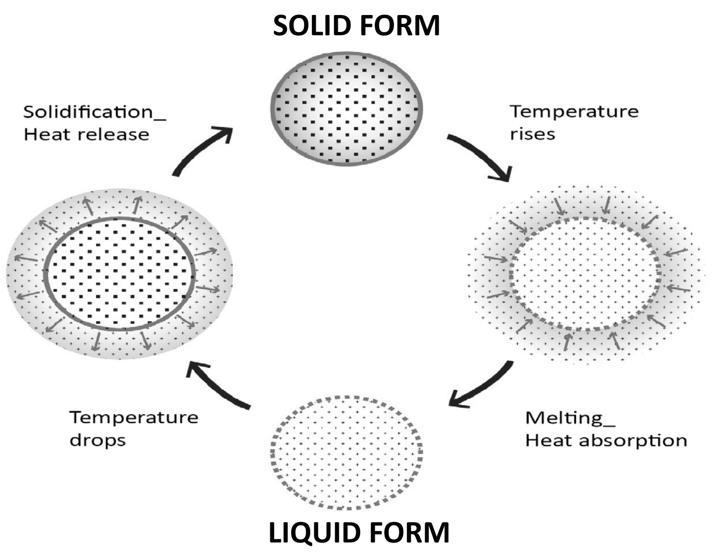


Figure 1.8: The thermal cycle of the PCMs, designed by the author

PHASE CHANGE MATERIALS|KEY PROPERTIES AND SELECTION CRITERIA

PCM KEY PROPERTIES

Phase change materials are used to store heat on melting and release it when they solidify. These materials possess latent heat per unit mass (or volume). However, taking encapsulation into account, just around 10% of the construction could constitute PCM. They also possess a melting temperature for which the solidification occurs slightly below this temperature. The closer the gap between melting and solidification, the more suited it is to the application. In the solid phase, it is mainly characterised by a thermal conductivity but in its liquid phase, convection effects need to be taken into account. Chemical and physical stability is a priority since the character of the material must not change during repeated melting and solidification. Most PCMs are safe since they are not toxic. However, some may be corrosive in which case, encapsulation is crucial.

1)latent heat per unit mass or volume – however, this also needs to take encapsulation into account as it may be that only 10% of the final construction is PCM
2) melting temperature – the temperature for solidification is usually a little lower than the melting temperature but for most applications it is best if they are similar
3) thermal conductivity, especially in the solid phase, as in the liquid phase heat will be transferred by convection as well
4) stability, so that it can melt and solidify many times without changing character
5) safety in handling – most PCMs are non-toxic but some are corrosive, in which case encapsulation is particularly important.**(Abhat ,1983)**

SELECTION CRITERIA OF PCMs

The PCM can be used in thermal storage systems if the accomplish desirable thermophysical ,kinetic and chemical requirements:
Thermophysical requirements :
1)Melting temperature in the desired operating temperature range.
2)High latent heat of fusion per unit volume so that the required volume of the container to store a given amount of energy is less.
3) High specific heat to provide additional significant sensible heat storage.
4) High thermal conductivity of both solid and liquid phases to assist the charging and discharging energy of the storage system.
5) Small volume change on phase transformation and small vapour pressure at operating temperature to reduce the containment problem.
6) Congruent melting of the phase change material for a constant storage capacity of the material with each freezing/melting cycle.**(Sharma et al, 2005)**
7)Reproducible phase change, also called cycling stability, in order to use the storage material as many times for storage and release of heat as required by the application.
8) Little or no sub-cooling during freezing to assure that melting and solidification can proceed in a narrow temperature range.**(Mehling and Cabeza,2008)**
Kinetic requirements:
1) High nucleation rate to avoid super cooling of the liquid phase.
2) High rate of crystal growth, so that the system can meet the demand of heat recovery from the storage system.
Chemical requirements:
1)Chemical stability of the PCM to assure long lifetime of material if it is exposed to higher temperature, radiation, gases, etc.
2)Compatibility of the PCM with the construction

PHASE CHANGE MATERIALS|TYPICAL PROBLEMS

A) PHASE SEPARATION

When a pure substance with only one component, like water, is heated above its melting temperature, it will melt and retain the same homogeneous composition in the liquid as before in the solid state. When the material is solidified by cooling it below the melting temperature, the solid will again be of the same homogeneous composition throughout and the same phase change enthalpy and melting temperature is observed at any place. Such a material is said to melt congruently.
However, when a substance is composed by two or more components, the system now behaves in a very different way. For example, a salt-water based PCM with a composition of 10 wt.% salt and 90 wt.% of water is a homogeneous liquid above -4 °C. When it is cooled under -4°C,the water freezes and the substance separates into two different phases, one with only water, and a second one with a higher salt concentration than initially. Because of the gravity the phase with higher density will sink to the bottom and the one with the lower density will rise to the top. This phenomenon is called phase separation or decomposition, because the original composition is changed.**(Mehling, Cabeza ,2008)**

B) MATERIAL LEAKAGE

In most cases, except for some applications of water-ice, the PCM needs to be encapsulated in order to hold the liquid phase of the PCM, and to avoid contact of the PCM with the environment, which changes the composition of the PCM. Additionally, the surface of the encapsulation acts as heat transfer surface. In some cases, the encapsulation also serves as a construction element, which means it adds mechanical stability. Encapsulations are usually classified by their size into macro- and microencapsulation.
Macro encapsulation means filling the PCM in a macroscopic containment that fits amounts from several ml up to several litres. These are often containers and bags made of metal or plastic.
Microencapsulation is the encapsulation of solid or liquid particles of 1 μm to 1000 μm diameter with a solid shell. Physical processes used in microencapsulation are spray drying, centrifugal and fluidized bed processes, or coating processes.

C) SUPERCOOLING

Subcooling (also called supercooling) is the effect that a temperature significantly below the melting temperature has to be reached, before a material begins to solidify and release heat (fig.5). If that temperature is not reached, the PCM will not solidify at all and thus only store sensible heat. (Mehling and Cabeza, 2008)
The most common approach to get rid of subcooling on the level of the PCM is to add special additives, also called nucleator, to the PCM to cause heterogeneous nucleation. Nucleators have been developed for most well investigated PCM, and reduce subcooling typically to a few K. Most nucleators are materials with a similar crystal structure as the solid PCM to allow the solid phase of the PCM to grow on their surface, but a higher melting temperature to avoid deactivation when the PCM is melted.

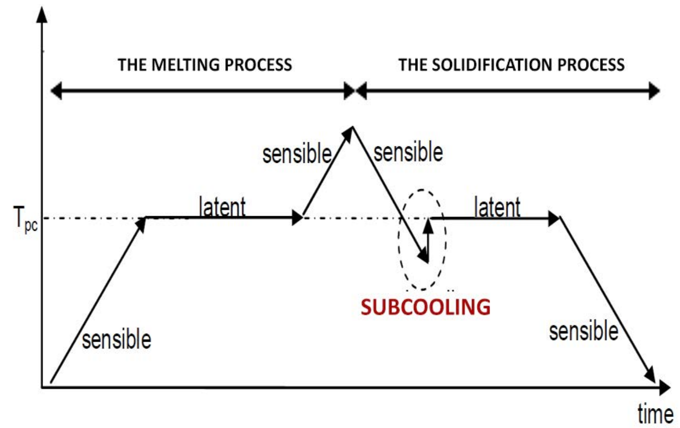


Figure 1.9 : Schematic temperature change during heating (melting) and cooling (solidification) of a PCM with subcooling

The heat capacity of the enclosing components is an important parameter for controlling the indoor temperature and reducing the temperature swings during the day.
The use of thermal energy storage for thermal applications has received significant attention during the past decades; a variety of thermal energy storage techniques have been developed as industrial countries have become highly dependent on electricity and other fossil energy resources.
Thermal storage in a building may be crucial for the reduction of cooling loads and rise of temperatures. External surfaces of building envelopes show higher or lower temperatures not only as a function of ambient air temperature, intensity of solar radiation and the radiation physics of the envelope itself, but also on their own thermal properties.
Additionally, the transmission of external temperature fluctuations through a building envelope is a function of the capacity of the envelope and the building structures' ability to store heat.
In this section, the basic methods of thermal energy storage systems and their basic principles are explained in detail. The differences and the application of each type are also analysed.
Thermal energy storage (TES) systems, commonly called heat and cold storage systems, allow the reuse of stored energy when it is required. To be able to retrieve the energy later, the method of storage needs to be reversible. Thermal energy quantities differ in temperature. As the temperature of a substance increases, the energy content also increases (Dincer and Rosen 2002).
The basic methods of thermal energy storage can be divided into physical and chemical processes. The physical methods of energy storage, which will be examined for the purposes of this study, are sensible and latent heat storage. The selection of a thermal energy storage system mainly depends on the storage period required (diurnal or seasonal), economic viability, operating conditions etc.

For heat storage, the material's thermal conductivity (how quickly it conducts heat) and the thermal capacity (how much heat it can store) are important because these affect how fast heat can be stored and used. For example, organic PCMs often have low conductivity and work best when used in small nodules in a larger matrix (Cabeza et al, 2007) or with additives to improve conductivity (Wang et al, 2009; Mei et al, 2011; Sari and Karaipekli, 2011).
The basic principle of all thermal energy storage applications is the same. Energy is supplied to a storage system for removal and is used at a later time. What mainly varies is the scale of the storage and the storage method used. A complete storage process involves at least three steps: charging, storing and discharging. In practical systems, some of the steps may occur simultaneously and each step may occur more than once in each storage cycle. There are numerous criteria to evaluate thermal energy storage systems and applications, such as technical, environmental, economic, energetic, sizing, feasibility, integration and storage duration.

The thermal properties that describe a PCM the best are:
a) its Phase Change Temperature (Tpc), and
b) its specific latent heat capacity (lpc).

a) PHASE CHANGE TEMPERATURE

The Tpc can be distinct (e.g. T_{pc}=21^{o}C) or given within a range (e.g. T_{pc}=21-23^{o}C), and for most substances is equal for melting and solidifying.
An ideal melting behaviour exists when both the melting and solidifying process occur at one Tpc. Any deviation from the ideal melting raises the complexity of a PCM system design.
The most common deviations in ideal melting are Hysteresis and Sub-cooling.It should be also taken into consideration that the melting does not take place at a fixed temperature but at small temperature range.
Hysteresis : Is the effect where the solidification process (liquid to solid) shifts to a lower T_{pc} than (solid-liquid). In other words, the PCM presents two different T_{pc}: T_{pc_melt} and $T_{pc\_solid.}$ (graph 1.2)
Sub-cooling : Means that the material does not solidify at its Tpc but at a temperature that can be much lower. After the solidification sets-in, the temperature increases until it reaches the T_{pc}, after when the process continues normally(graph 1.3),(Mehling and Cabeza 2008).

b) LATENT HEAT CAPACITY

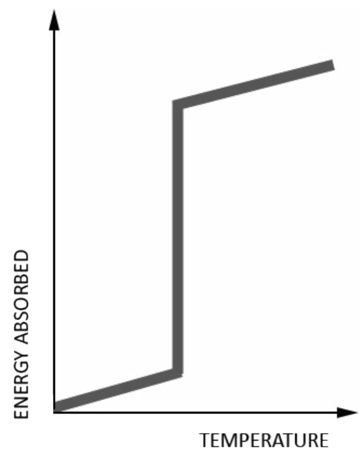
Latent Heat : Is the heat absorbed or released by the material when it undergoes a phase change. (McMullan, 2002). The phase change process is isothermal, meaning that during heat absorption or release the temperature of the material remains constant.
The quantity of heat by regards to the mass is given by the formula:

$$Q_{pc}=m\,l_{pc} \qquad (1.1)$$

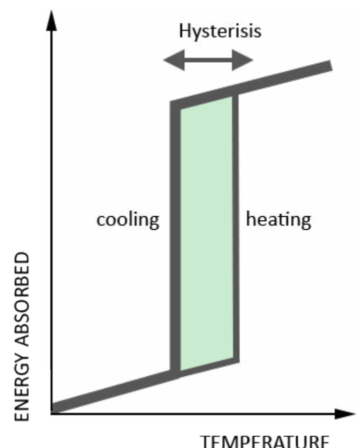
Q_{pc} [J]:the quantity of the latent heat,
m [kg] :the mass of substance,
l_{pc} [J/kg]: the latent heat of that substance
Either way, if we want to calculate by regards to the Volume, we substitute V·ρ for m

$$Q_{pc}= V\,\rho\, l_{pc} \qquad (1.2)$$

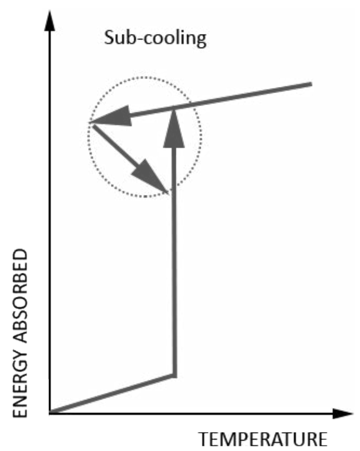
Q_{pc} [J] :quantity of the latent heat,
ρ [kg/m]:density,
l_{pc} [J /kg] :the latent specific heat of that substance



Graph1.1 : The energy absorbed over time,-made by the author



Graph1.2: The hysterisis ,made by the author



Graph1.3: The subcooling ,made by the author

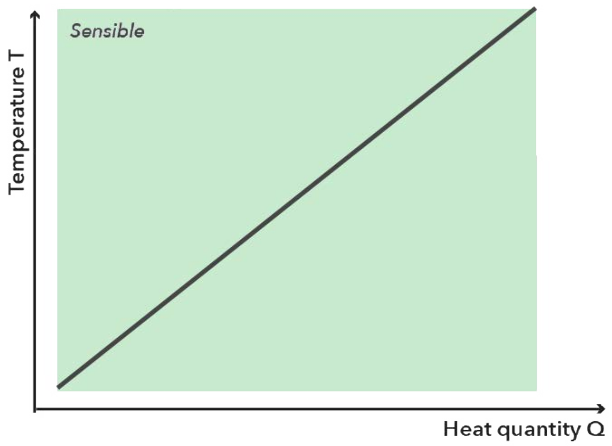
SENSIBLE HEAT STORAGE

Sensible Heat Is the heat transferred to the storage medium and leads to increase of its temperature. Specifically ,it is the quantity of energy stored when one kilogram of material increases one degree in temperature.
When a substance changes temperature, the amount of sensible heat absorbed or released is given by the following formula:

$$Q_s = m\, C_p\, \Delta T \qquad (1.3)$$

Qs [J] the quantity of the sensible heat
m [kg] the mass of substance,
Cp [J/kg·K] the sensible specific heat of that substance
ΔT [K] the temperature change.

Sensible heat storage systems utilize the heat capacity and the change in temperature of the material during the process of charging and discharging.



Graph 1.4: Heat stored as sensible heat leads to a temperature increase when heat is stored, made by the author

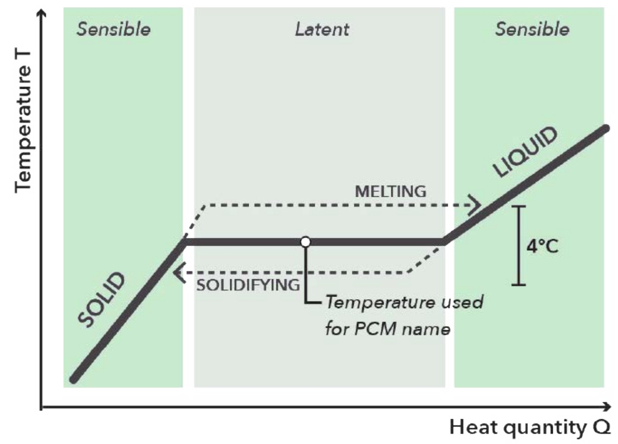
LATENT HEAT STORAGE

Latent heat is the quantity of energy stored when one kilogram of material changes phase at uniform temperature.
Latent Heat Storage (LHS) is based on the heat absorption or release when a storage material undergoes a phase change from solid to liquid or liquid to gas or vice–versa.
In a change of aggregate state a large amount of energy, the latent heat, can be stored or released at an almost constant temperature. Thus, a small difference in temperature can be used for storing and releasing the stored energy. The system with PCM depends on the phase change of the material for capturing and releasing the energy. Processes such as melting/ solidifying and evaporation/condensation require energy inlets or outlets. Heat is absorbed or released when the material changes phase from solid to liquid and vice versa.
If heat is stored in latent form, the energy stored is largely associated with phase change in the storage medium. Latent heat storage provides a high energy storage density and has the capacity to store heat as latent heat of fusion at a constant temperature corresponding to the phase transition temperature of the phase change materials.(ASHRAE,1998)
Latent heat storage can be accomplished through solid-liquid, liquid-gas, solid-gas and solid solid phase transformations, but the only two of practical interest are the solid-liquid and solid -solid. The phase change solid-liquid by melting and solidification can store large amounts of energy, if suitable material is selected. Materials with a solid-liquid phase change, which are suitable for heat or cold storage, are commonly referred to as latent heat storage materials or simply phase change materials.

Melting is characterized by a small volume change, usually less than 10%. If a container can fit the phase with the larger volume, usually the liquid, the pressure is not changed significantly and consequently melting and solidification of the storage material proceed at a constant temperature. During this process the material absorbs a certain amount of heat, known as melting enthalpy. Despite the heat input, the temperature of the material stays at a relatively constant temperature, even though phase change is taking place. We thus speak of latent heat having been taken up by the material. Equally, when the phase change process is reversed, that is from liquid to solid, the stored latent heat is released, again at a nearly constant temperature.(Sharma et al ,2005)
The ability of storing energy at a constant makes LHS applicable for the purposes listed below.

- Reducing the peak power of the cooling system.
- Shifting the peak power to off-peak periods.
- Facilitate a thermal buffer.
- Increase the cooling output to meet higher demand without enlarging the existing infrastructure

The graph 1.5 shows the function between temperature and latent heat stored by the materials. Because of the small volume change, the stored heat is equal to the enthalpy difference. The latent heat, that is the stored heat during the phase change process, is then calculated from the enthalpy difference between the solid and the liquid phase.
Latent heat storage is more attractive than sensible heat storage because of its high storage density with smaller temperature swing. However, many practical problems are encountered with latent heat storage due to its low conductivity, variation in thermo-physical properties under extended cycles, phase separation, sub-cooling, incongruent melting, volume change and high cost. Phase separation occurs in a substance that consists of two or more components and instead of keeping the same homogeneous composition while melting, it separates into different phases one for each component.



Graph 1.5: Heat stored as sensible heat leads to a temperature increase when heat is stored,made by the author

PCMs, which are integrated in structures, have the ability to stabilize the indoor environment thermally and shift peak-hour cooling loads. In building envelopes, the available surface area for heat transfer is much larger compared to the encapsulated local heat storage applications. This means that in envelopes, large amounts of energy can be stored with minimal fluctuations in the transition temperature. As a result of the improved thermal performance gained with the PCM implementation, lighter and thinner building envelopes can be constructed to take full advantage of the thermal performance (Kośny, 2015).

A.FIRST PCM APPLICATION FOR PASSIVE HEATING

The first house with integrated PCMs in its envelope was designed in Dover, Massachusetts, USA by Maria Telkes in 1948. It utilised vertical south facing heating collectors and energy storage in 4 m^3 of Glauber's salts, contained in steel drums (Duffie and Beckman, 2013). More specifically, the system was located in the southern glazed sun spaces that were ventilated with fans to move the warm air into the living space during the winter. In summer months, PCM thermal storage was able to cool surrounding rooms as well. Unfortunately, Glauber's salt disintegrates during a short-time period and loses its phase transition capability, if not sealed and chemically enhanced. During the third winter season in the Dover house, containers with Glauber's salts permanently stopped working.

Figure 1.10: Eleanor Raymond, Architect, and Dr. Mária Telkes (right) at the Dover Solar House in Dover, Massachusetts. Photo, courtesy of Harvard University Graduate School of Design (BWAF, 2014).

B. PCM SOLAR THERMAL STORAGE WALLS

PCM solar walls are typically used in temperate and cold climates. A key ingredient of these walls is their heat storage capacity. In conventional Trombe walls, the storage capacity increases weight and volume of passive solar systems. These systems cannot conform to the modern lightweight constructions and cannot be easily implemented in existing buildings. To deal with this issue, PCM can take the place of the heavy thermal mass materials applied in Trombe walls.

PCM solar walls are designed to trap and transmit solar energy efficiently in a building. They are sometimes called solar thermal storage walls with PCM. A single or double-glazing is used in the outer layer of the wall to act as a thermal barrier and provide greenhouse effect. The Trombe wall system is a way of sensible heat storage as it is shown in Figure 11. Single or double-glazing is usually located on the exterior surface of the massive heat storage module, with an air cavity between these two materials. The exterior surface of the heat storage part is usually painted black so as to absorb the solar energy, which is then stored and conducted through the wall over the period of the day. During the winter period, at night, when there are higher heating energy demands and the indoor temperature drops, heat from the wall storage radiates into the building from the Trombe wall over several hours.

In the last decades, the basic design of the conventional Trombe wall has undergone several adaptations. Originally, Trombe walls were constructed using either masonry or water to provide the appropriate sensible heat storage capacity. This required a lot of space in order to construct the walls. PCMs can be integrated into the existing systems and optimize the space for other practical uses. Thinner PCM walls are also much lighter in weight in comparison to the traditional concrete and masonry materials used in Trombe walls (Tyagi and Buddhi 2007).

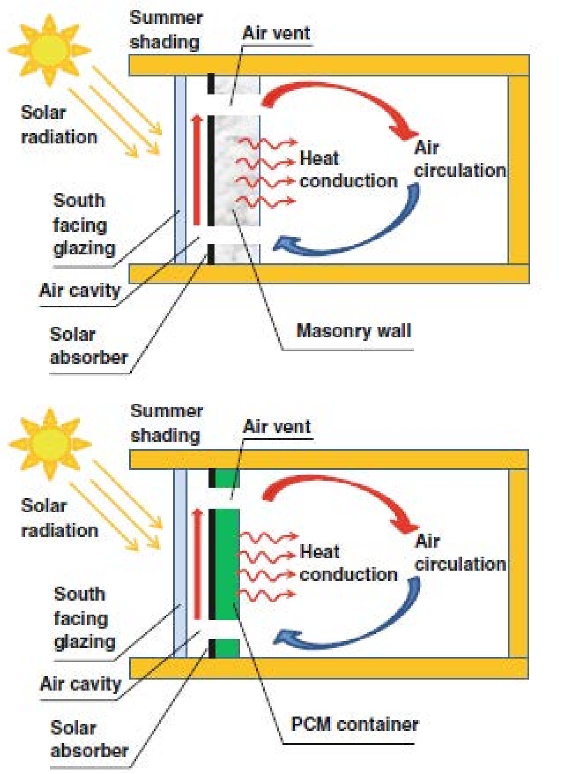


Figure 11: Schematics of conventional Trombe Wall and PCM-enhanced Trombe Wall(Kośny,2015)

C. IMPREGNATED CONCRETE BLOCKS AND CERAMIC MASONRY

For decades, masonry blocks or other building materials impregnated with a PCM have been tried in building construction, resulting in successful applications in structures with enhanced thermal inertia and without the heavy-weight mass associated with it. However, the PCM integration in concrete masonry materials is a complex technological process. Some of the concerns include volume changes during melting and freezing, slow heat transfer rates of inorganic PCM products, problems of PCM leakage, and adverse effects on the physical properties of the PCM carrier materials. One of the simplest PCM-enhancement methods consists of impregnation of the concrete block with PCM in a constant volume liquid PCM (Lee et al. 2000). This is a flexible method, which can be applied to different PCM transition temperatures. Concrete blocks can be impregnated as a part of continuous process during their manufacturing.

The thermal performance of several organic PCMs, such as butyl stearate, dodecanol, tetradecanol, and paraffin, in different types of concrete masonry products have been studied by Hawes et al. (1990) and Hawes and Feldman (1993). They found out that most of the addition methods of PCM to the masonry products may have drawbacks of interacting with building structure and change the material matrix, causing possible leakage over its lifetime, among other issues (Schossig et al. 2005). PCM leakage has been observed in many building applications after repeated thermal cycling. To reduce potential durability problems, van Haaren (2012), made an attempt to introduce PCMs into the concrete in two different ways: (1) The sand from a standard mixture was replaced by PCM particles and (2) porous lightweight aggregates were impregnated with PCM and later a concrete mix was made with use of impregnated and not impregnated lightweight aggregates (Fig 12)).

Figure 12: Microscopic view of the concrete—inorganic PCM mixture (left) and test samples of PCM-enhanced concrete (right) (van Haaren 2012)

D. PCM-ENHANCED GYPSUM BOARD AND INTERIOR PLASTER PRODUCTS

As mentioned in the previous section, PCM can be easily blended with many construction materials, including gypsum-building products. This makes it possible to increase the latent heat capacity of lightweight constructions by applying it in the form of interior plaster or finish gypsum boards.

For decades, paraffinic PCM has been the most widely used latent heat storage material for thermal enhancement of gypsum boards and plasters. The reason is that the paraffin has a melting range between 19 and 24 °C, which is close to human comfort level. However, due to its flammability, and origin in non-sustainable petrochemicals, other organic PCMs are being explored now, including fatty acids, coming from agricultural and food industry waste.

Interior building surfaces of walls, ceilings, or floors have been traditionally considered as the best locations for the PCM. In gypsum board and plaster applications, PCM is used to stabilize the temperature of the building interior. As shown in Fig. 12, PCM concentrated in gypsum boards interacts mostly with the interior of the building. The energy storage capacity of the PCM-enhanced gypsum is used to reduce interior space temperature swings and absorb solar gains coming through the glazing.

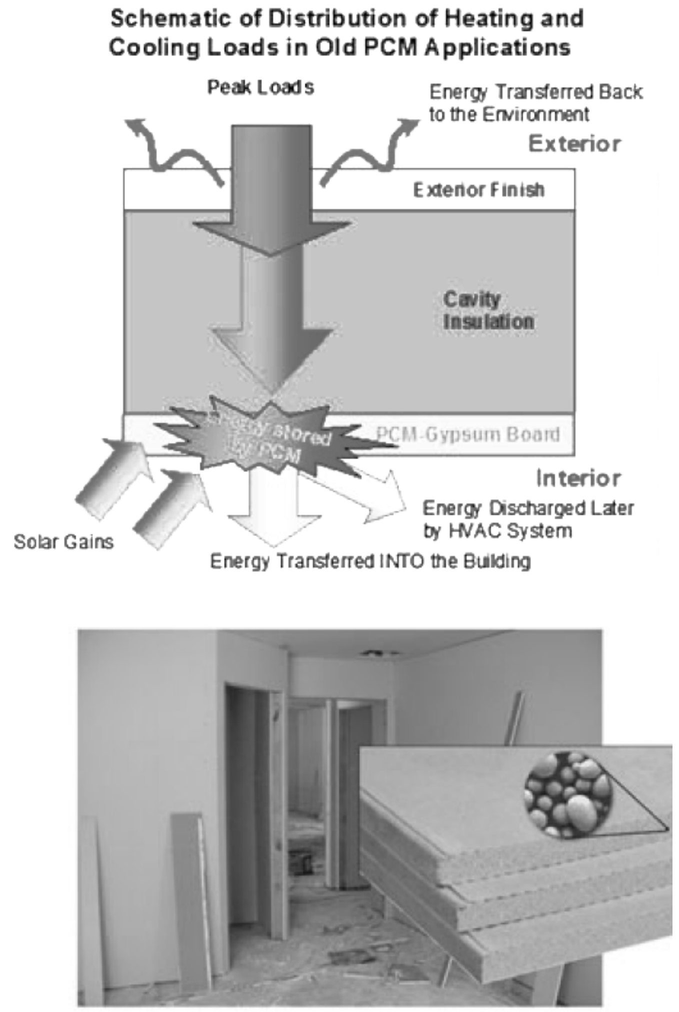


Figure 13: PCM as part of the interior surface of the building envelope(http://www.micronal.de)

E. USE OF PCM – ENHANCED WALL CAVITY INSULATION

As described earlier, PCM applications in wall masonry units, air gaps in massive walls and framed wall cavities can be very convenient locations for PCM. In the figure below, it is shown that the PCM that is placed inside the wall cavity takes advantage of the large temperature fluctuations that take place on the exterior building envelope surfaces. These energy fluctuations, which can be a significant part of the building cooling and heating loads, are largely absorbed by the PCM enhanced insulation and later transferred to the environment without affecting the interior building energy balance. In this application, phase transition temperature range of PCM should be as close as possible to the interior space set point temperature.
As a result, heat transfers between the core of the building envelope and the interior space is reduced. This simple change in material configuration results in real space conditioning and energy savings. It is also expected that this new placement method for PCM should significantly reduce flammability issues that were common in earlier technology developments. In addition, detailed optimisations performed for PCM applications, showed significant potential for reduction of initial costs and a corresponding reduction in cost payback time (Kośny et al. 2012a).
PCM-enhanced cellulose was one of the first successful developments of PCM enhanced thermal insulations in the building area (Fig. 14). Subsequently, PCM blended with blown fiberglass and building plastic foam insulations were introduced (Kośny et al. 2007, 2010b; Mehling and Cabeza 2008). From 2006 to 2007, ORNL performed a series of dynamic hotbox tests of wall assemblies containing PCM-enhanced insulations. For the wood-framed wall containing PCM-enhanced foam insulation, Kośny et al reported that it could reduce wall-generated peak-hour cooling loads by about 40 % (Kośny et al. 2007, 2010a). The major advantage of PCM-enhanced insulations is their capability of significant lessening and shifting the peak-hour thermal loads generated by building envelopes.

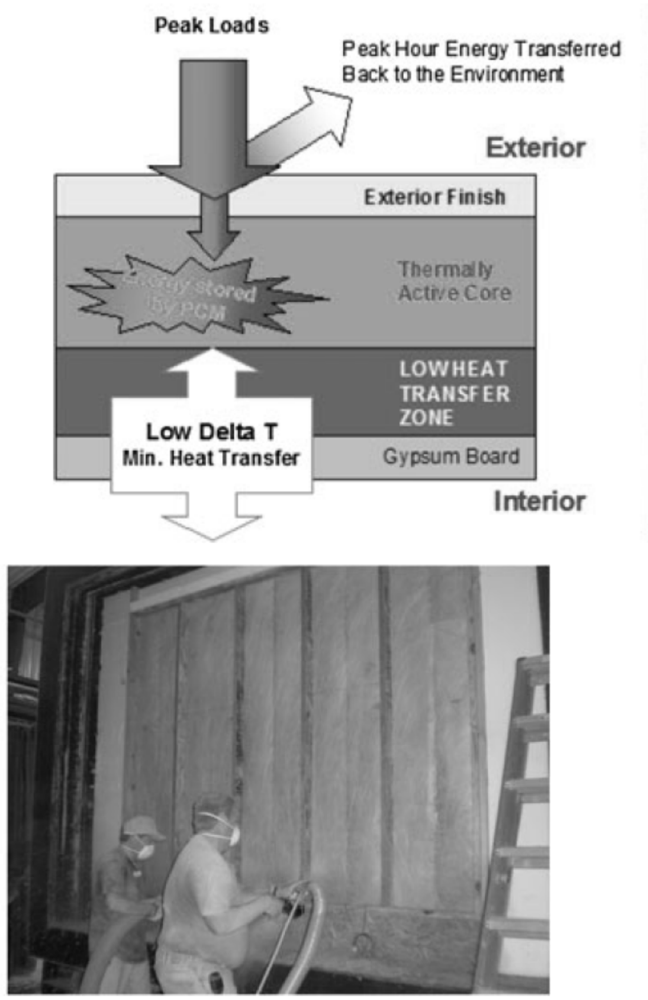


Figure 14: PCM-enhanced materials used as an integral part of the building thermal envelope. Right picture shows construction of an experimental double wall with exterior layer of cavities containing PCM-cellulose insulation(https://c.ymcdn.com/sites/www.nibs.org/resource/resmgr/BEST/BEST1_E7-1.pdf)

PCM APPLICATIONS | CEILING SYSTEMS

PCM-ENHANCED CEILING SYSTEMS

From the design perspective, PCM cooling applications in ceilings are either passive (similar to PCM-enhanced wall gypsum boards or internal plasters) (Fig.15), or active, which are usually a part of more complex, dynamic air conditioning systems using over-night pre-cooling with often incorporated space conditioning components (i.e., hydronic systems, micro-tubing heat exchangers, and air channels) (Fig. 16).

Comfort is improved due to minimization of air motion and surface temperature differences, elimination of noise coming from fan coils, and uniformity of indoor air temperature. Also, peak cooling loads may be reduced because of cool storage within the ceiling and adjoining structural elements. Decades of testing and demonstrations worldwide have proven that adding PCM to the ceiling cooling systems can notable improve their energy performance and reduce a risk of moisture condensation.

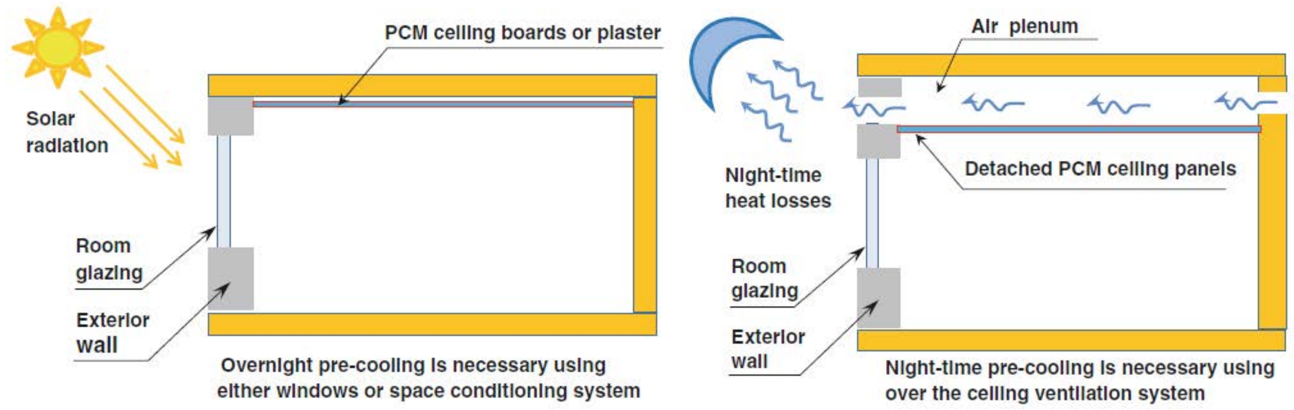


Figure 15: Passive applications of PCM-enhanced ceiling systems.(Kośny,2015)

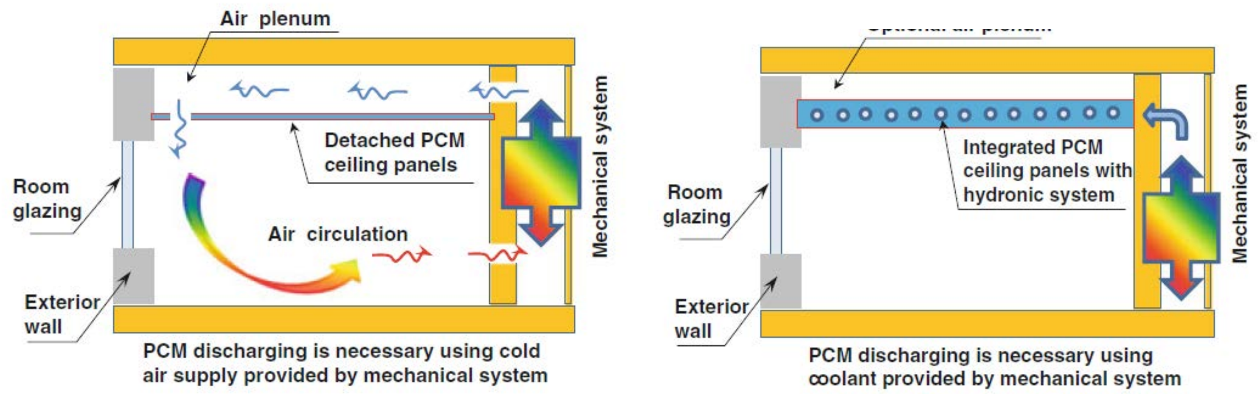


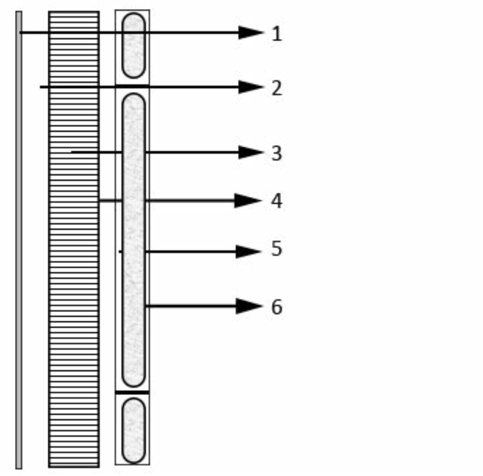
Figure 16: Active applications of PCM-enhanced ceiling systems.(Kośny,2015

PCM APPLICATIONS | TRANSPARENT BUILDING ELEMENTS

As it was discussed before, the use of phase change materials can enhance the energy performance of buildings. In the past few years, PCMs have been integrated into transparent envelope components and many techniques of testing their thermal performance have been devised. In the current chapter, their applications as transparent building envelopes will be briefly discussed. In addition to this, the current practices of testing PCM efficiency and future technologies involving these PCMs will be described.

PCM-INCORPORATED TRANSPARENT GLAZING DEVELOPMENT

The first attempt to integrate PCMs as a way of using latent heat was by Dr.Maria Telkens, a researcher of Massachusetts Institute of Technology in 1948. With the help of Eleanor Raymond, an architect; she became one of the pioneers in this field through the construction of the very first PCM heated house. The Solar One building utilized vertical south (Duffie and Beckman,2013).
This building made use of South oriented heating collectors and energy storage in 4 m3 of Glauber's salts, contained in steel drums. More specifically, the system was located in the Southern glazed sunspaces that were ventilated with fans to drift the warm air into the living space during the winter. During the summer months, the PCM system was able to cool surrounding rooms as well. In fact, this system was able to keep the house warm for approximately 11 sunless days. After 3 years, owing to the loss of the PCM's heat storage capacity, the house failed (Koekenbier,2011). The results of this attempt encouraged research in the development of PCMs for passive heating (Peippo et al,1991).
A team was formed to study the application of translucent PCMs. The team of this research project designed a two-layered passive wall system that made use of a salt hydrate PCM and a transparent honeycomb-type insulation material . The PCM was filled into commercial glass blocks (Manz et al, 1997).



LAYER	MATERIAL
1	GLASS PANEL
2	AIR GAP
3	TRANSPARENT INSULATION MATERIAL
4	GLASS PANEL
5	AIR GAP
6	PCM IN A GLASS CONTAINER

Figure 17 :The building system by Manz et al,made by the author

PCM-INCORPORATED TRANSPARENT GLAZING FUNDAMENTALS OF OPERATION

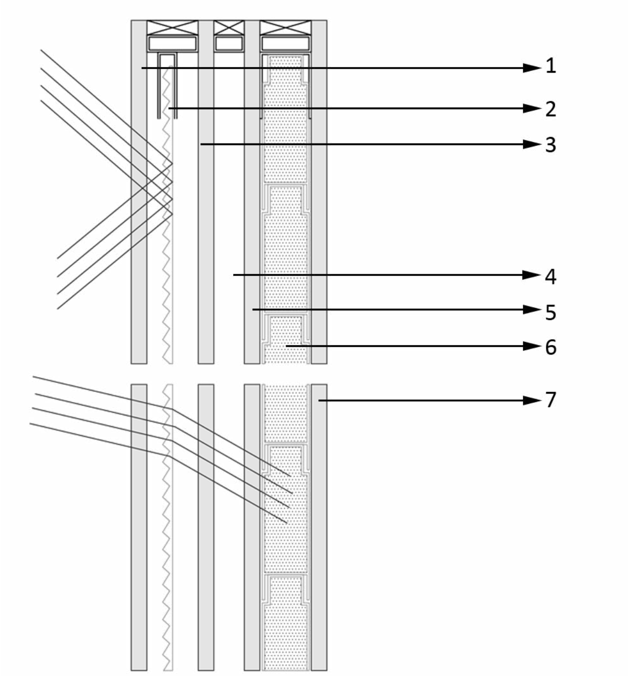
The company- Glaswerke Arnold and ZAE Bayern made an investigation to use partly transparent PCM so that the whole element could be constructed in such a way as to transmit light and illuminate the building interior.
The compound material from Rubitherm, as well as the double skin sheet from Dorken, shows a transparency, which transitions to some degree between the solid and liquid state of the PCM, and therefore they can be used to provide diffuse illumination to the space behind the wall element.

INGLAS PCM ELEMENT

The presence of a macro-encapsulated PCM on the inside layer and a transparent insulation of two glass sheets on the outside layer of construction constitute a complete system. INGLAS, a company; developed a system known as INGLAS PCM element which consists of a heat reservoir for facades with transparent thermal insulation. These systems are capable of absorbing light from the sun and processing the heat developed to melt the wax-like filling of the elements. This way, large amount of energy can be stored and utilised within the building when the material cools down and undergoes solidification. INGLAS PCM, removes the need of several centimetres of concrete and brick, which would be used in conventional buildings. More design possibilities arise from the variable translucency of the material.

XGLASS PRODUCT

The passive solar mechanism of PCM glazing systems is offered by the outer and inner insulating glazing units. One such example is a system developed by Dietrich Schwarz, a Swiss architect, consisting of plastic elements filled with paraffin. Its components include a wall element called GLASSX crystal, which consists of four functional units: a transparent insulation, a protection from overheating, an absorber, and the heat storage. The transparent insulation consists of three glass sheets with a total U-value of 0.5W/m2K. A sophisticated prismatic filter reflects high-angle sunlight out and transmits only the low-angle sunlight into the inner unit. This inner unit, which is sealed with polycarbonates, encapsulates the PCM. This filtering of incoming sun light prevents the wall element from overheating. This mechanism is shown in Fig18.



LAYER	MATERIAL
1	OUTER GLASS PANEL
2	PRISMATIC COMPONENT
3	GLASS PANEL
4	AIR GAP
5	GLASS PANEL
6	POLYCARBONATE BLOCKS FILLED WITH PCM
7	INNER GLASS PANEL

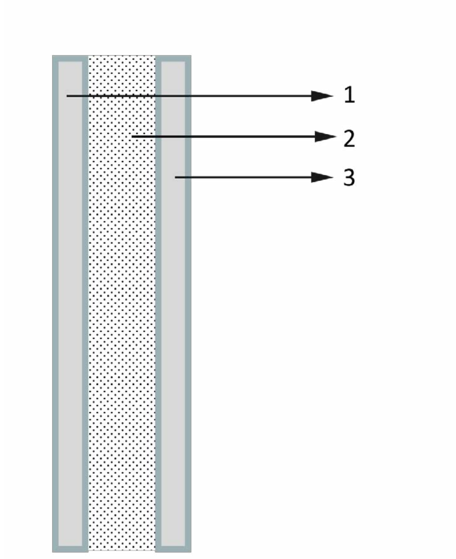
Figure 18 :The XGLASS components,made by the author

CURRENT PRACTICES OF TRANSPARENT PCM INCORPORATED SYSTEMS

Recent studies have involved the design of transparent building elements with the integration of translucent or transparent PCMs. This kind of PCM allows the light to pass through but absorbs the infrared part of the spectrum. This increases the temperature of the PCM beyond its melting point, after which its temperature remains constant. The PCM can be transparent to the internal space, and act like a window, or it may be transparent to an opaque material in front of which it is installed.

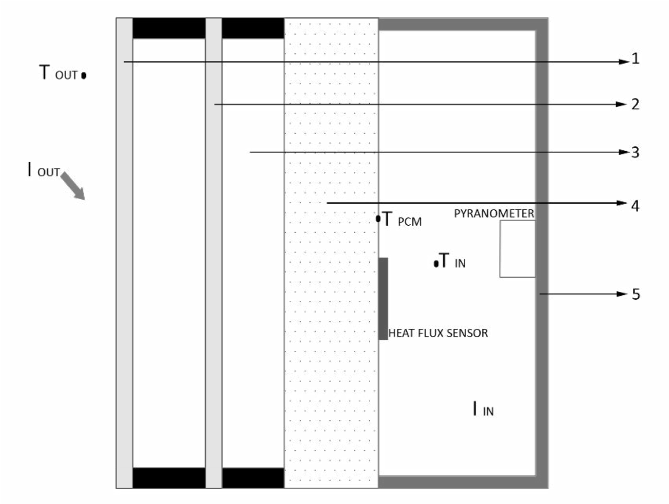
Ismail and Henriquez presented a relatively simple and effective concept. The design is about a double glass window, in which the gap between the two glass sheets is filled with a PCM of certain fusion temperature(Fig.19)

Weinlader et al. [25] had a similar logic. Their technique involved the encapsulation of PCMs in transparent plastic containers, which were placed behind a conventional double-glazing with an air cavity of 10mm (fig.20). For this study, double-glazing and PCMs were combined to create day lighting elements. Three different kinds of PCMs were checked for this application to study their thermal and their optical properties. Thermal modelling was conducted using the finite difference method so as to check the thermal performance of the system. In addition to this, optical modelling was done to determine the complex spectral refractive indices of the liquid PCMs from transmittance and reflectance measurements for various thicknesses. Finally, an experiment was conducted using plastic containers, which were placed behind a conventional double-glazing with an air gap of about 10 mm (Weinläder, 2004).



LAYER	DESCRIPTION
1	GLASS SHEET
2	PCM
3	GLASS SHEET

Figure 19 :The building system design by Ismail and Henriquez,made by the author



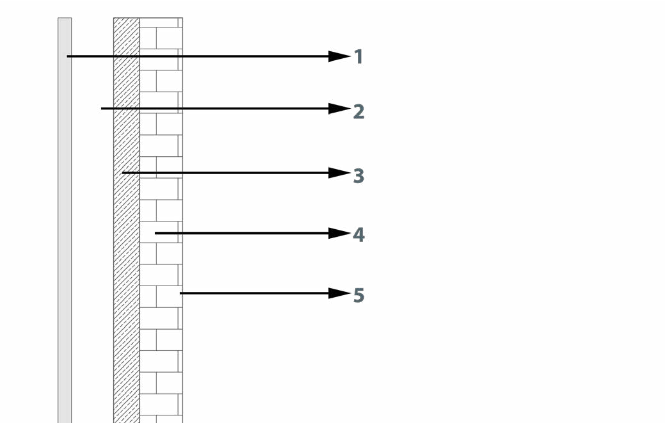
LAYER	DESCRIPTION	THICKNESS (mm)
1	EXTERNAL SHEET CONTAINING PCM	20
2	VENTILATED AIR GAP	60
3	EXTRUDED POLYSTYRENE INSULATION	50
4	BRICKWORK INNER WALL	70
5	GYPSUM PLASTERBOARD	2

Figure 20 :The experiment set up by Weinlader-made by the author

PCM-INCORPORATED TRANSPARENT GLAZING FUNDAMENTALS OF OPERATION

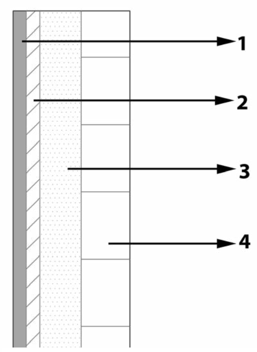
Several PCMs have been used to store energy for heating and cooling and enhance the thermal comfort of the buildings. More specifically, Diarce et al designed a new ventilated façade that consisted of a PCM in the external layer placed in an aluminium encapsulation system, which was capable of being used in building restoration. The system was composed of the PCM layer with a thickness of 20mm, a ventilated air channel 60 mm thick and the insulation material (50-mm-thick plates of extruded polystyrene) .The inner layer was a brickwork wall made of 70-mm-thick hollow common bricks, and a 2-mm-thick plasterboard lined the inner walls of the room.

Gracia et al. presented a new type of ventilated facade with macro-encapsulated PCM in its air cavity(Fig. 22).The ventilated facade presented an air channel of 15 cm thick which represented 0.36 m^2 of channel area. The inner layer was based on the alveolar brick constructive system while a glass layer constituted the outer envelope. An extra outer layer of expanded polyurethane panels was placed to cover the transparent glazing during the summer period since solar radiation inside the cavity was omitted for cooling purposes.



LAYER	MATERIAL
1	OUTER GLASS SHEET
2	INNER GLASS SHEET
3	AIR CAVITY OF 10MM
4	PLASTIC CONTAINER FILLED WITH PCM
5	WALL

Figure 21:The facade system designed by Diarce made by the author



LAYER	DESCRIPTION	THICKNESS (mm)
1	EXTERNAL SHEET CONTAINING PCM	20
2	VENTILATED AIR GAP	60
3	EXTRUDED POLYSTYRENE INSULATION	50
4	BRICKWORK INNER WALL	70
5	GYPSUM PLASTERBOARD	2

Figure 22:The ventilated facade designed by Garcia et al, made by the author

CURRENT PRACTICES IN TESTING THE THERMAL PERFORMANCE OF TRANSPARENT PCM-INCORPORATED SYSTEMS

Laboratory and outdoor testing facilities along with specialised equipment were employed for the definition of the thermal performance of the proposed transparent building elements incorporating translucent PCM. Manz et al [1997] tested the PCM optical properties indoors in a laboratory using a spectrophotometer and Abbe refractometer, while the experimental investigation of the TIM and transparent PCM prototype facade was conducted in outdoor test facilities consisting of a cooling/heating apparatus and heat flow sensors. Their laboratory equipment allowed them to also define the refractive index of the PCM, while their outdoor test facility enabled them to measure the liquid mass flow temperatures, the heat flux, and the solar irradiance. Ismail and Henriquez [2012] characterised optically, the different glass sheets of different thicknesses and panels of double sheets of different spacing and fillings employing a spectrophotometer. Consequently, their measurements were limited to the determination of transmittance, reflectance, and absorbance of the PCM. Weinlaeder et al [2004] and Goia et al [2013] set up their experiments for the PCM-integrated glazing systems in outdoor test cells. Temperature, heat flux, and incoming and transmitted solar radiation measurements were taken in the work of Weinlaeder et al [2004], while the outside test cell of Goia et al [2013] , equipped with thermocouples, heat flux meters, and pyranometers collected data regarding the indoor surface temperatures of the glazing, the outdoor solar irradiance, the indoor surface heat flux, and also the transmitted solar irradiance of the PCM glazing system. Subsequently, Goia et al [2013] employed the Characterization of Advanced Transparent Materials (CATRAM) facility for the investigation of the proposed PCM-incorporated transparent system consisting of a halogen lamp and three array spectrometers.

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Additionally, meteorological data were taken from a nearby meteorological station. De Gracia et al [2013] used house-like cubicles with thermocouples, moisture/temperature transducer, an electrical network analyser, a heat pump, an air flow velocity–temperature transmitter, a pressure transmitter, and heat flux sensors for the investigation of their ventilated facade with macro-encapsulated PCM. Additional equipment, including solar pyranometers and an anemometer, was used for the data collection of the outdoor weather conditions. Their testing facility and equipment allowed them to take a range of measurements to evaluate the performance of the ventilated facade with macro-encapsulated PCM.

The active ventilated façade with a PCM, suggested by Diarce et al [2012] was studied in a PASLINK test cell with temperature probes and also employed air velocity sensors and pyranometers. Thus, in their work, Diarce et al [2012] presented data of the global vertical radiation, the outdoor temperatures, and the temperatures inside the PCM at the bottom and the top of the façade.

KINETIC FACADES | CLIMATE RESPONSIVE DESIGN

With the climate-responsive design the building acts as an environmental filter. A balance is found between the exclusion of unwanted forces and the admittance of the beneficial ones. According to Hastings’ definition climate-responsive design puts an emphasis on the potential of buildings as being an intermediate between indoor and outdoor environment. This intermediary function of the building is considered a key aspect in the realization of comfortable buildings as well, along with the allowance for human intervention in climate control to satisfy subjective needs (Fountain et al. 1996, Mahdavi and Kumar 1996).

Climate-responsive design takes advantage of the natural energy sources present in the built environment for passive or low-energy comfort provision. The building space and mass acts as an intermediary, where the indoor environment is controlled in close interaction with dynamic outdoor conditions.

Responsive Facades are the facades with the ability to respond to their environment by either typological change of material properties alter the overall form or local alteration by regulating their energy consumption to reflect the environmental condition that surrounds it.

Kinetic Facades describe the actual movement or motions through geometric transformation in space that affect the changing state or material properties or physical structure of the building facades without compromising the overall structural integrity.(Sharaidin,2014)

KINETIC CLIMATE RESPONSIVE FACADES|CHARACTERISTICS

FLEXIBILITY

Comparatively to the conventional building skins, kinetic climate responsive skins are able to change their behaviour over time. Although static systems, facades are designed to respond to many scenarios and perform functions that can be contradictory to each other: daylighting versus energy efficiency, ventilation versus views and energy generation. By actuating the facades and making them responsive, they can better adapt to the conditions, provide for improved comfort of the occupants, and achieve a more sustainable design .Facades can now sense the environment and make their own modifications in order to achieve prescribed goals. (Kensek,Hansanuwat,2011)

In other words, one benefit that the kinetic facades have is flexibility as they provide high levels of performance as they can cover multiple functions when the environmental conditions and the functional requirements alter in a predictable or unpredictable way.

ADAPTABILITY

The definition of the term “adaptability” is the ability of a system to deliver intended functionality considering multiple criteria under variable conditions through the design variables changing their physical values over time (Ferguson, 2007). Kinetic facades can respond to changes in ambient environment and act as climate mediators sitting down with the comfort needs and what is available in the surroundings of the building. Doing this offers a potential for energy savings compared to conventional buildings because the valuable energy resources in our environment can be actively exploited, but only at times when these effects are deemed favourable. (Loonen,2010) .

ACCLIMATION

Acclimation is the ability of an organism to adjust its behaviour in response to contextual changes, allowing it to adapt to shifts in temperature. Acclimation is an integral function of building systems. A simple example is the ability for a building’s skin to open or close such as with windows to control the flow of air and interior temperature.(Crawford,2010)

RESPONSIVENESS

Systems with moving parts ,as they are appeared in kinetic facades, require a signal to tell them the correct time to respond. This can be as simple as flipping a switch to turn on a light bulb or a chain of events can lead up to the signal. Sensors give a system the ability to sense environmental changes so the system’s behaviour can change even without a person present.

Responsive behaviour can be defined as a readily reaction to some kind of stimulus. The reaction is a desired change of state in order to maintain certain functionality. This change of state can either be an architectural change of elements or a physical change of material characteristics. In the case of climate-responsive design the functionality to maintain is comfort provision. The stimuli are changing indoor comfort demands and variable outdoor conditions. (Crawford,2010)

KINETIC FACADES|ENVIRONMENTAL MEDIATORS

The implementation of the dynamic facades in office buildings has introduced a new control strategy of the environment.

Adaptive systems are able to coalesce both, low energy use as well as building environment control; which are the best two strategies that are currently available. As the name suggests, if such systems can adapt to diurnal temperature fluctuations, the building becomes less dependent on conventional energy sources. Its characteristic ability to control the heat flow volume and direction in response to internal and external conditions is what makes it special. These properties help bring in thermal comfort to the users.

The use of these adaptive facades as environmental mediators has been done under the control of 3 main factors: solar thermal control, day lighting control, and ventilation control.

SOLAR-THERMAL CONTROL

The Solar - thermal control can be done by devices in a kinetic façade, ranging from automated louvers to adjustable overhangs. These systems aim either to let the sun light penetrate in the building or to prevent the solar irradiation inside the office space. For example, in the winter period the buildings need more sun exposure so as to reduce the expenses for the heating of the building and on the other hand, during the summer shading is essential so as to limit the solar heat gain inside the office building. To put it differently, when the kinetic facades are solar-responsive aim to maximize the acceptation of solar heat in winter and minimize solar gains in summer.

Cloud 9’s Media-TIC building in Barcelona includes a characteristic system of solar and thermal control in its façade. This digital technology hub uses distributed sensors to control solar shading by ethylene tetrafluoroethylene (ETFE) skins on the south-east and south-west facades. ETFE’s light and anti-adherent nature make it very versatile, but this membrane protects with a sun-filtering factor of 0.20. This dynamic interface has two different formats to match the building’s orientation to the sun. The south-west facade filters solar radiation through a screen of vertical cushioned panels containing nitrogen and oil, which coalesces as a ‘cloud’ sunscreen. The inflatable cushions are embedded with sensors reading the heat and the angle of the sun. Layers of ETFE create three inflatable chambers within each triangular frame, which provide both shade and thermal insulation.

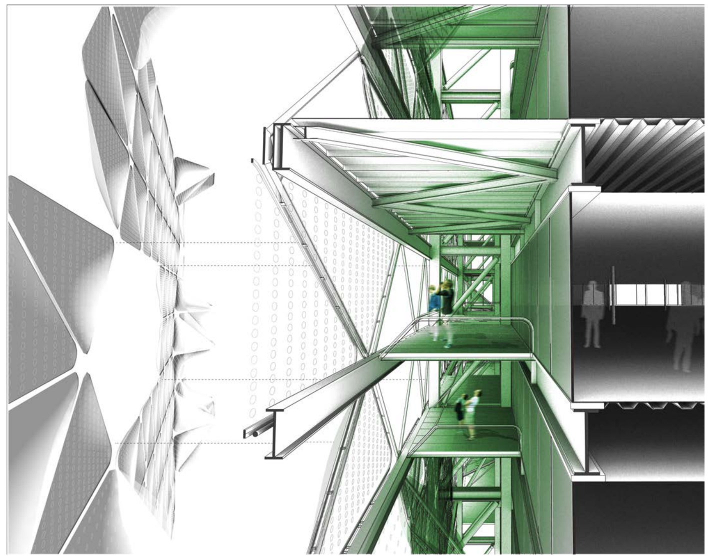

Figure 23:Perspectiive 3d view of Cloud 9 project.Reviewed from: https://nl.pinterest.com/pin/198369558560728153/

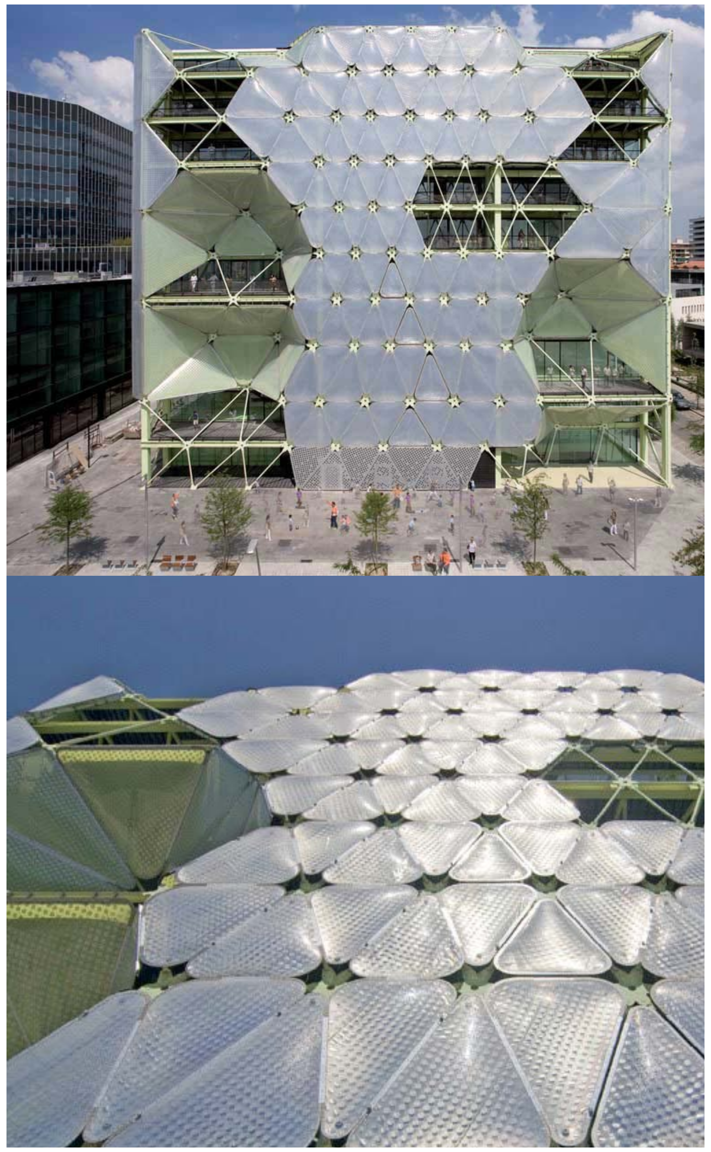

Figure 24:The Cloud 9 project.Reviewed from:http://www.ruiz-geli.com/projects/built/media-tic

DAYLIGHTING CONTROL

Daylighting control is another aspect, which the kinetic facades take into consideration so as to perform efficiently. For example blinds, louver or shading systems are used to control the amount of daylighting, which can range from zero to complete light intrusion depending on the angle of the louvers which is changeable according to the sun's path. Overhang systems are also highly effective systems for daylighting control, but do have limitations depending on the site conditions and hourly, daily, and annual conditions. (Zeinab El Razaz, 2010) In general, these dynamic systems control indoor illuminance levels, distributions, windows views and glare, particularly for museums and galleries and office spaces, enhancing the visual comfort, satisfaction and the productivity levels of the employees and minimize the energy consumption for the artificial lighting of the building.

An indicative façade example is the Kiefer Technic Showroom, constructed in 2007 in Austria by Giselbrecht + Partner ZT GmbH. The building is composed of 2 floors and its use is office and showroom. Along the 28.75 m long southwest facade of the building, aluminium panels used as horizontal folding shutters have been mounted on a 7.75 m high supporting aluminium framework arranged in front of the showroom's glazed facade. Rollers and electrically-operated motors allow the panels to be raised, lowered and folded together. To open the shutters, the elements at the top of each floor are raised and those at the bottom lowered, folding together to create horizontal cantilevered sun canopies.(Schumacher et al,2010) In the closed position, light passes into the showroom through perforations in the panels.. The movement control uses a programmable BUS/PLC system that defines the degree of the folding required according to the sunlight. The façade provide light control having shading function which is changeable according to the sun's radiation and regulates the lighting levels inside the office space according to the users preferences(Alexiou,2013).

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Figure 25:The motorized shading system by Kiefer,Reviewed from:http://www.dailytonic.com/dynamic-facade-kiefer-technic-showroom-by-ernst-giselbrecht-partner-at/.

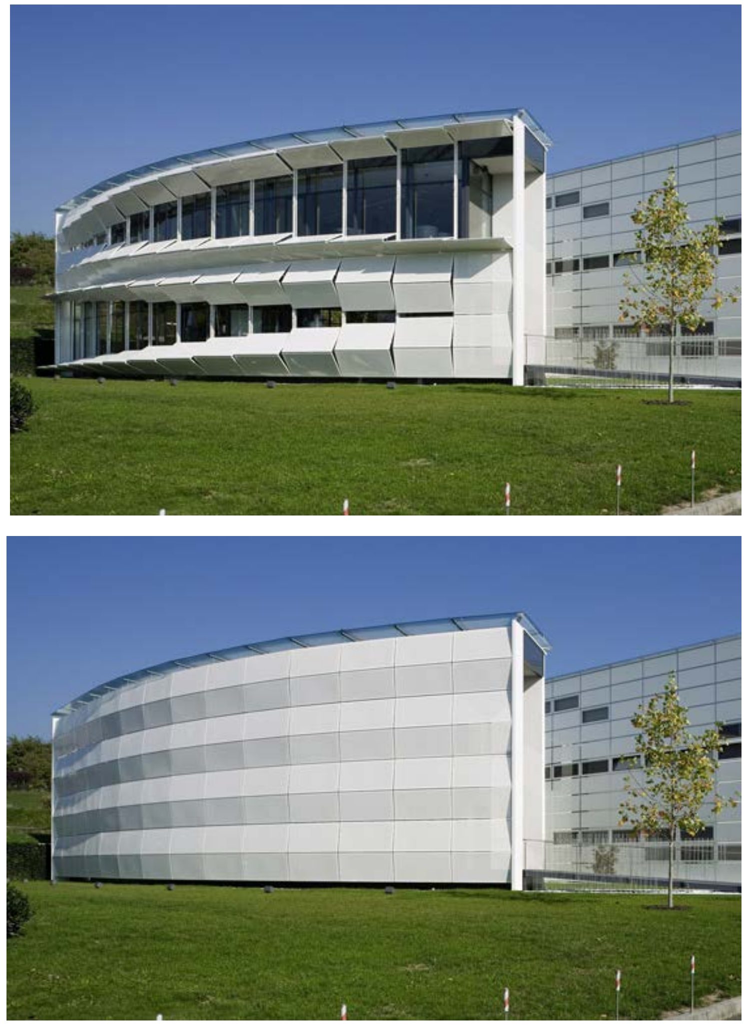


Figure 26:The facade responding different in order to provide changing shading levels,Reviewed from:http://www.dailytonic.com/dynamic-facade-kiefer-technic-showroom-by-ernst-giselbrecht-partner-at/.

VENTILATION CONTROL

Ventilation control by the kinetic facades offers great potential in the field of the natural cooling of the offices. Many buildings that use kinetic systems for ventilation control by including variable louver systems or double-skinned envelopes utilizing the stack effect. For the ventilation, the kinetic behaviour is influenced by the air exchange and circulation for indoor thermal comforts and air quality. The kinetic double-skins envelopes are applied on this case so as to promote the natural cooling of the building.(Wang et al, 2012)

A characteristic project is the CF: Responsive Kinetic Façade from SOM+ SCI-Ar. The exterior surface is a composition of points that will expand the entire threshold based on the thermal conditions. Once they interact, the outer skin will shrink/ stretching in some areas opening the "pores" for natural ventilation. In the winter, the skin is more stable , leaving the "pores" in a closed mode so as to keep the heat in the interior space of the building. The actuators move in a horizontal direction, pushing the skin in and out to create these movements. The exterior skin opens and closes in order to regulate the temperature of the entire building while the secondary ventilation on the interior skin gives local control to the temperature of each room.(Diaz,2012)

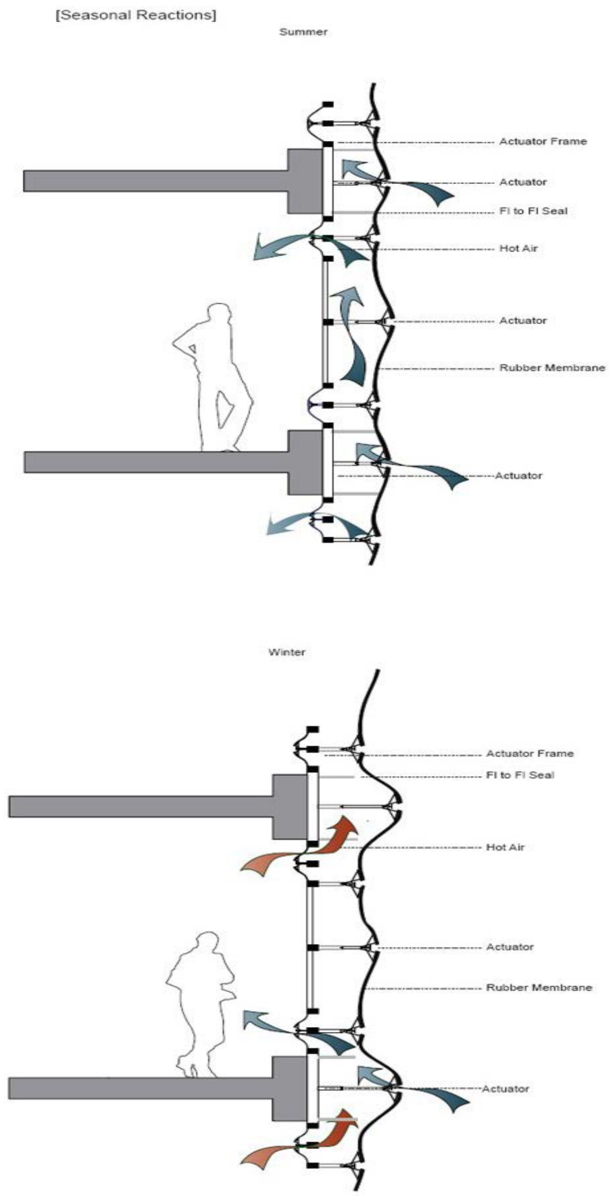


Figure 27: Responsive kinetic facade,Reviewed from: https://nl.pinterest.com/pin/86272149083742781/

DOUBLE FACE :A System for Adjustable Translucent Thermal Mass
Research Team:
Delft University of Technology
dr. Arch. Michela Turrin
dr. ir. Martin Tenpierik
ir. Paul de Ruiter, ir. Winfried Meijer
dr. ir. Willem van der Spoel
Carlos Alfredo Chang Lara
Eindhoven University of Technology
Dipl.-Ing. Florian Heinzelmann
prof. Dr.-Ing. Patrick Teuffel
ing. Wout van Bommel

DESCRIPTION

The Double Face project aims at designing an adjustable translucent system that will improve the thermal comfort of the indoor and semi indoor space with a passive way by using PCM materials integrated in a lightweight system for latent heat storage. The system is designed taking into account the thermal principles of the trombe walls and provides thermal insulation and thermal absorption in a calibrated manner, which is adjustable according to different heat loads during summer- and wintertime.

PERFORMANCE

Double Face proposes a system based on interior design elements, taking advantage of the dynamic behaviour of PCM as well as its appearance. This design is meant to enhance the aesthetics of the indoor space. The elements are translucent and they are located in front of a (full) glass façade, where there is high heat impact from outside. Additionally, the system is adaptive in order to enhance the thermal benefits. Exposing thermal mass to winter solar radiation (passive heat gain) and protecting it from the summer one (passive cooling) and therefore acting as thermal buffer. This happens by rotating the elements towards the source of incoming heat or the sink for heat release. In winter, the PCM side would face the exterior and be thermally charged during the day by the low winter sun. During night times, oriented towards the interior, it releases the accumulated heat. In summer, during the day in combination with external sun shading, it would store the heat from interior heat loads and during the night release this heat to the outside environment by means of night ventilation, thus acting as a cooling plate.

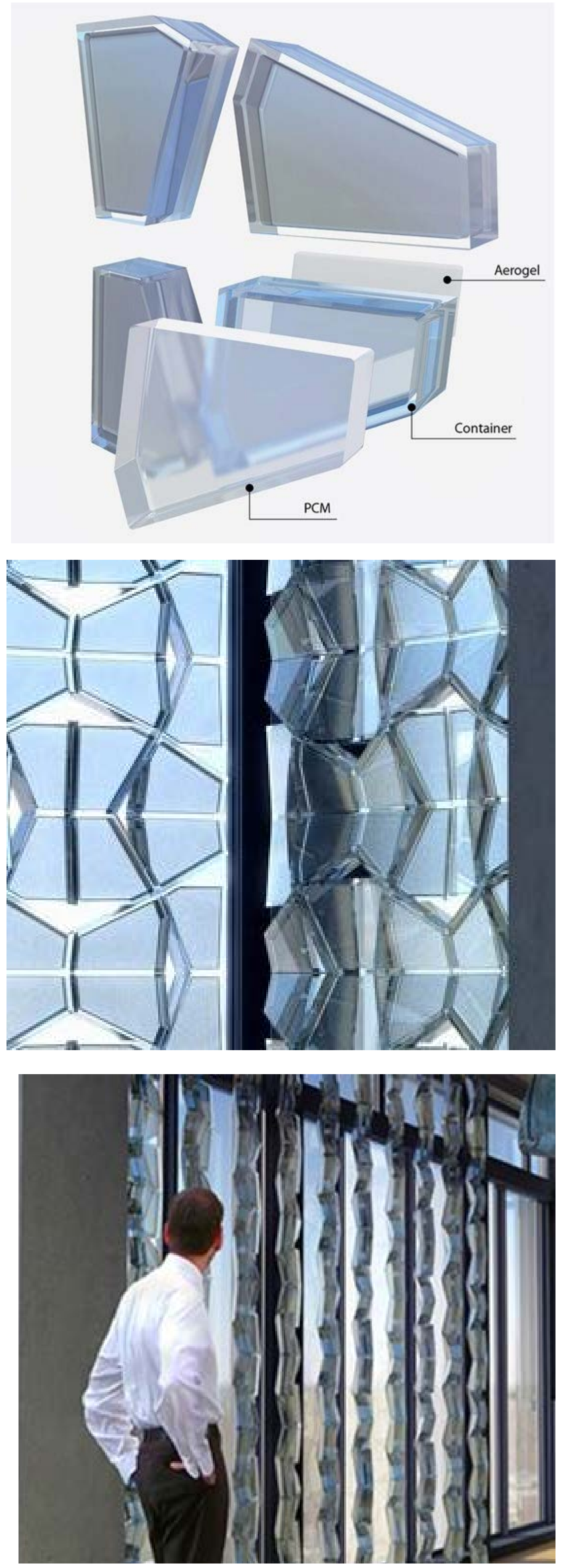


Figure 28:DOUBLE FACE perspective views,Reviewed from: https://www.4tu.nl/bouw/en/LHP2014/doubleface/

RESEARCH PROCESS

The research process started with a wide inventory of existing PCM; an analysis of their properties; and a consequent short-list of selected materials. For each of the selected PCM, digital simulations were conducted to analyse the thermal behaviour. They were conducted for single layers of PCM in various thicknesses; and for combinations of two layers, one of PCM in various thicknesses and one of translucent insulation, also in various thicknesses. The translucent insulation was simulated as a layer of Aerogel; and as a system of cavities trapping air within a translucent 3D printed material. Based on the digital simulations, the system of layers was pre-dimensioned for a total thickness of 7cm (5 cm PCM, 1 cm aerogel and 1 cm container wall thickness).
Several samples (17x17x7cm) were made for a number of selected PCM with different melting temperatures. These samples were tested in the laboratory for Building Physics at Eindhoven University of Technology for their thermal behaviour; and at Delft University of Technology for their light transmittance so as to define which PCM have better performance and which thickness of the material is more efficient. As a result, PCM thickness was reduced to 4 cm. Furthermore, using the measured properties as input, simulations of the thermal behaviour of a standard room equipped with this Trombe wall system were run in Design Builder to study several variations including PCM layer thickness, insulation layer thickness, extra cavities and percentage of holes in the wall. These simulations showed that an opening percentage of roughly 10% was ideal for this Trombe wall system.In order to simulate the kinetic behaviour of the wall panels, a new simulation model was created in Matlab/Simulink. The model simulated the rotation of the panels and the results were really encouraging as they showed that the Double Face system leads to an energy reduction of roughly 40% as compared to the 'no Trombe wall situation'.

Reviewed from: https://www.4tu.nl/bouw/en/LHP2014/doubleface/

THERMOMETRIC FACADE
Architect: Davidson Rafailidis
Primary Investigator : George Rafailidis (Davidson Rafailidis; assistant professor, Buffalo School of Achitecture+Planning (B/a+p), University at Buffalo, the State University of New York)

DESCRIPTION
With the concept of the thermometric facade, the potential of shaping and designing latent heat accumulators made out of wax is being investigated. Following a material investigation that juror Gordon Gill called “valuable and interesting,” the concept for Thermometric Façade then took shape—literally. The project uses the thermal and volume-expansion behavior of wax-based phase-change materials to create a modular, structural glass block that becomes clear or opaque depending on the ambient temperature. Stacked together, the blocks can create dynamic walls that react to programmatic or environmental conditions. “It turns something discreet and hidden into an element of design,” juror Martina Decker said.

PERFORMANCE
The wax-based phase change materials (PCM) inside the glass blocks provide thermal storage capacity and can provide different levels of visibility depending on the PCM state. Phase change materials in liquid form fill the the glass block. As the ambient temperature rises, the phase change materials changes to liquid and expands to fill the glass block volume.

DESIGN
The block structure and shape was derived from experimentation and design iterations. The interior geometry of this version has air pockets, an overflow space, and a structural exterior. The block geometry allows individual blocks to interlock and transfer loads to a structural support. It is used 10% of volume dilatation within the phase transformation. This is usually seen as a disadvantage to create a temperature-sensitive glass-stone, that is able to modulate clouding and opacity and works as a heat reservoir as well. The glass-stone is manufactured in the common press-glass-process

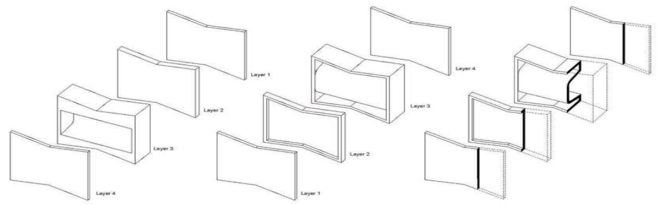


Figure 29:The layers of each facade panel,Reviewed from:http://www.architectmagazine.com/project-gallery/thermometric-facade

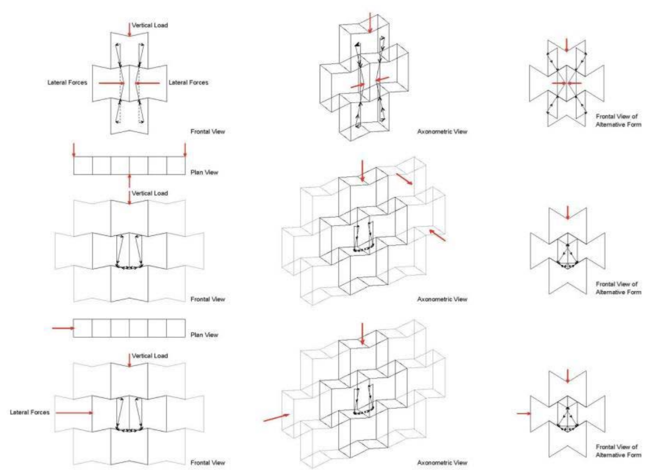


Figure 30:The connection details,Reviewed from:http://www.architectmagazine.com/project-gallery/thermometric-facade

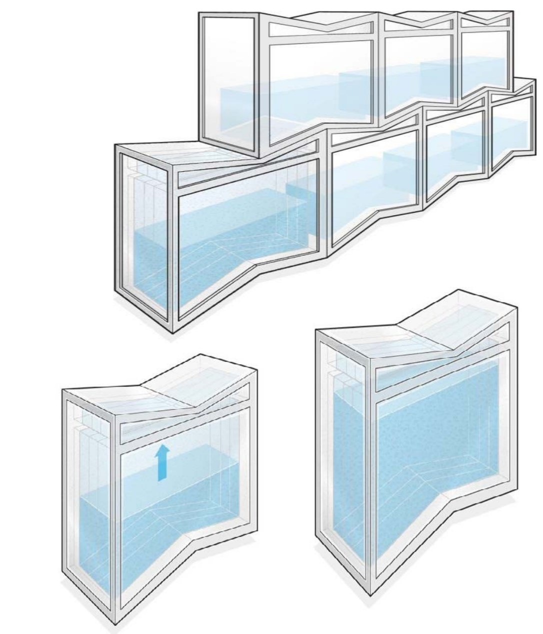


Figure 31:Perspective view of the system,Reviewed from:http://www.architectmagazine.com/project-gallery/thermometric-facade

ADVANTAGES OF PCMs INTEGRATING IN BUILDINGS

PCMs improve the indoor thermal comfort in buildings. Potentially, PCMs can provide a means to regulate temperature with a little extra input of energy. This should be viewed as a thermal management tool, integral to the total climate concept of a design. It cements its place at the top of the pyramid when it comes to building services. The basic need that any building should fulfill is the provision of shelter. Installations need to be added to regulate and improve indoor climatic conditions. We wish to do this in a sustainable way by reducing the energy required for building operation and materials required for construction. This is where PCM could prove to be part of the solution. They work advantageously in several ways:
1. In a typical room temperature range, PCMs have a very high thermal storage capacity compared to conventional building materials, since they melt and solidify at a point within a range. Consequently a vast amount of heat can be stored in a small volume. When PCM is applied the thermal mass of a building will be increased, without adding much extra bulk to the walls or structure.
2. PCMs reduce extreme temperature peaks that occur daily. Temperature fluctuations are evened out since any excess heat above the melting point is absorbed and released later when ambient temperature dips below the freezing point of the PCM. This results in keeping the indoors cooler during the day and warmer at night.
3. Indoor temperatures increase at a slower rate, meaning that it takes more time to reach its peak value. This is good for office buildings since the point where overheating in summer occurs happens after working hours when the building is largely unoccupied. During winter, the building is warmer at the start of the day because it has less time to cool down overnight.
While the above-mentioned advantages are common with sensible thermal mass, PCMs have certain added advantages over them. One of the advantages is that they are required in lesser quantities. It also has the ability to maintain a constant temperature during heat transfer. This implies that it offers higher exergy for the same amount of storage capacity, thereby making it more interesting, exergically.

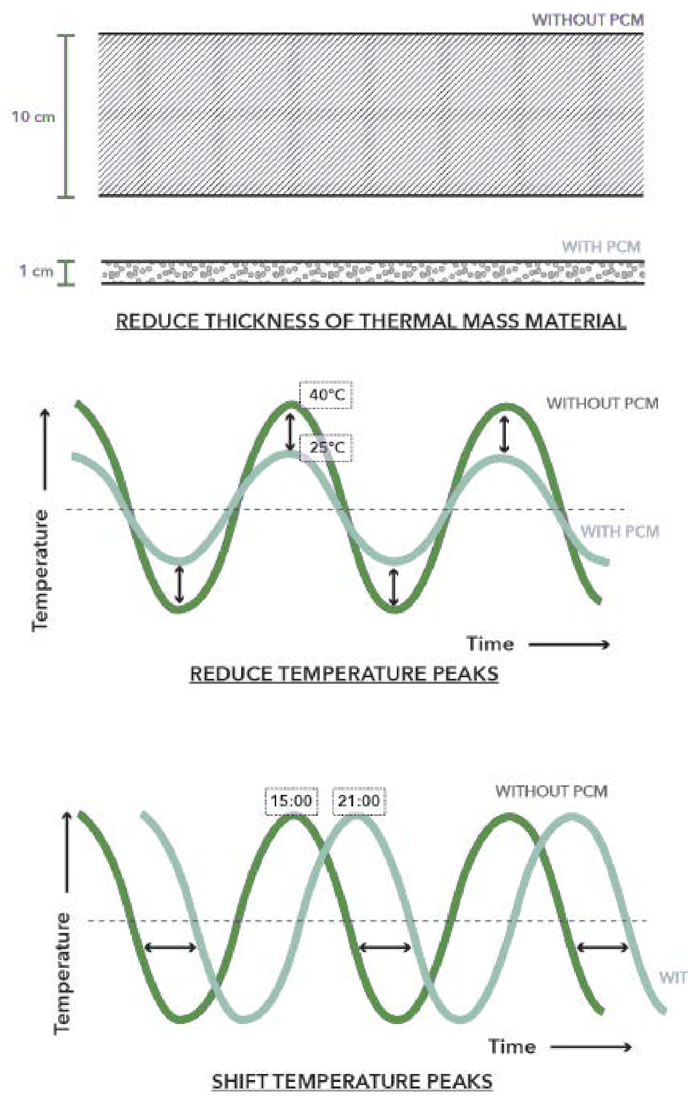


Figure 32:The advantages of the PCMs integrating in buildings,made by the author

REPRESENTATIVE REAL PROJECTS INTEGRATING PCMs

EnBW Zentrale

Internal sun blinds _ System concept
ZAE Bayern _ PCM Engineer
Office building _ Type
Karlsruhe, Germany _ Location
EnBW Energie Baden-Württemberg AG _ Client

While the EnBW Zentrale building looks ordinary but is packed with special features. It is one of the four buildings in Germany that incorporates PCM systems. The sun blinds in several of the offices are loaded with PCMs, which facilitate the heating of the room through absorption. The use of blinds causes an increase in heat in the room through the absorption of it by the sun blinds; which can be regulated by the integrated PCM. A temperature reduction was seen in the range of 10-15 °C with a drop in the operating temperature of the room by 3 °C. The thermal comfort of the room increased by a significantly during working hours thereby directly indicating the promising results. Retrofitting PCM-enhanced sunblinds is probably one of the most basic applications of a PCM in building engineering. Even though there have been some good results, PCMs can't be thought of an immediate solution to tackle the issues of overheating. Either way, it may be good idea to control the heat entering the building premises. PCM blinds are thus best deployed in retrofit or in new designs where the use of external sun shading is otherwise not possible e.g. in high rise office buildings.

Figure 33:Thefacade of the ENBW Zentrale,Reviewed from:http://www.aufildurhin.com/de/mitglieder/enbw

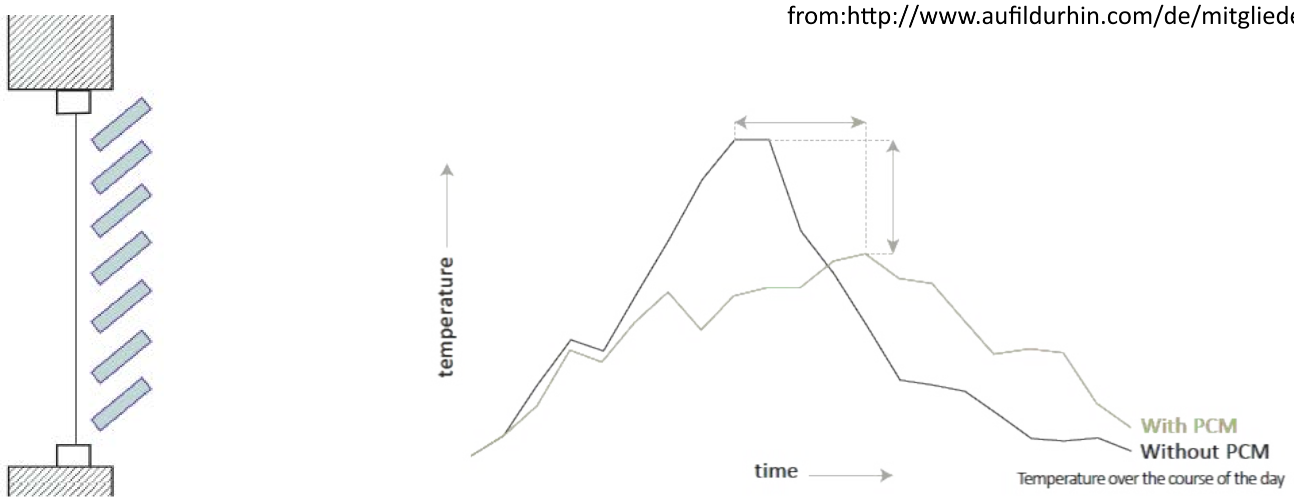


Figure 34:The impact of the PCMs in the building, made by the author

WILO BUILDING

21 °C _ Melting point PCM
Paraffin grains, mixed with concrete _ PCM
Semi-passive application, active discharge using cold water tubes _ System concept
BASF _ PCM Engineer
Office building _Type
Westzaan, Netherlands _ Location
WILO Nederland BV _ Client
Benthem Crouwel Architects _ Architect
Pieters Bouwtechniek Delft _ Structural Engineer
2009 _ Realised

Wilo Headquarters, a class of Dutch modern lightweight buildings, has built a strong reputation for its innovative roofing system that prevents overheating. It makes sense to add thermal mass in the form of PCMs since the entire building has a steel structure. The roof plate is perforated and profiled; and uses a clever combination of PCMs and cooling circuits thereby increasing its ability for efficient sound absorption to cool the subjacent space. The use of concrete infused with paraffin grains in the roof panels has an insulation layer on top. Liquid pumped through pipes that are embedded in the concrete ensure an even temperature distribution. This is because the water circuit in the steel plate provides radiative cooling and also helps removing all the heat at night which is buffered in the PCM during the day should the heat removal through night ventilation be insufficient. Peak cooling loads have found to be dropped by 40-50 %. However, temperature fluctuations after office hours have been recorded when the energy requirements are at a minimum.

Figure 35:The Wilo Headquarter's external view,Reviewed from :http://www.hafkon.com/en/systems/design/design/wilo-office-building-westzaan/

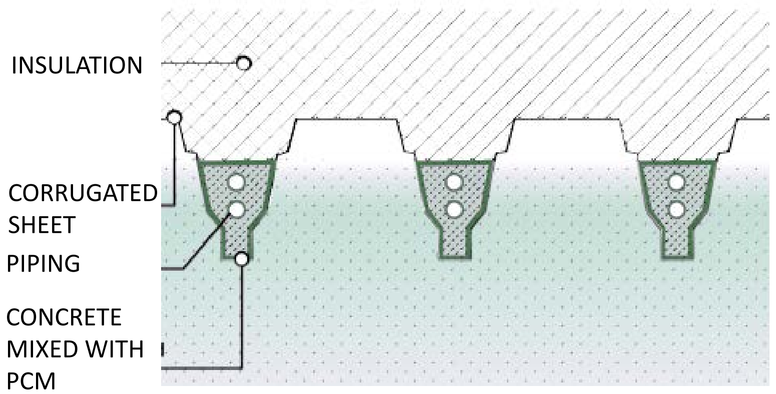


Figure 35:Concrete infused with paraffins,made by the author

Eulachof Glass X

alciumchloridehexahydrate, hermetically sealing in polycarbonate _ PCM
Quadruple glazing with prismatic outer layer and PCM core _ System concept
Allianz Suisse _ PCM Engineer
Residential building _ Type
Profond Pension Fund_ Client
Winterthur, Switzerland _ Location
Dietrich Schwarz Architekten, GlassX AG _ Architect
2006 _ Realised

Eulachhof Glass X, a Swiss low-rise building which does not utilise any external energy, but incorporates a variety of PCMs embedded in a quadruple glazing in different parts of its façade. The addition of a thermal buffer in windows severely reduces heat loss associated with having large glazed areas in facades. The innter core of GlassX is made out of PCM with a transparent prism forming its outer boundary. These windows are capable of storing as much heat as a 220 mm thick concrete wall and have the tenacity to be exposed to 8 hours of direct sunlight whilst not experiencing complete melting. The prism structure is designed to reflect steep sunbeams, causing a temperature reduction of 3-5° C. The window assembly prevents entrapment of heat in the rooms during summer. This results in the limiting of solar gain whilst it also improves the thermal insulation. During the winter, the solar radiation is less intense and sun rays at an angle below 35° can pass through the outer prism nearly unhindered. This results in the maximization of solar gain during winter. This effect of the PCM considerably decreases the heating loads upto 200 kWh/m2 during winter and energy loads by 30-50% during summer.

Figure 37:Thefacade of the Eulachof Bulding,integrating GlassX products,Reviewed from:http://www.schwarz-architekten.com/en/project/

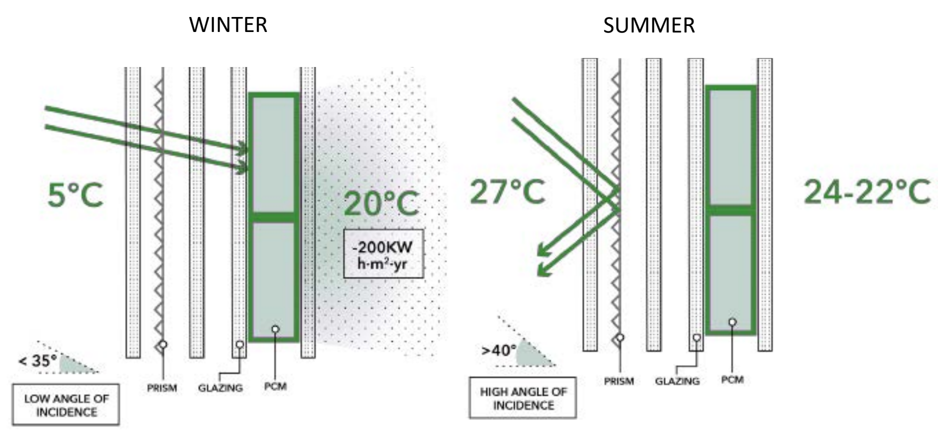


Figure 38:The performance of GlassX according to the season,made by the author

IMTECH HAUS

Paraffin graphite composite _ PCM
Decentralized facade ventilation units with latent heat storage tank_ System concept
_PCM Engineer
Office building_Type
Hamburg, Germany _ Location
Imtech Deutschland GmbH & Co. KG _ Client
nps+partner GbR _ ArchitectDura
_Structural Engineer
2006 _ Realised

The Imtech office in Hamburg, is the testing ground for a PCM ventilation device. Its 50 modules are mounted on the inside of the building parapet so as to provide individual air conditioning. A paraffin graphite composite is used as a storage medium which freezes at 22°C. Since an intake is integrated in the windowsill, each unit can either let in ambient air or cool by recirculating inside air. The modules are installed such that a PCM distribution of 5 kg/m2 is available which is sufficient for large office spaces. If the temperature at night lies below 18 °C during summer, indoor temperatures will remain under 26 °C making it quite comfortable. The only electrical energy is required is for the functioning of the circulation pump and the control equipment. This system provides 82 % cooling with 5-7 % of electricity consumption compared to a conventional cooling system. These results prove to be fantastic as it results in a total electrical saving in the range of 60-90 %. At the start of the working hours, only one thermal storage unit supplies fresh air to the occupied area while other thermal storage units are dormant. Only when the indoor temperature limits are reached, the units switch to recirculation mode. The warm air at the limiting temperature is fed through the PCM battery, where it is cooled down to 22 °C and circulated back to the room to balance the warming. After the working hours however, the thermal storage capacity drops down since all devices shut off and the fresh air supply gets depleted. If this occurs during working hours, air intake is increased to prevent unnecessary overheating of the occupied area. At night, PCM stacks are regenerated using the outside cold air and hot air is purged through a centralised exhaust system.

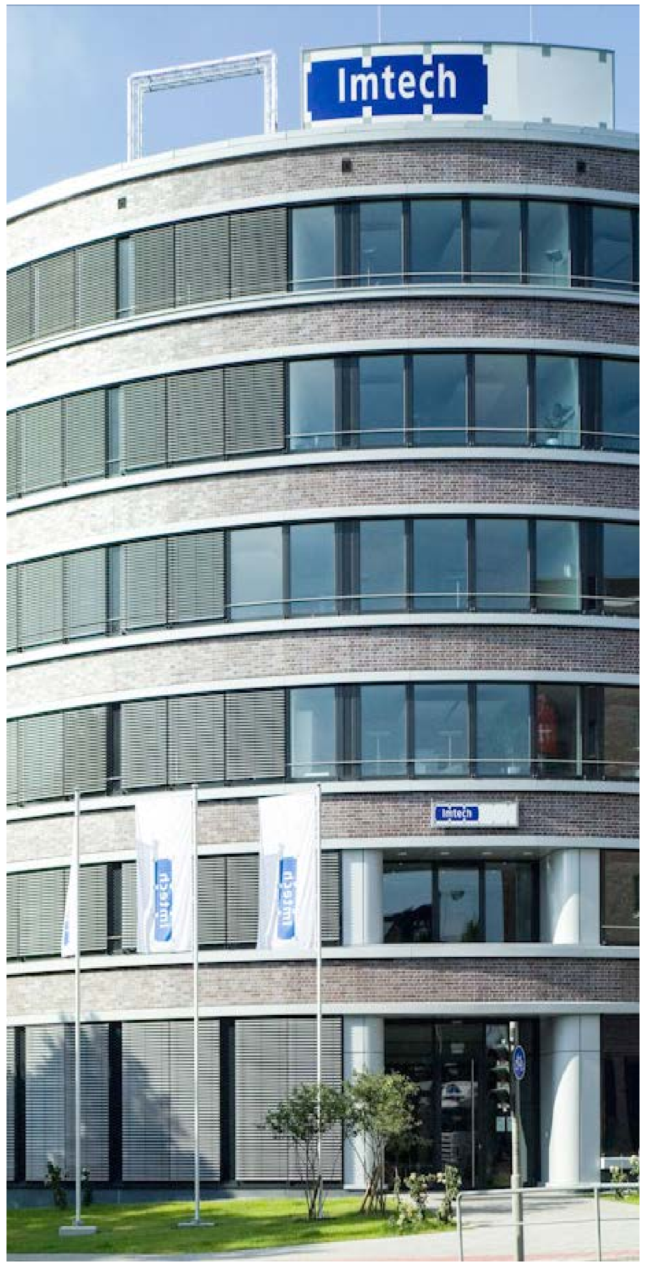


Figure 39:The IMTECH HAUS,external view,Reviewed from: http://www.wolff-mueller.de/imtech-haus-hamburg.html?PHPSESSID=uiwwopkfumci.

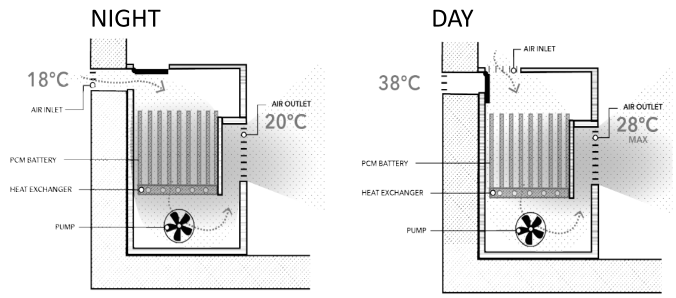


Figure 40:The operation of the heat storage unit(day and night mode), made by the author

2

research methodology

RESEARCH METHODOLOGY

PROBLEM STATEMENT

Nowadays, it is increasing the need to regulate the indoor environment of the building by using mechanical heating and ventilation systems. However, these systems sometimes can cause poor indoor air quality due to the lack of natural ventilation and health problems in the occupants of the building. Some studies made clear that the mechanically controlled indoor environments that function completely separated from the outdoor environment can even be far from comfortable and healthy (Mahdavi & Kumar, 1996).

Moreover, high amounts of energy are consumed in all buildings so as to improve the indoor environmental quality. More specifically, in the library buildings there are increasing demands for artificial lighting and mechanical ventilation and heating systems so as to retain a pleasant atmosphere for the students and a comfortable working environment for the employees of the building. In other words, in libraries high energy cost caused by the extensive use of air-conditioning and lighting systems.

The problem of the excessive energy consumption of the building is presented also as there is absence of thermal storage components which can be used to store or use the waste energy flow and minimize the energy costs.

As far as the building's envelope is concerned, it is noticeable that most of the modern facades lack of flexibility and multi – functionality so as to respond to climate change and temperature fluctuations in order to provide thermal comfort without any expenditure of conventional auxiliary energy. On the other hand, traditional buildings were built with considerations to climatic conditions for keeping the inside building spaces cool in summer and warm in winter by adapting passive façade systems. This lack of climate responsiveness in the facades can create unpleasant an indoor environment with overheating or undercooling problems in the summer and winter respectively.

More specifically, a facade system which is integrated in order to improve the thermal and the visual comfort in the libraries is the fully glazed double skin facade.However, many times these systems are very expensive in terms of construction (expensive type of glazing) in order to achieve satisfying levels of thermal insulation and high levels of visual comfort.The lack of flexibility of the double skin facade systems in terms of climate responsiveness, heat storage and their decreased possibilities of thermal regulation create overheating during the summer and increased energy loads for heating and cooling .

An alternative solution to this problem is given through this research and it is based to an adaptive double skin facade based on PCMs that is capable of storing heat, respond to different climate conditions and provide thermal comfort in the indoor space of the libraries.

RESEARCH QUESTION

What should be the design of an adaptive façade system based on PCMs and how should it respond to different climate conditions so as to provide thermal comfort in the indoor space of libraries whilst minimising the energy use for heating, cooling and lighting?

THE AIM

The general aim of this façade design is to develop comfortable indoor climate conditions in the libraries that will have a positive impact in occupant's health, psychology and efficiency. In reality, there is a strong connection between improved indoor environment and augmented performance of employees or students in the educational buildings. For this reason, the goal of this façade system is to create pleasant indoor atmosphere that will ensure thermal and optical contact in the users' of the library buildings. To put it differently, the main goal of the research is to create a thermally comfortable environment in the indoor spaces of the libraries.

Another objective of the research is to provide guidelines to the facade designers who plan to integrate phase change materials in facades.

SUB-OBJECTIVES

• To develop a typology of integrated systems of thermal storage in the building envelope using smart materials in combination with a smart kinetic system.

• To find out how a passive heat storage strategy can be integrated by the use of PCM s in the building s envelope as a strategy to reduce building energy consumption (the heating and cooling loads)in temperate and Mediterranean climates.

• To find out which are the ventilation principles of the façade system based on PCMs for each climate separately so as to achieve thermalcomfort in libraries?

• To find out which are the façade design principles of the PCM based system so as to achieve optimal climate responsiveness to Mediterranean and temperate climates.

• To find out to what extent the magnitude of PCM melting temperature and its quantity in the façade container affects the thermal performance of the adaptive façade.

1)What should be the most efficient melting temperature for each climate(temperate and Mediterranean) so as to ensure maximum levels of energy performance in the indoor space of libraries?

2)What should be the optimal quantity of the PCM in each climate separately(temperate and Mediterranean) so as to take full advantage of the heat storage capacity of the PCM which will be chosen for the facade system.

• To find out what should be the kinetic façade performance in the summer so as to achieve thermal comfort and minimise the cooling and the heating loads (for each climate separately).

.• To find out the ideal proportion of the kinetic and fixed parts so as to achieve thermal comfort and natural ventilation.

• To find out what is the ideal ratio of the transparent to the opaque elements so as to achieve both visual and thermal comfort.

CONSTRAINTS

The climate-responsive façade behaviour can be achieved by the implementation of different smart materials or intelligent systems. However, this research focuses on the use of PCM in combination with an adaptive kinetic system.

PCMs can be integrated in different building components to improve the thermal performance of the indoor space (concrete slabs ,roofs, shutters, gypsum plaster boards).In this project PCM s are implemented in the building's envelope.

A climate responsive façade with PCMs has potential in all building types and in all climates. The design will focus on newly –built libraries and it will be evaluated in two different climates: Temperate Climate (Amsterdam, Netherlands) and Mediterranean climate (Athens, Greece).

Library building have specific heating ,cooling standards and lighting requirements as it happens with office buildings. On the other hand, in dwellings heating ,cooling and lighting demands can differ according to the user 's preferences. Moreover, unlike offices, the operating hours of the conventional libraries are from 8 am to 12 pm. This means that both day and night mode of the façade system should be taken into consideration.

GENERAL DESCRIPTION

The main aim of the project is to design an adaptive façade modular system based on PCM opaque and translucent kinetic components. This facade is going to perform as a heat storage system that will have responsive character to the changing climate conditions so as to ensure optimal thermal performance in the inner space of libraries.

Some basic design principles that are integrated in the façade system are the double skin façade , the window box façade elements and the climate responsiveness.

The system will use passive methods for the heat storage and the general thermal performance and kinetic façade components based on active design so as to achieve satisfying natural ventilation(operable façade elements) and visual comfort(adjustable shading system with opaque and translucent elements).

RESEARCH BY DESIGN

This research follows the "study by design" logic as it aims to the development of knowledge about the PCM applications in the field of the façade design. This will be achieved by designing and studying the effects of a climate responsive façade design based on PCMs on the thermal comfort in libraries, changing the façade design itself or its context and studying the effects of the façade transformations. The procedure will have an experimental character as physical experiments and digital tools are used to investigate the thermal performance and the heat storage possibilities of an adaptive façade system based on PCM. The data collection techniques that are used are lab measurements and simulation models that will check the thermal performance of the façade system with specific PCMs applied undergoing climate changes.

STEPPED METHODOLOGY

More specifically,the research is divided into 4 steps :

1)Literature Study/Case Studies_ Knowledge background
2)Definition of the main research subject,the primary objectives of the research and the
3)Analysis framework generated by the interplay through the literature review , weather data analysis of the research areas ,hand calculations and digital simulations, concept design and performance drawings , experimentation and parametric design tools.
4)Evaluation of the performance of the system by changing its kinetic behaviour and optimization of the facade design and the answer to the research question creating a designer's manual.

1)LITERATURE REVIEW

The first part of the research includes literature study on many different aspects in order to set the basis of the design. Most information derives from relevant academic sources and research studies and additional from similar case studies. The Literature study is very important in order to understand the nature of the PCMs, their main characteristics, their working principle, and the ways by which they can be applied in the buildings.

It also helps in the understanding of how PCM integration in the building 's envelope can affect the energy performance. Moreover, the aspects of thermal and visual comfort in working environments, heat and its transmission, heat loss and gain were studied, in order to define the variables that affect the indoor environment in an office building and subsequently in library buildings.

2) MAIN RESEARCH QUESTION_PROBLEM STATEMENT

The main research question remains the same as it was defined from the P2 phase and it was presented previously.
The problem statement refers to the lack of the flexibility, thermal regulation and heat storage systems in the fully glazed double skin facades.
In this research a comparison will be made between the fully glazed double skin facade and the proposed system based on PCMs.

3) DESIGN PROCESS

Weather Data Analysis
Weather data related to the solar irradiation , the mean and the average maximum temperatures and the wind speed are collected through the Climate Consultant software and through grasshopper for both study areas (Amsterdam, Athens). This step was really important because with these data, hand calculations were made in order to find out in an approximate way the thickness of the PCM containers for each area , the temperatures that can be appeared in the façade during the four seasons for both climates and the melting temperatures that can be used for each climate separately.
Energy Simulations
Initials energy calculations using as a study case the silent room of the TU Delft library creating an approximate but more normalized rectangular geometry of the room and checking different ratios of PCM and glazing , different PCM types so as to get an insight on how the type of the PCM and the ratio between the pcm and the glazing in the outer skin of the façade can affect the totals energy demands of the building.(artificial lighting, heating and cooling)

DESIGN PARAMETERS

Specifically, in this research they are examined different façade patterns applying simple geometries (applied in hexagonal or a rectangular grid).
More specifically, different types of PCM façade containers are created having as a base the hexagonal or the rectangular shape. Each one of these types have different ratio between the glazing and the PCM .The alternate designs that are examined have to do with different combinations of these different types.
Unlike the initial design logic which was referred to the exploration of different geometries for the containers which would contain the same type of PCM and the same ratio between the glazing and the PCM , now the design is more focused on the experimentation of simple geometries for the containers and the possibility of implementing façade modules with different melting temperatures and different ratios between the PCM and the glazing per panel.
The logic has been changed so as to end up in a more feasible façade design that could be easily constructed and create a final realistic façade product. The use of different melting temperatures instead of only one temperature in the façade design is a result coming from a series of initial digital simulations ,hand calculations and from my own assumption that the façade will be able to respond undergoing different weather conditions in an efficient way through the whole year.

EVALUATION/HAND CALCULATIONS,-EXPERIMENTATION AND DIGITAL SIMULATIONS

The façade design is evaluated through a series of numeric calculations, simulations and physical tests.PCM façade panels are constructed with different transparency levels ,different PCM quantity and different melting temperatures so as to make physical measurements that show the thermal and the optical behaviour of the PCMs(heat flux ,duration of thermal cycle, optical properties changing with the solar irradiation and the changes in the air temperature).

RESEARCH PLAN

INTRODUCTION_KNOWLEDGE BACKGROUND
Firstly, the literature research was based in the climate-responsive facades which use kinetic mechanisms and their main characteristics(flexibility, acclimation, learning).In second level, the knowledge background was enriched by studies focus on smart materials and more specifically PCMs, their characteristics and their applications on the building industry. Moreover, ways on how PCM materials can be implemented in passive heating storage systems were explored so as to form a general understanding on thermal energy storage with phase change materials (PCMs) in building applications.
INITIAL DESIGN CONCEPT
In next step, an initial exploration in different façade and thermal principles is done by creating a series of conceptual sketches. The first designs are created in Rhinoceros 3d software in order to manipulate digitally the size and the geometry of the façade components.
The façade components are composed of the PCM containers and the PCM ,the window frames and the glazing of the façade.
COMPUTATIONAL DESIGN APPROACH
A specific computational facade approach will be used so as to create alternative facade patterns with different ratios of Glazing and PCM in the facade and different ratios of the different PCM used in the facade.Then ,the areas that cover the facade with different PCMs and the percentage of the glazing is going to be measured and this data will be an input for the simlutions that are conducted.
SIMULATIONS
DESIGN BUILDER
To start with the simulations specific properties of the PCM used should be introduced in the model:
1)thickness of PCM (m) .The thickness indicates the quantity of the PCM material inside the container.
2)density of PCM(kg/m3)
3)specific heat capacity (J / Kg*K)
4)heat conduction coefficient(W/m* K
5)Latent heat (J/kg)
Moreover ,the depth of cavity between the PCM containers and the window glazing should be taken into account(m).

Similarly to the PCM material the physical and the thermal properties of the glazing should be included in the simulation model.
In order to study the effect of the ratio of glazing and PCM in the facade on the overall energy consumption the following simulations are going to be performed. All the simulations were carried out for the whole year taking into account climate data for Athens and Amsterdam relatively.
1)Room with PCM façade components (first facade pattern) and double glazing elements
2) Room with PCM façade components (second facade pattern) and double glazing elements
3) Room with PCM façade components (third facade pattern) and double glazing elements
4) Room with PCM façade components (fourth facade pattern) and double glazing elements
5) Room with fully glazed double skin facade
The energy required for heating, cooling and lighting will be used to evaluate each scenario in terms of energy performance.

PHYSICAL MEASUREMENTS
Lab tests are done in a specific office room at TU Delft so as to get to know the thermal conductivity of the PCM material used and the thermal behaviour of the façade modular system undergoing different climate conditions.

EVALUATION
After evaluating the previous results coming out of the simulations and the physical tests , the design is going to be optimized so as to enhance its thermal performance.(extra energy simulations with integrated shading system and cfd analysis).

DETAILING
The optimized design is going to be further developed in a more detailed scale and construction details are going to be design.

RESEARCH METHODOLOGY| THE STEPS

1 LITERATURE REVIEW
- research on PCM based studies and general informations
- Heat transfer and heat storage / general data
- climate responsive facades

2 MAIN RESEARCH QUESTION
- Problem Statement
- Aim
- Objectives

3 DESIGN PROCESS
INPUT – PROCESS – OUTPUT
- Initial design concept | Design principles
- Computational design procedure
- Alternative Designs
- Experimentation
- Testing
- Case Study

EVALUATION
- Comparison of the different designs (energy performance)
- Comparison with fully glazed double skin facade
- Critical analysis of the system in both climates

BUILDING SYSTEM
- Construction Details

4 CONCLUSIONS
- Does the system work?
- Drawbacks/Future improvements?

BACKGROUND KNOWLEDGE| RESEARCH INTERESTS

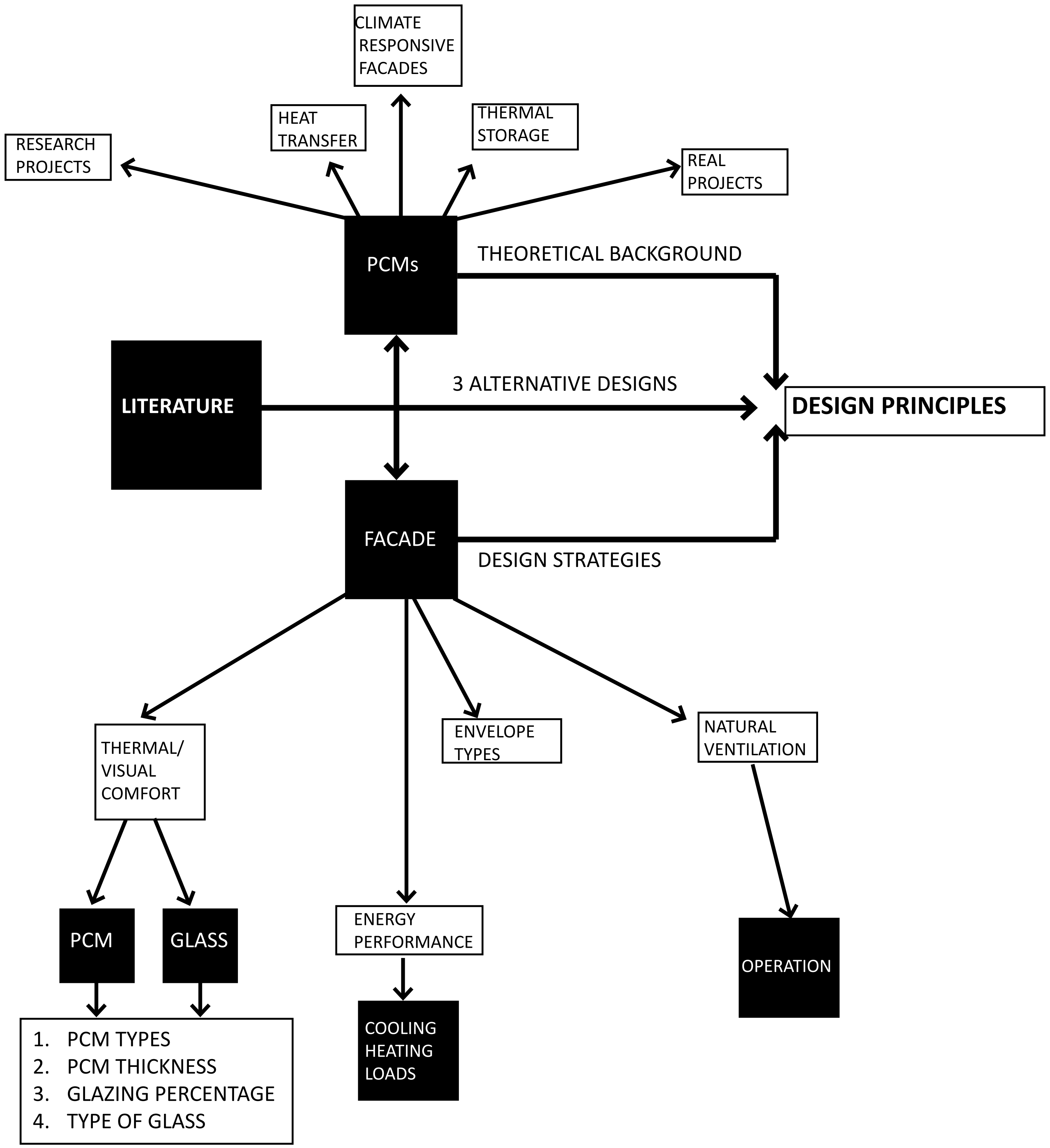


Diagram 2.1: Background knowledge process, made by the author

MAIN RESEARCH QUESTION|PROBLEM STATEMENT

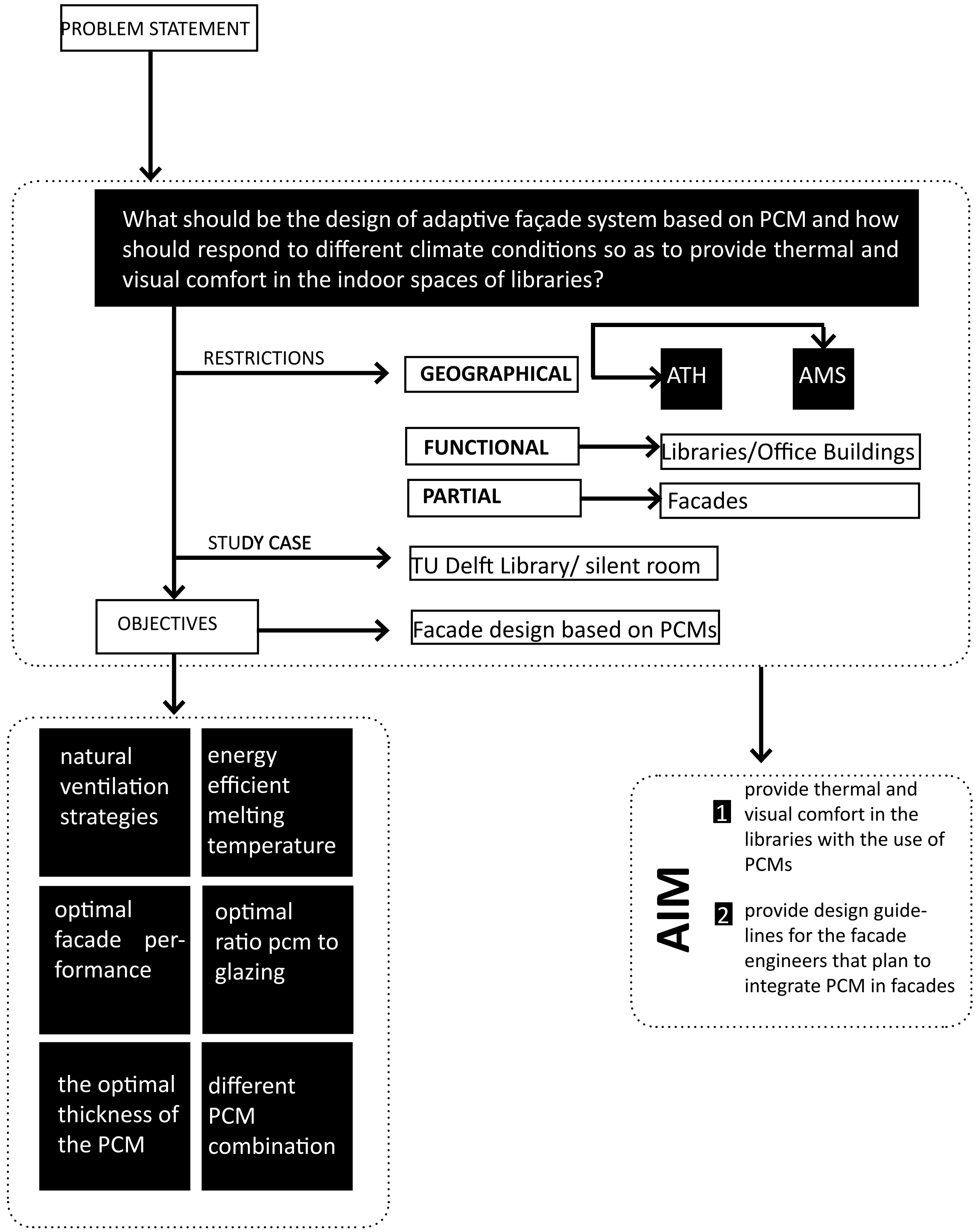


Diagram 2.2: Main research process, made by the author

DESIGN PROCESS | DESIGN STRATEGIES AND EVALUATION

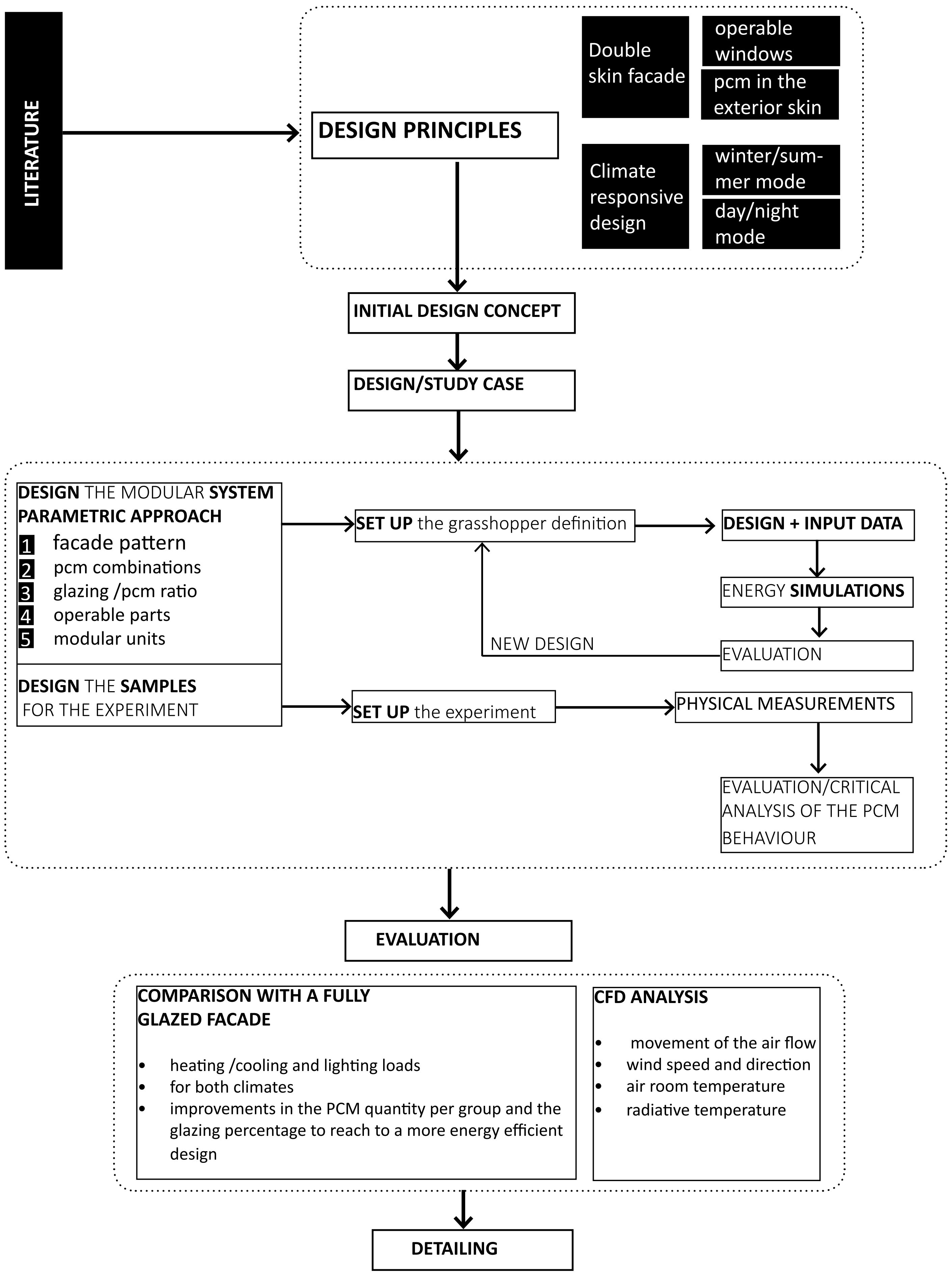


Diagram 2.3: Design process, made by the author

CONCLUSIONS | CRITICAL ANALYSIS AND FUTURE STUDIES

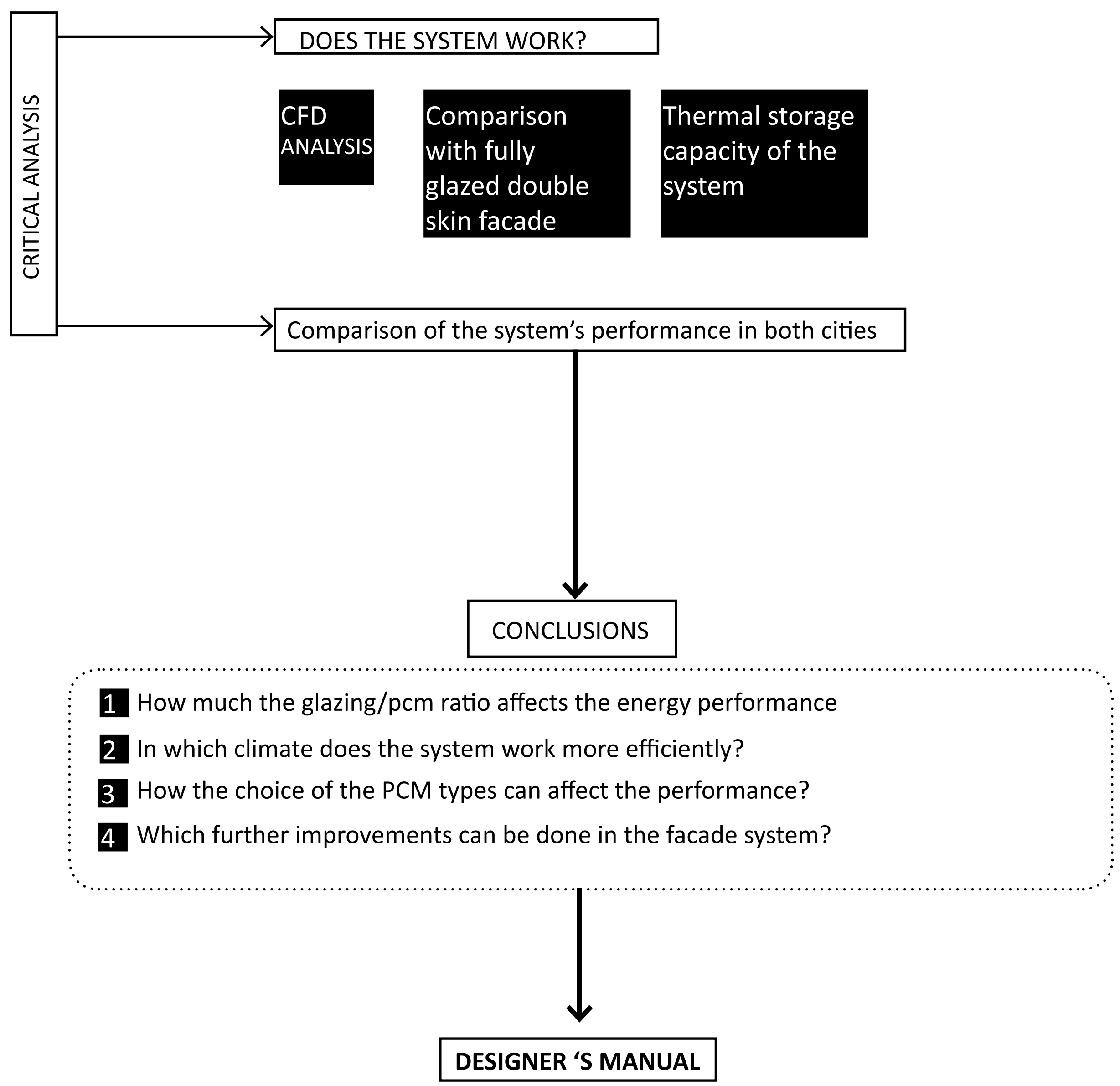
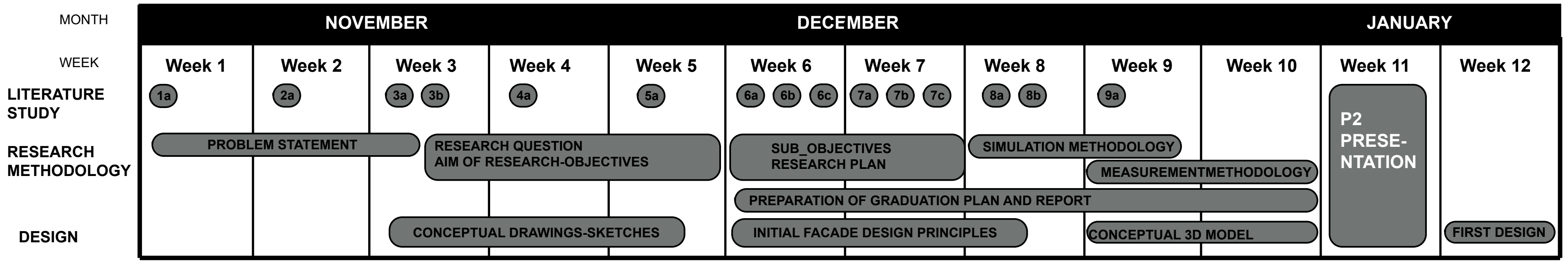
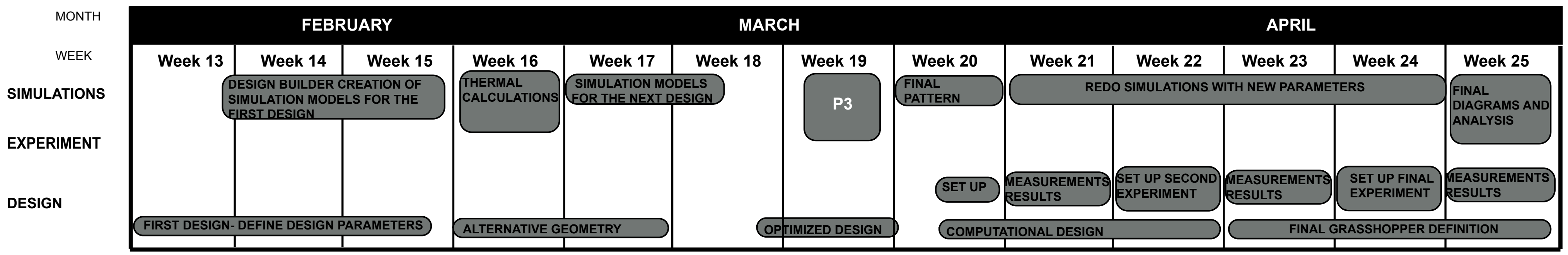


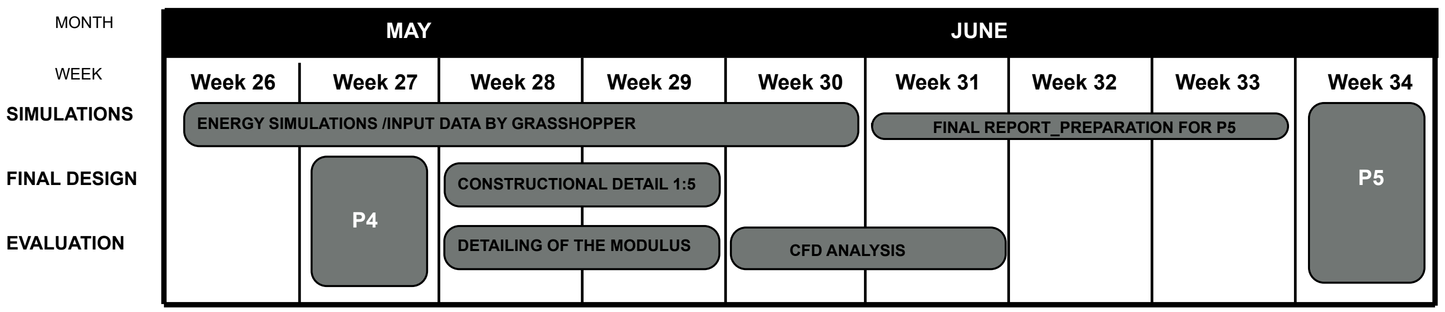
Diagram 2.4: Steps for critical analysis and future studies, made by the author

DESIGN PROCESS|GRADUATION WORKING PLAN



1a.PCM working principle/general properties
2a.Climate Responsive Facade Design_characteristics
3a.PCM Categories
3b.Scientific projects based on PCM
4a.GLASS X applications
5a.PCM in building applications
6a.PCM supercooling phenomenon
6b.Phase separation
6c.Material leakage_PCM Encapsulation
7a.PCM requirements
7b.Latent -sensible heat
7c.Passive heat storage systems based on PCM
8a.Study on Double2Face simulation methodology
8b.Study on Double2Face measurement methodology
9a.Experimental studies on PCM based projects





3

initial design

1ST DESIGN APPROACH|FIXED PCM ELEMENTS (PCM PLACED IN TRANSPARENT CONTAINERS) _OPERABLE DOUBLE GLAZED ELEMENTS

This system contains PCM based panels and double glazed units which are fixed and operable elemetnts respectively.The glazing elements open so as natural ventilation to take place.The PCM based panels are fixed and cannot operate.This means that the heat will also be released to both sides and as a result it cannot taken full advantage of the heat stored in the PCMs for passive heating of the building.

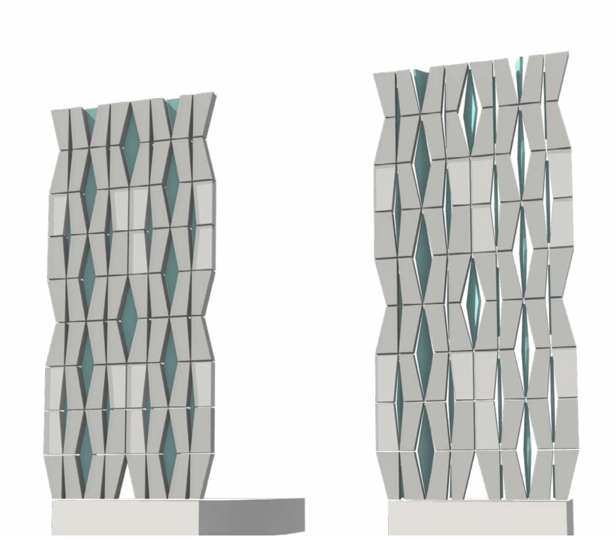


Figure 3.1: Conceptual 3d showing the operation of the facade elements, made by the author

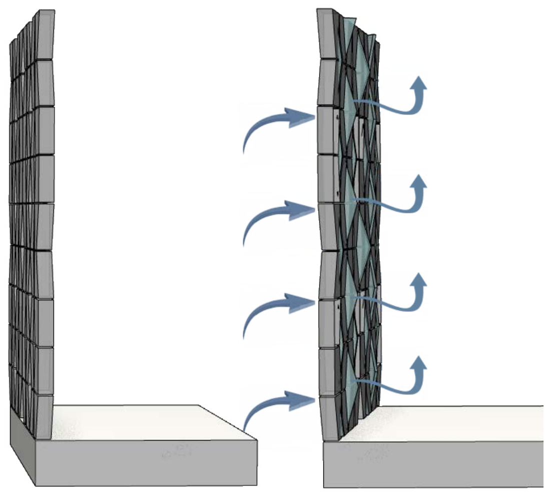


Figure 3.2: The operation of the glazing elements for natural ventilation, made by the author

2ND DESIGN APPROACH|FIXED DOUBLE GLAZING UNITS ,KINETIC PCM BASED PANELS (PCM PLACED IN TRANSPARENT CONTAINERS)

This system has exactly the opposite logic using fixed double glazing units and operable PCM based panels.With this way, it can be ensured that a larger amount of heat can be released to the outside when the PCMs solidify in the summer case.This can happen because at the time of the solidification process the PCM based panels can open releasing the heat to the outside.
However, during the winter, the facade cannot operate to allow natural ventilation because they are single skin facade and many heat losses will occur under these conditions.

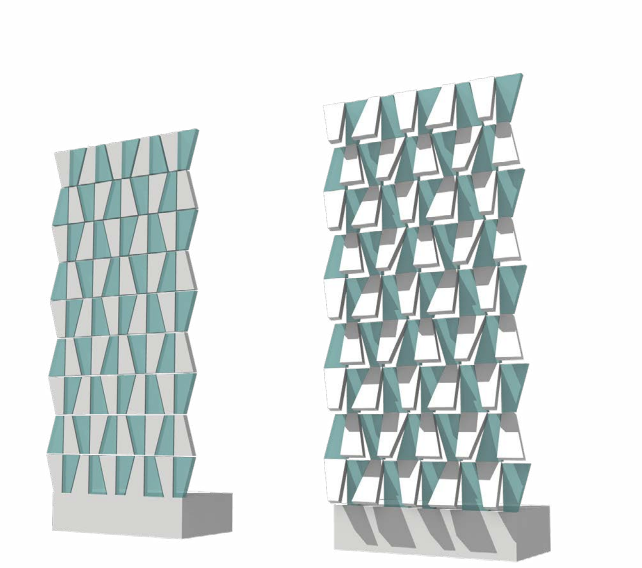


Figure 3.3: Conceptual 3d showing the operation of the facade elements, made by the author

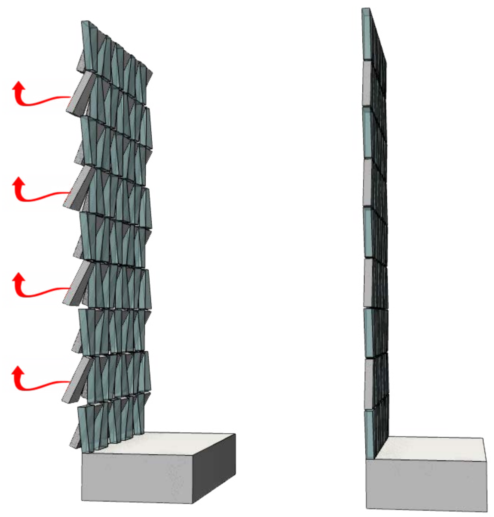


Figure 3.4: Day: Charging by the solar heat Night: Discharging to the outside

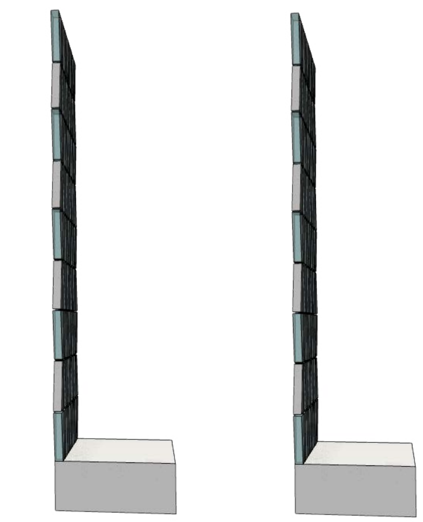


Figure 3.5: Day: Charging by the solar heat Night: Discharging to the inside

3RD DESIGN APPROACH | DOUBLE SKIN FACADE SYSTEM BASED ON PCMs (OPERABLE BOTH PCM AND GLAZING COMPONENTS)

This system is a double skin facade system with operable glazing elements and PCM based facade panels.This seems a more flexible solution as natural ventilation can be occured the whole year and the facade can respond in a different way in different weather conditions(show image).

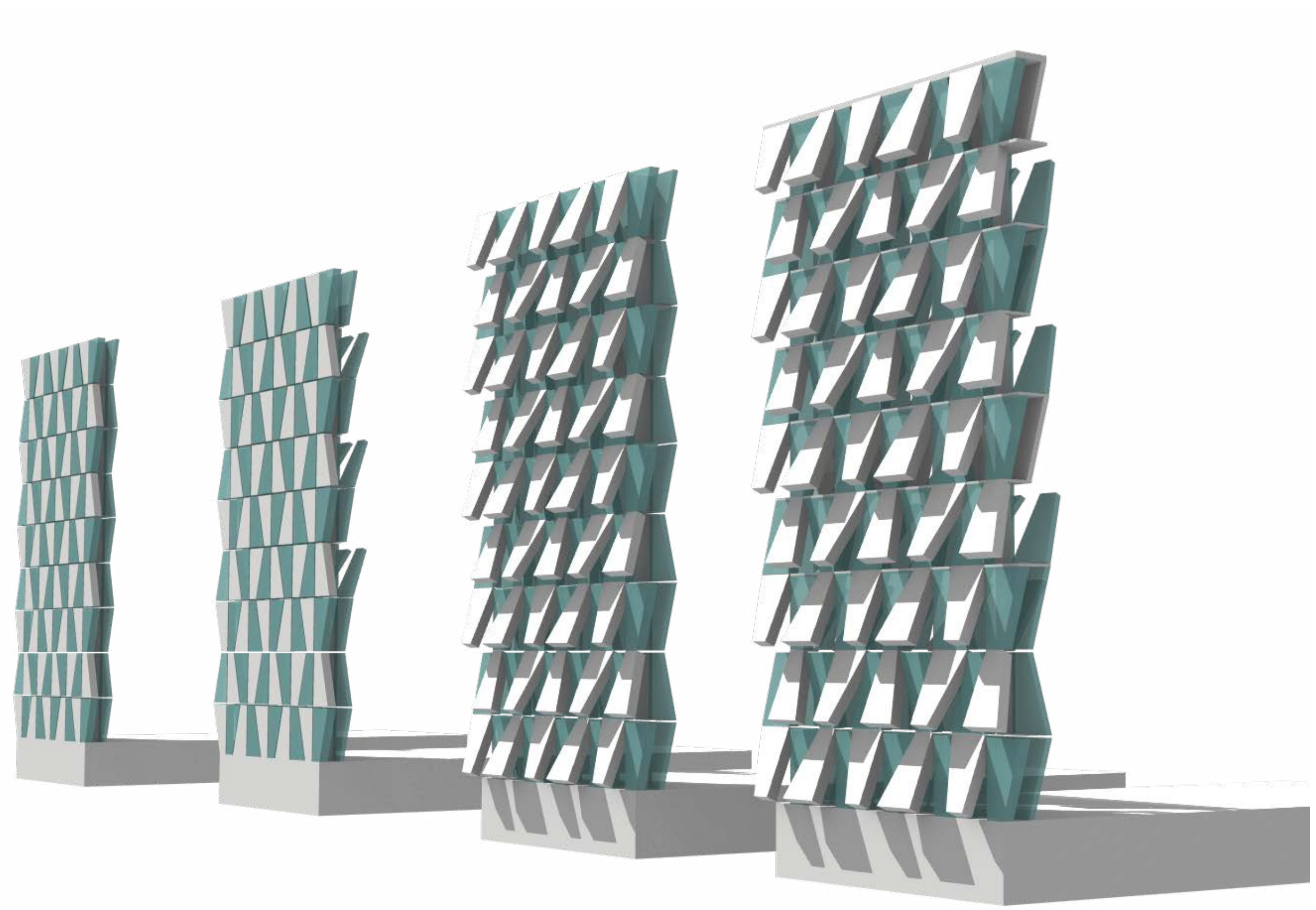
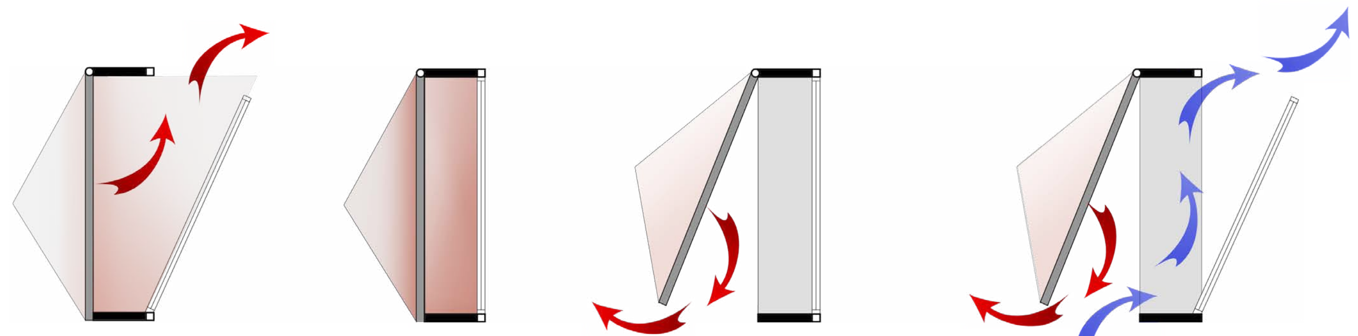


Figure 3.6: Conceptual 3d showing the operation of the facade elements



discharging to the interior
passive heating

charging by the sun
discharging in the cavity

discharging to the exterior
avoid overheating

discharging to the exterior
natural ventilation

Figure 3.7: The responsiveness of the PCM based panels according to the weather conditions, made by the author

COMPARISON | SINGLE SKIN VS DOUBLE SKIN

When it comes to choosing between a single skin PCM and double skin PCM based façade, there are several factors to be taken into account.

The single skin PCM offers an easier set up, construction and operation making it cost effective relative to its counterpart. However, it lacks flexibility while operating during different seasons. During winter, the operable parts of the façade need to remain closed so that occupants are not exposed to the weather conditions that come with the season- rain, snow and gusts of air. In the summer, the system needs to be open to offer natural ventilation and to curb down overheating.

The double skin PCM offers much more flexibility but at a cost- it involves more components and hence a sophisticated design. This increases the expenditure towards maintenance. The ability to minimise solar gain through the façade and hence decrease the cooling load of the building reduces energy consumption. The presence of the external skin provides natural ventilation through the cavity whilst not compromising the comfort of occupants during harsh weather conditions. It also provides greater insulation by increasing the external heat transfer resistance during winter. Flexibility is seen in the fact that it uses kinetic elements in the system, which enables taking advantage of the properties of the PCM during melting and solidification with respect to the operations corresponding to the weather conditions. The presence of operable windows, in addition to the kinetic elements, facilitates in the regulation of air and temperature in the building, thereby increasing the comfort of the occupants.

It is clear that the advantages of the double skin PCM outweigh those of the single skin PCM and consequently the 3rd design approach will be the starting point of the design process.

	SINGLE SKIN PCM BASED SYSTEMS			DOUBLE SKIN PCM BASED SYSTEM
ADVANTAGES	LESS COMPLEXITY			REDUCTION IN THE ENERGY CONSUMPTION/ LIMIT THE SOLAR GAINS THROUGH THE FACADE LESS HEATING AND COOLING DEMANDS
	COST EFFECTIVE/ LOWER MAINTENANCE REQUIREMENTS LESS CONSTRUCTION MATERIALS			FLEXIBILITY NATURAL VENTILATION THROUGHOUT THE YEAR
DISADVANTAGES	LACK OF FLEXIBILITY ONLY TWO MODES:	CLOSED WINDOWS OPEN WINDOWS	CLOSED PCM BLOCKS OPEN PCM BLOCKS	MUCH COMPLEXITY IN TERMS OF COSTRUCTION AND ASSEMBLY AND OPERATION HIGH CONSTRUCTION COST
	LACK OF NATURAL VENTILATION WHEN THE FACADE IS EXPOSED TO HARSH CLIMATE CONDITIONS			ADDITIONAL MAINTENANCE AND OPERATION COSTS

Table 3.1: Comparative data of the systems, made by the author

4

the concept

INITIAL CONCEPT|OPERATION IN THE 3rd DESIGN APPROACH

DESCRIPTION

WINTER

Phase change materials (PCM) absorb solar radiation during the day and store it as latent heat while undergoing melting. At night, the heat is released to the interior causing the material to solidify. This form of passive heating keeps indoors warm for a considerable amount of time. There will be convective circulation inside the cavity of the façade system but it remains inside since the cavity is sealed. During the day, it gets heated up and during the night, while the PCM solidifies, more heat is accumulating in it since the PCM panel and the window are closed. This system behaves as a thermal buffer. The temperature of the internal skin now increases, resulting in the reduction of conductive, convective and radiation heat losses. This prevents the release of heat from indoor to the external environment and thereby reduces the heating loads. There is also an alternative behaviour of this system when the external layer of the PCM is shut and the inner double - glazed window is left open. This facilitates heat transfer from the PCM panel to the interior space.

SUMMER

Just like in winter, the PCM absorbs heat from solar radiation during the day and stores it in the form of latent heat.A point of attention is the fact that the PCM can reach really high temperature above is maximum operative temperature,that can cause damage to the material.In order to protect the PCM from intense solar irradiation a shading system can be applied in front of the PCM based panels.During the night, while it solidifies, heat is released. The operation of the window elements in both skins is needed in order night cooling takes place and prevent excessive heat accumulation in the air cavity and the indoor space, coming from the PCM heat release

REFLECTION

Research has shown that ideally in a Mediterranean country melting point should be around 29 ^{0}C and in a Western European climate around 25 ^{0}C.

The performance of the system as it is proposed initially does not the potential of the PCM in a warm situation in order to cool the space.If the PCM that is used has melting temperature lower than the temperature of the room in the summer, when it solidifies can cool down the space.

Owing to the fact that the PCM element is exposed to the exterior environment, the heat released during its solidification in winter cannot be fully harnessed because a certain quantity of it is also released outside. However, this configuration is useful in the summer since some of the heat is released to the exterior environment. This prevents overheating when both the PCM and double-glazed element are closed.

If the entire façade consists of PCM with the same operating temperature, all the thermal processes will occur at the same point. This also implies that the operating temperature has to be reached in order for the system to be effective. However, there is a possibility of integrating PCMs with different operating temperatures. This provides a wider range of operating temperatures and hence offers more flexibility.

For summer and winter different amounts of PCM may be needed.In winter more PCM is needed in order to keep the temperature of the PCM stable and to ensure that all solar heat is taken up (radiation driven). In summer you need less PCM because there is slower heat transfer into the PCM (temperature driven).

NEW DESIGN APPROACH|GENERAL ASPECTS RESPONSIVE FAÇADE CONCEPT

Responsive envelope concepts are façade design solutions that aim to a balance between optimum interior environmental conditions and environmental performance by reaching in a controlled and holistic manner to changes in external or internal conditions and to occupant intervention on. This specific façade concept is based on an integrated multi-disciplinary process which optimizes the thermal performance of the system and creates a thermally comfortable environment. This façade concept is based on the use of different kinds of PCMs with different melting temperatures and the adaptive behaviour of the façade according to the external climate conditions. The design is organized in 3 levels: the concept level, the system level and the component level. The first one has to do with the idea behind the façade design. It's the underlying logic, thinking, and reasoning for how the facade is designed. The concept contributes to making choices about the design (PCM materials in the façade, different melting temperatures, adaptive behaviour according to the weather conditions). The next level comprises of the system's performance. This is a very important step of the design as specific operation parameters should be defined and the thermal performance of the façade should be evaluated by trying different alternatives with computation tools. Then, component level follows which treats the individual parts that constitute the façade. In this specific design, we can refer to façade modules that are grouped in different teams according to their physical and their thermal properties (different PCM quality, different ratios between glass and the PCM).

RESPONSIVE FACADE CONCEPT

Responsive envelope concepts are façade design solutions that aim to a balance between optimum interior environmental conditions and environmental performance by reacting in a controlled and holistic manner to changes in external or internal conditions and to occupant intervention. This specific façade concept is based on an integrated multidisciplinary process which optimizes the thermal performance of the system and creates a thermally comfortable environment. This façade concept is based on the use of different kinds of PCMs with different melting temperatures and the adaptive behaviour of the façade according to the external climate conditions. The design is organized in 3 levels: the concept level, the system level and the component level. The first one has to do with the idea behind the façade design. It's the underlying logic, thinking, and reasoning for how the facade is designed. The concept contributes to make choices about the design(PCM materials in the façade, different melting temperatures, adaptive behaviour according to the weather conditions).In next level, it comes the system 's performance. This is a very important step of the design as specific operation parameters should be defined and the thermal performance of the façade should be checked by checking different alternatives with computation tools. Then, it follows the component level that it is relative to the individual parts that constitute the façade. In this specific design we can refer to façade modules that are grouped in different teams according to their physical and their thermal properties(different PCM quality, different ratio between glass and the PCM).

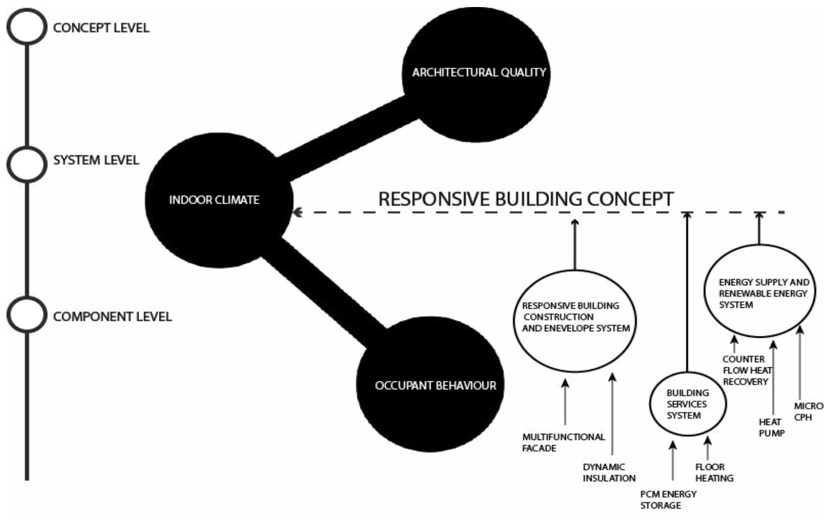


Figure 4.1: Responsive facade concept, image made by the author

The working principle of this PCM façade element is to use the air gap between the two glazed panels (external single glazing with PCM panel, internal double glazing) to reduce the thermal impact of the outdoor environment on the indoor climate conditions.The air gap may use natural ventilation schemes, or simply act as a small air buffer. The figures aside sketches the façade physics, showing the complexity and impact of solar radiation, conduction, convection and air flow through the double-skin gap.

The main functions that should be provided by such a double skin façade are:

•to recover heat during cold seasons and/or to preheat the ventilation air through the cavity,
•to use the energy released by the PCM in the solidification process for passive heating
•to improve the thermal insulation of the glazed system during cold seasons
•to reduce solar loads and enhance natural lighting control without the drawback of increasing the heat gains,
•to extend the use of natural ventilation systems

The double skin façade follows the Box-window (BW) logic as it is divided both vertically and horizontally, forming different " boxes ".

The key principles for the PCM adaptive façade is based on its ability to perform a responsive action based on:

•Dynamic behaviour
•Adaptability
•Capability to perform different functions

The "dynamic" and "adaptable" principles translate into the fact that functions, features and thermo-physical properties of these PCM based façade elements may change over time and suitably fit to different building and occupants requirements or needs (heating/cooling, higher/lower ventilation, etc.) and to different boundary conditions (meteorological, internal heat).The optimum balance between the energy efficiency and the indoor conditions is one of the aims of this façade design. More specifically, this façade concept should goal to high thermal performance of the façade (thermal energy storage, and decreasing heating loads) and pleasant and comfortable indoor environment in the library buildings.

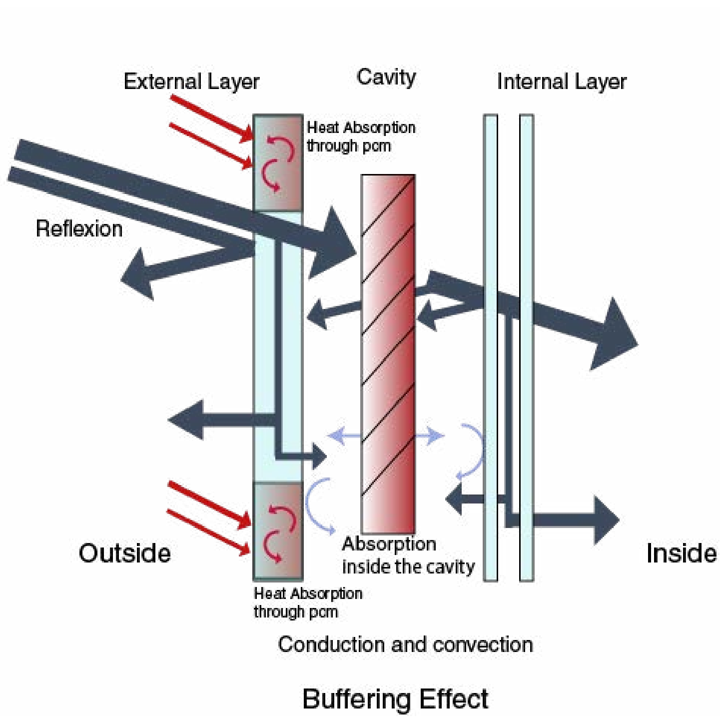


Figure 4.2: Buffering Effect: The facade acting as a buffer system, made by the author

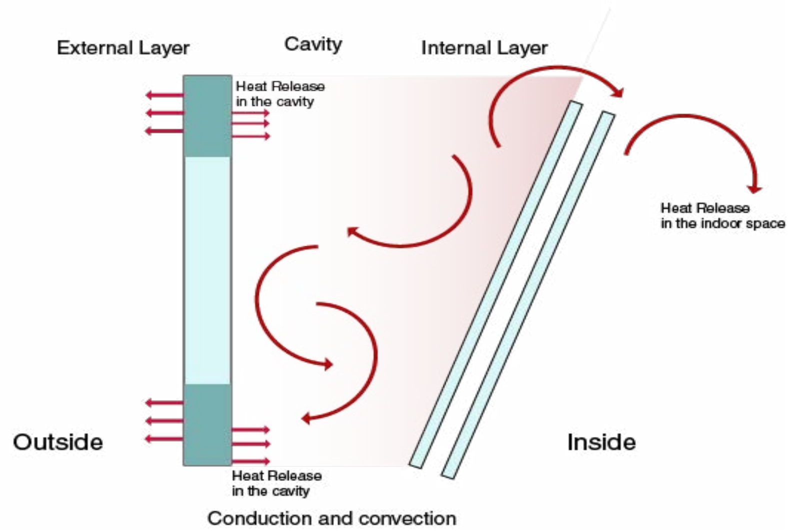


Figure 4.3: Heat release to the interior, made by the author

ADVANTAGES OF AN INTEGRATED FAÇADE CONCEPT|

RESPONSIVE PCM BASED COMPONENTS

The implementation of the responsive façade elements based on the use of phase change materials in the building's envelope has several positive aspects. Facades no longer act as rigid objects that need a large heating installation in winter and big cooling equipment during summer to 'correct' the indoor climate, but buildings become an additional 'living' skin around the occupants keeping them in contact with nature, but at the same me protecting them from extreme weather conditions.

With the integration of responsive façade elements, the indoor environment of the building interacts with the exterior and the building has the ability to store energy, reject the added heat when it is needed and redirect it in the indoor space so as to regulate the thermal comfort. By making use of PCMs in the façade, solar heat can be stored in a passive way when PCMs are in a melting phase and then the heat can be released either to the outside (to avoid overheating during the summer) or to the inside (to provide passive heating during the winter) according to the climate conditions.

• The integration of responsive building elements with energy systems will lead to substantial improvement in operating cost performance as with the use of PCM, the use of mechanical heating and cooling can be decreased.

•It will further enable and enhance the possibilities of passive storage of energy (buffering).

•It will integrate architectural principles into energy efficient building concepts.

•It will enhance the development of new technologies and elements in which multiple functions are combined in the same façade element.

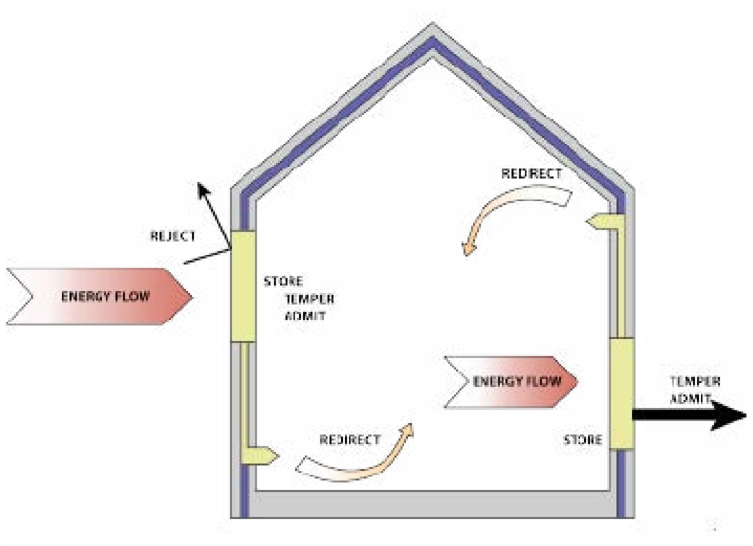


Figure 4.4: Climate responsive facade concept, made by the author

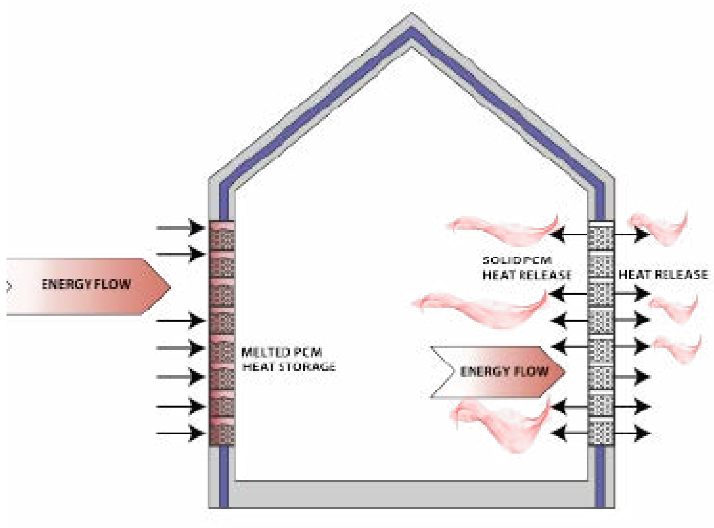


Figure 4.5: Climate responsive facade concept based on PCMs, made by the author

5

design strategies

WEATHER DATA ANALYSIS|AMSTERDAM

In order to define specific design parameters that are going to affect the facade design and make decisions about the PCM combinations that can be used in both locations ,weather data analysis is done for both Amsterdam and Athens. The analysis is done through the software Climate Consultant 6.0.

AMSTERDAM

SOLAR IRRADIATION

The average high solar radiation is seen to peak from the end of February to a maximum of 400 W/m2 during March. After March, there's a slight fall in the solar radiation and is more or less the same during summer and the beginning of autumn where the trend begins to change.

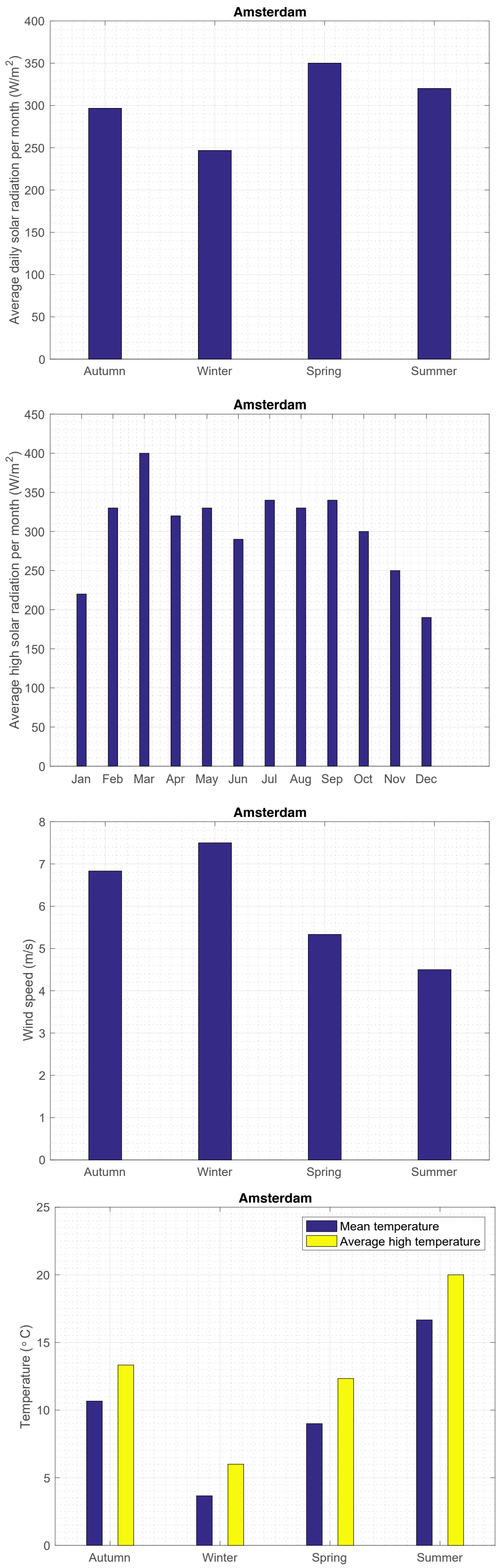
The solar radiation is seen to decline continuously to a low of around 190 W/m^2 in the beginning of winter during December. As far as seasonal variation is concerned, spring and summer are characterised by high levels of solar radiation while autumn and winter are accompanied with moderate and low levels of solar radiation respectively.

WIND SPEED

Wind speeds are high in the Netherlands hitting a peak average of around 7.5 m/s during winter and a low of around 4.5 m/s during summer. Autumn is seen to have significantly large wind speeds compared to spring.

AVERAGE HIGH TEMPERATURE

The mean and mean high temperatures are two significant parameters of temperature. Seasonally speaking, the average high and average temperatures during summer are 20°C and 16.5°C respectively. In the winter, they are 6°C and 3.5°C respectively. Autumn and spring are relatively pleasant and have nearly the same temperature.



Graphs 4.1 (a) to (d): Weather data analysis for Amsterdam from Climate Consultant

ESTIMATION OF APPROPRIATE PCM MELTING TEMPERATURE|

HAND CALCULATIONS

The weather data analysed before can be used in the following equation in order to calculate the temperature of the facade undergoing different weather conditions(different level of solar irradiation, different wind speedn different air temperature).This will give the designer a feedback on which PCM melting temperatures can be used according the climate of the area.The equation is:

$$T_{surf} = \frac{T_{out} + (\alpha_{pcm} * q_{sol})}{\alpha_e} \qquad (1)$$

where:

T_{out} the external air temperaure (^{0}C)

T_{surf} the temperature of the facade(^{0}C)

q_{sol} the solar irradiation(W/m^2)

α_e is the heat transfer coefficent that can change with the winter speed as it is shown in the next equation:

Convective heat transfer coefficient

$$q_{conv} = \alpha_{conv} (T_{surface} - T_{air})$$

$$\alpha_e = \alpha_{conv} \text{ [W/m}^2\text{K]}$$

e.g. α_{conv} = 5,8 + 4 . v (v = 1 to 5 m/s)

α_{conv} = 7,1 v (v > 5 m/s) forced convection

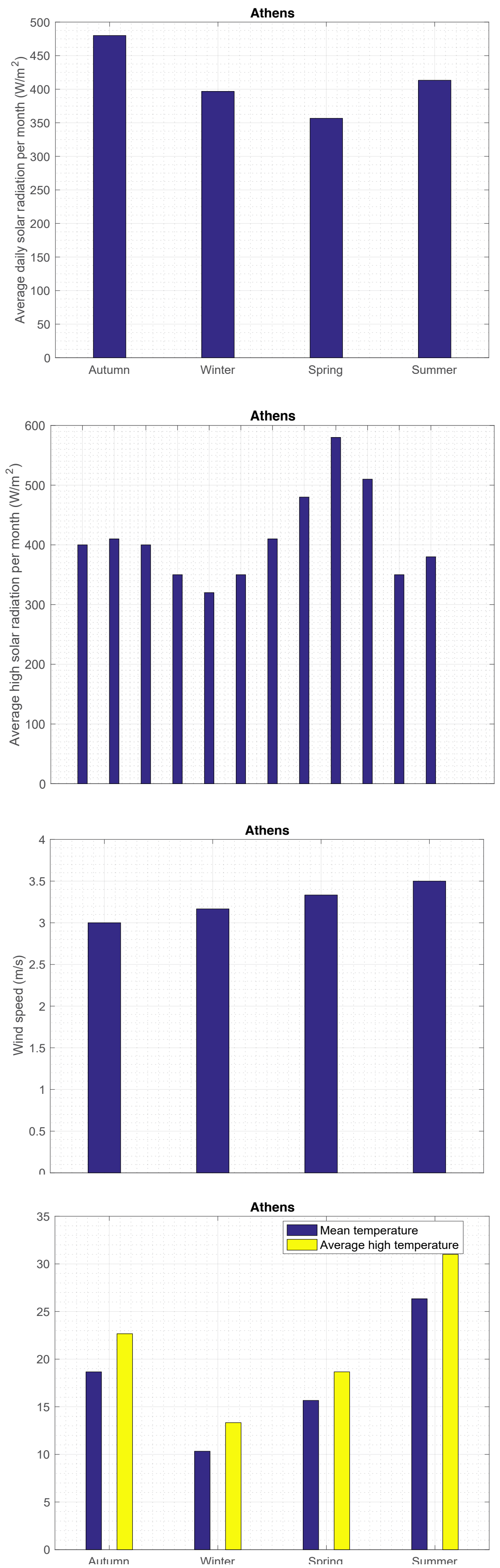
Amsterdam				
South façade				
	Winter	Spring	Summer	Autumn
q_{sol} (W/m^2)	137	108	99.31	142
wind speed (m/sec)	7.5	5	4.5	7
T_{out1}(^{0}C)	4	19	32	19
α_l	0.63	0.63	0.63	0.63
T_{out2}(^{0}C)	-1	10	19	11
α_{SOLID}	0.97	0.97	0.97	0.97
α_e	25	25	25	25
T_{surf1}(^{0}C)	7.45	21.72	34.50	22.58
T_{surf2}(^{0}C)	4.32	14.19	22.85	16.51
Melting Temperatures		11, 21, 25	11, 21, 29	

Table 4.1: Estimation of melting temperature (Amsterdam); made by the author

According to the tabular data and the hand calculations the combinations of PCMs that can be used effectively in the facade in Amsterdam are SP11, SP21, SP25 and SP11, SP21, SP29 respectively.

WEATHER DATA ANALYSIS| ATHENS

SOLAR IRRADIATION
The average high solar radiation is seen to peak from the beginning of May to a maximum of 580 W/m^2 during September. After reaching this peak, there's a gradual decline in the solar radiation and drops to a low of around 380 W/m^2 in November before beginning to increase gradually in December. In general, Athens is characterised by really high solar radiation with the highest amount in autumn and summer.
WIND SPEED
Wind speeds are moderate in Athens hitting a peak average of around 3.5 m/s during summer and a low of 3 m/s during autumn, clearly not much of a difference.
AVERAGE HIGH TEMPERATURE
The mean and mean high temperatures are high during all seasons except during winter, which is pleasant. The average high and average temperatures peak to 31°C and 26°C respectively. In the winter, they are 13°C and 10°C respectively. Autumn and spring are relatively pleasant.



Graphs 4.2 (a) to (d): Weather data analysis for Athens from Climate Consultant 6.0

ESTIMATION OF APPROPRIATE PCM MELTING TEMPERATURE| HAND CALCULATIONS

Th equation 1 is used again in order to calculate the surface temperature of the PCM based panels.The results are shown in the following table. The calculated temperatures are higher in Athens than in Amsterdam because the solar irradiation in Greece is much higher and the wind speed much lower than in Netherlands.

Athens				
South façade				
	Winter	Spring	Summer	Autumn
q_{sol} (W/m^2)	200	400	600	200
wind speed (m/sec)	5	5	5	5
T_{out1} (^{0}C)	6.3	12.7	20.33	14
α_I	0.63	0.63	0.63	0.63
T_{out2} (^{0}C)	1.3	5	12.3	7.7
α_{SOLID}	0.97	0.97	0.97	0.97
α_e	25.6	25.6	25.6	25.6
T_{surf1} (^{0}C)	11.22	22.54	35.10	18.92
T_{surf2} (^{0}C)	8.88	20.16	35.03	6.33
Melting Temperatures (^{0}C)		21, 25, 29	21, 25, 31	

able 4.2: Estimation of melting temperature (Athens); made by the author

According to the tabular data and the hand calculations the combinations of PCMs that can be used effectively in the facade in Amsterdam are SP21, SP25, SP29 and SP21, SP25, SP31 respectively.

ESTIMATION OF PCM THICKNESS|STORAGE HEAT CAPACITY AND SOLAR IRRADIATION

AMSTERDAM

In order to calculate the thickness of the PCM that can be used in the facade panels in Amsterdam, the solar irradiation, the density and the heat storage capacity of the material play an important role(show the table).
From the tabular data, it is shown that for 3 different PCMs the thickness should be around 0.03m.

PCM Melting Area 21 ^{0}C	Amsterdam	
Density Liquid kg/l	1.4	
Density Solid kg/l	1.5	
Average Density kg/l	1.45	
Heat Storage KJ/kg	170	
Average Solar Irradiation	2.01	7236
	KWh/m2	KJ/m2
Solar Irradiation/Heat Storage of PCM		42.56
Density (kg/m^3)	1450	
PCM Thickness(m)	(Solar Irradiation/Heat storage)/Density	
	0.029	3 cm

PCM Melting Area 25 ^{0}C	Amsterdam	
Density Liquid kg/l	1.4	
Density Solid kg/l	1.5	
Average Density kg/l	1.45	
Heat Storage KJ/kg	180	
Average Solar Irradiation	2.01	7236
	KWh/m2	KJ/m2
Solar Irradiation/Heat Storage of PCM		40.2
Density(kg/m^3)	1450	
PCM Thickness(m)	(Solar Irradiation/Heat storage)/Density	
	0.028	3 cm

PCM Melting Area 31 ^{0}C	Amsterdam	
Density Liquid kg/l	1.4	
Density Solid kg/l	1.5	
Average Density kg/l	1.45	
Heat Storage KJ/kg	180	
Average Solar Irradiation	2.01	7236
Solar Irradiation/Heat Storage of PCM		40.2
Density(kg/m^3)	1350	
PCM Thickness(m)	(Solar Irradiation/Heat storage)/Density	
	0.03	3 cm

Table 4.3: Estimation of PCM thickness (Amsterdam); made by the author

ATHENS

The same calculations are done also for Athens and they lead to a conclusion that the PCM thickness that can be used is 0.04- 0.045 m(show the tables)

PCM Melting Area 22-23 ^{0}C	Athens	
Density Liquid kg/l	1.4	
Density Solid kg/l	1.5	
Average Density kg/l	1.45	
Heat Storage KJ/kg	170	
Average Solar Irradiation	3	10800
	KWh/m2	KJ/m2
Solar Irradiation/Heat Storage of PCM		63.53
Density (kg/m^3)	1450	
PCM Thickness(m)	(Solar Irradiation/Heat storage)/Density	
	0.044	4.5 cm

PCM Melting Area 25 ^{0}C	Athens	
Density Liquid kg/l	1.4	
Density Solid kg/l	1.5	
Average Density kg/l	1.45	
Heat Storage KJ/kg	180	
Average Solar Irradiation	3	10800
	KWh/m2	KJ/m2
Solar Irradiation/Heat Storage of PCM		60
Density(kg/m^3)	1450	
PCM Thickness(m)	(Solar Irradiation/Heat storage)/Density	
	0.041	4 cm

PCM Melting Area 31 ^{0}C	Athens	
Density Liquid kg/l	1.4	
Density Solid kg/l	1.5	
Average Density kg/l	1.45	
Heat Storage KJ/kg	180	
Average Solar Irradiation	3	10800
	KWh/m2	KJ/m2
Solar Irradiation/Heat Storage of PCM		60
Density(kg/m^3)	1350	
PCM Thickness(m)	(Solar Irradiation/Heat storage)/Density	
	0.044	4.4 cm

Table 4.4: Estimation of PCM thickness (Athens); made by the author

DISCUSSION

In order a facade designer to have a general insight of the PCM types that can integrate in the facade, he/she should make a weather data analysis, checking for the solar irradiation, the air temperatures per season, the wind speed of the area where the facade system will be applied. The thickness of the material is a parameter that can change and become larger in case of intense solar irradiation (mediterranean climates) and lower when the wind speed is quite high and the air temperature and the solar iradiation in a lower level.

The wind speed affects the heat transfer coefficient and consequently the surface temperature of the panel. A low wind speed corresponds to a higher surface temperature. Greater the incoming solar radiation, greater is the rise in surface temperature. And lastly, greater the ambient temperature, higher is the surface temperature of the panel.

Moreover, the storage capacity of the PCM along with the solar iradiation and the density of the PCM used can change the thickness of the material.

THE STUDY CASE| SILENT ROOM_TUDELFT LIBRARY

The study case in which the facade design will be applied is the studying area of TU Delft library. However, the space is not exactly the same and it is simplified in terms of geometry as it is shown in the following drawings.The ground floor of the room consists of an open studying area and a smaller enclosed area.The first floor has a useful area which is above the enclosed room and it is again an open studing area.The overall height is 8.40 m , length 52.80 m and depth 12.50 m.

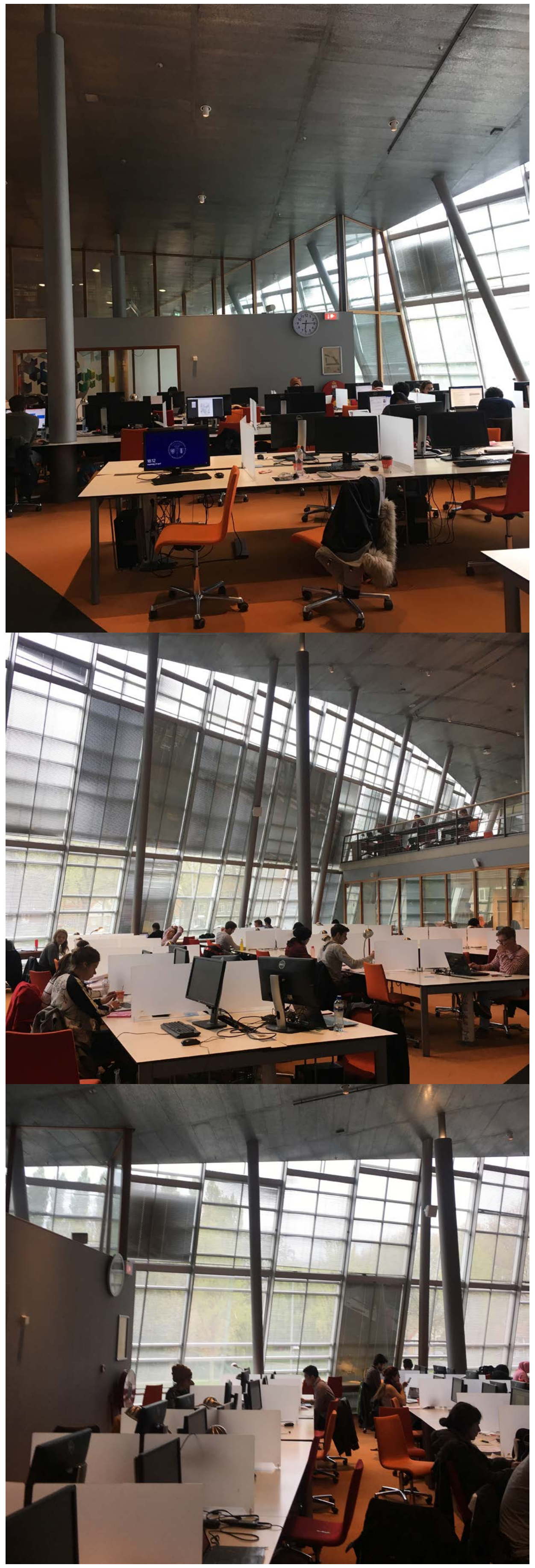
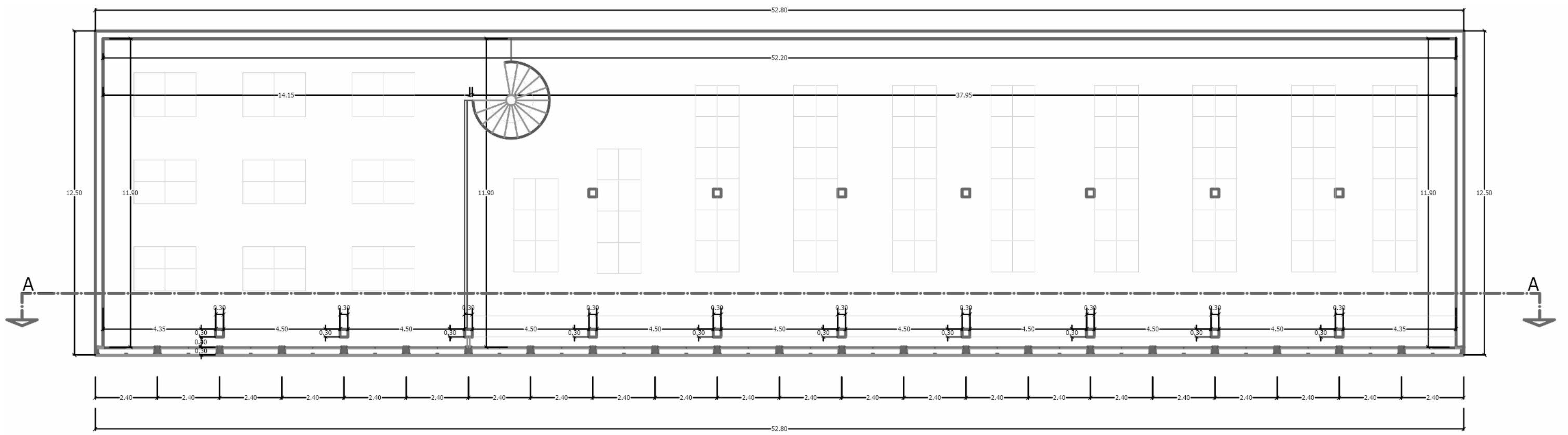
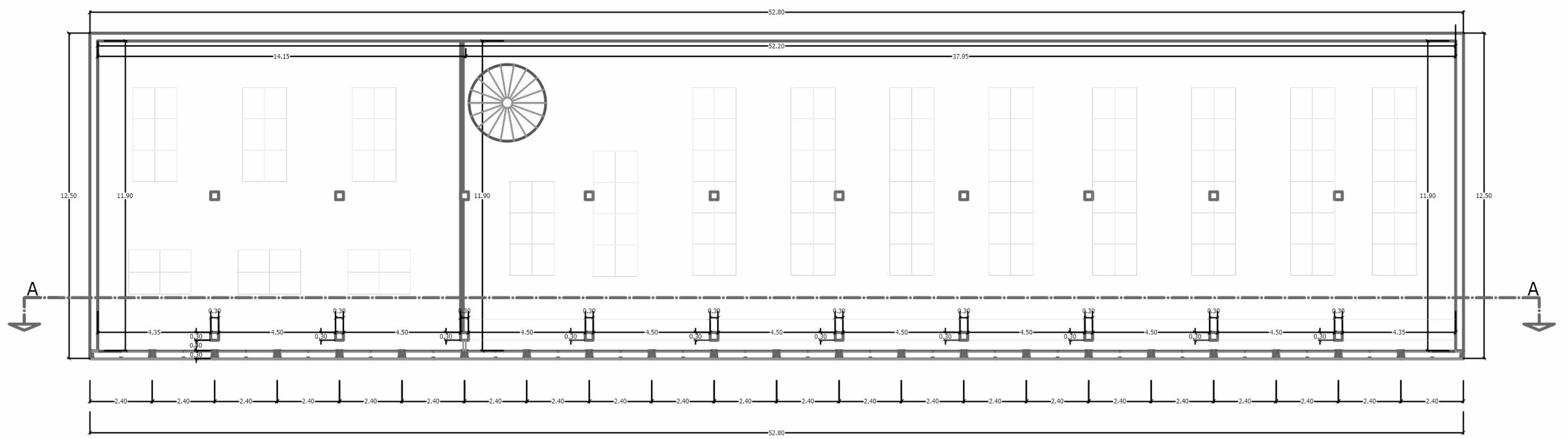


Figure 4.1: The indoor space of the Silent Room_TU Delft Library, picture taken by the author

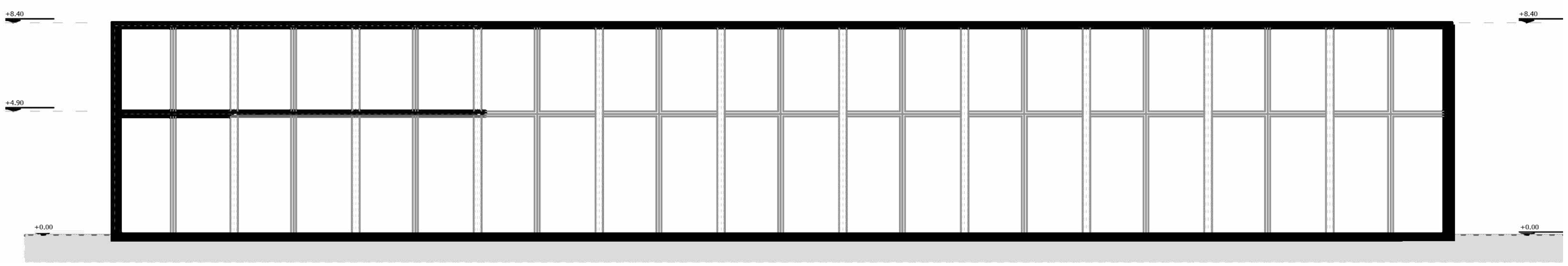
THE STUDY CASE|DRAWINGS (SIMPLIFIED VERSION)



FIRST FLOOR PLAN
SCALE 1:200



GROUND FLOOR PLAN
SCALE 1:200



SECTION A-A
SCALE 1:200

PANEL PLACEMENT | OPTICAL CONTACT WITH THE EXTERIOR

As it is shown from the picture the facade is made out of hexagonal modular units based on PCM and a hexagonal structural grid.There are 4 different types of panels and are placed in the facade in such a way so as to ensure visual comfort.More specifically, the type 0 and 1 which have no or a little glazing are placed in front of the slabs and the columns where there is no need for transparency.On the other hand, the other two types which provide more transparency are placed infront of the working zone area so as to provide to the occupants of the space optical contact with the outside environment.Moreover, above the working area zone , there is the daylight zonewhichialsocoveredwithpanelsthat providemoretransparecysoastoachievegoodlevelsof natural lighting.

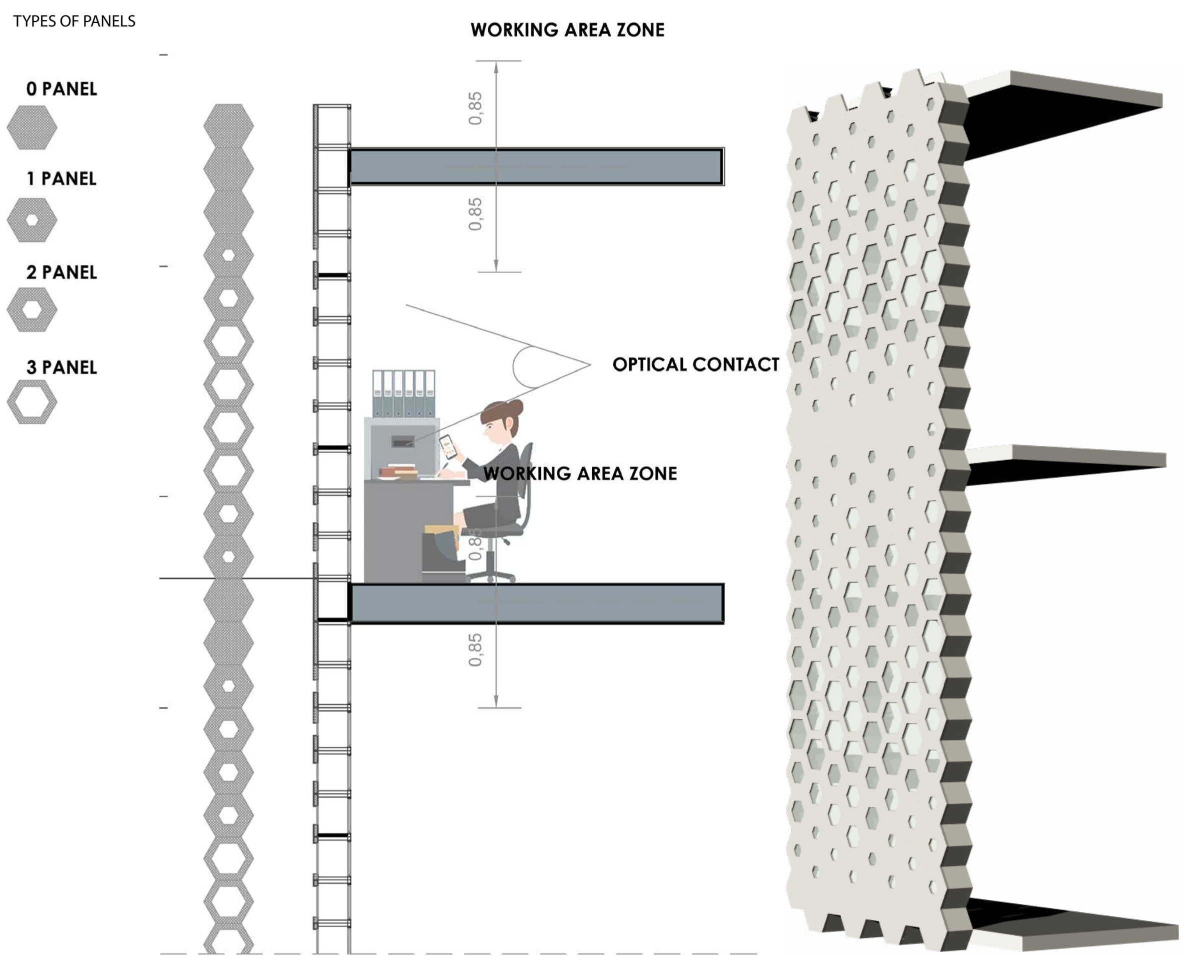


Figure 5.1: The panel placement for optical contact with the exterior; designed by the author

PANEL PLACEMENT | THERMAL COMFORT

The system is composed of modular units, which include x*y panels.As it was discussed before the facade will be composed of different categories of PCMs so as to cover a large number of temperatures in order for the facade system to work efficiently during the whole year.The panels will be grouped in categories A panels , B panels and c panels. Each category will cover one thermal zone as it is shown
in the picture.A starting point is that the panels will be placed starting with the lowest rows where the A panels are placed ,then the B panels and in the top the C panels. It is assumed that the panels with the lowest melting temperature can be placed in the bottom of each floor and the panels with the highest melting temperature in the top. However, such placement and alternative placement ways will be checked later in th Design Software so as to end up in more specific guidlines.

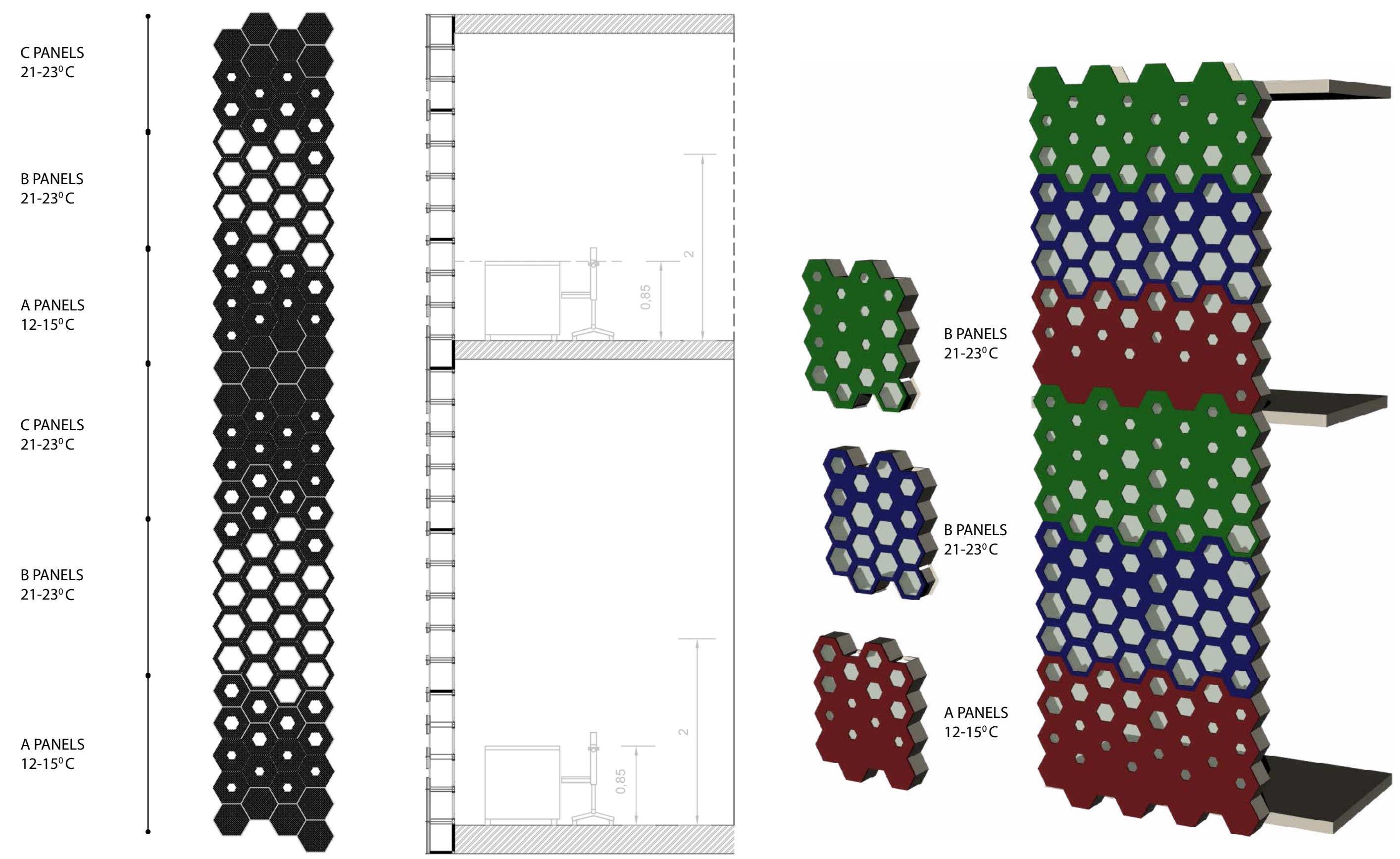


Figure 5.2: Panel placement according to thermal comfort

DESIGN CONCEPT | FIRST LOGIC : MODULAR UNITS PER PANEL

PERSPECTIVE VIEW AND DRAWINGS

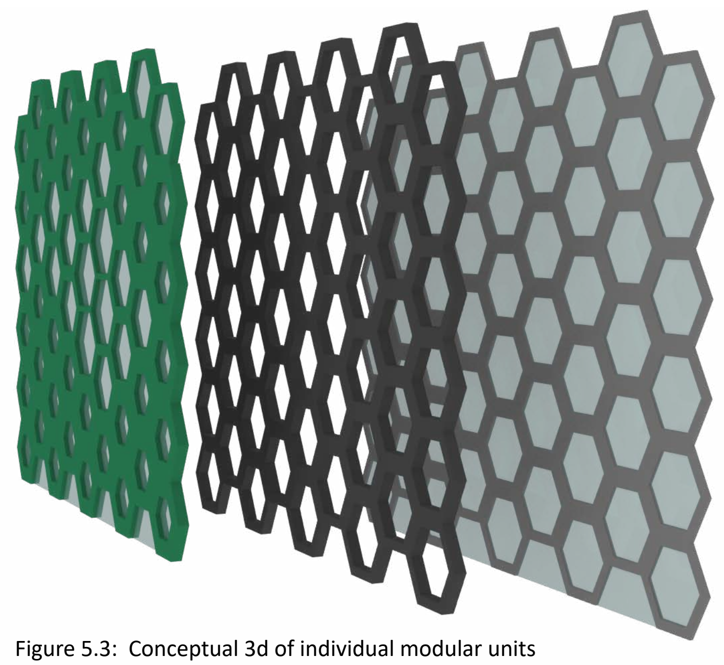


Figure 5.3: Conceptual 3d of individual modular units

1ST LOGIC
EACH MODULE CONTAIN ONE PANEL

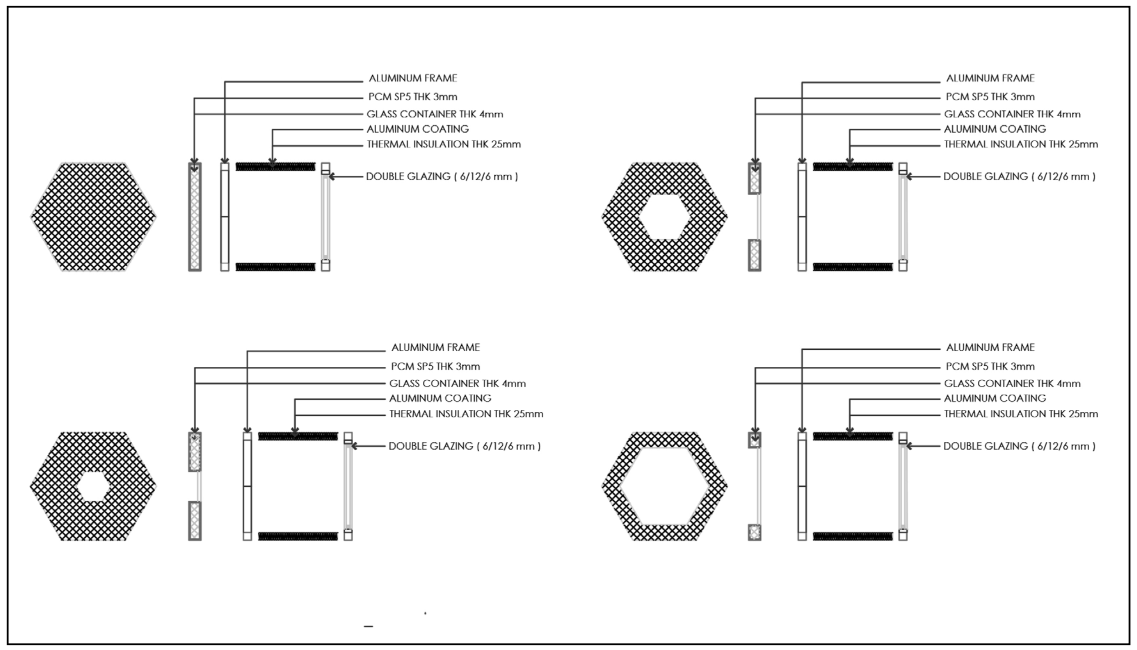


Figure 5.4: An individual modular unit

DESIGN CONCEPT | SECOND LOGIC : MODULAR UNITS PER MULTIPLE PANELS

PERSPECTIVE VIEW AND DRAWINGS

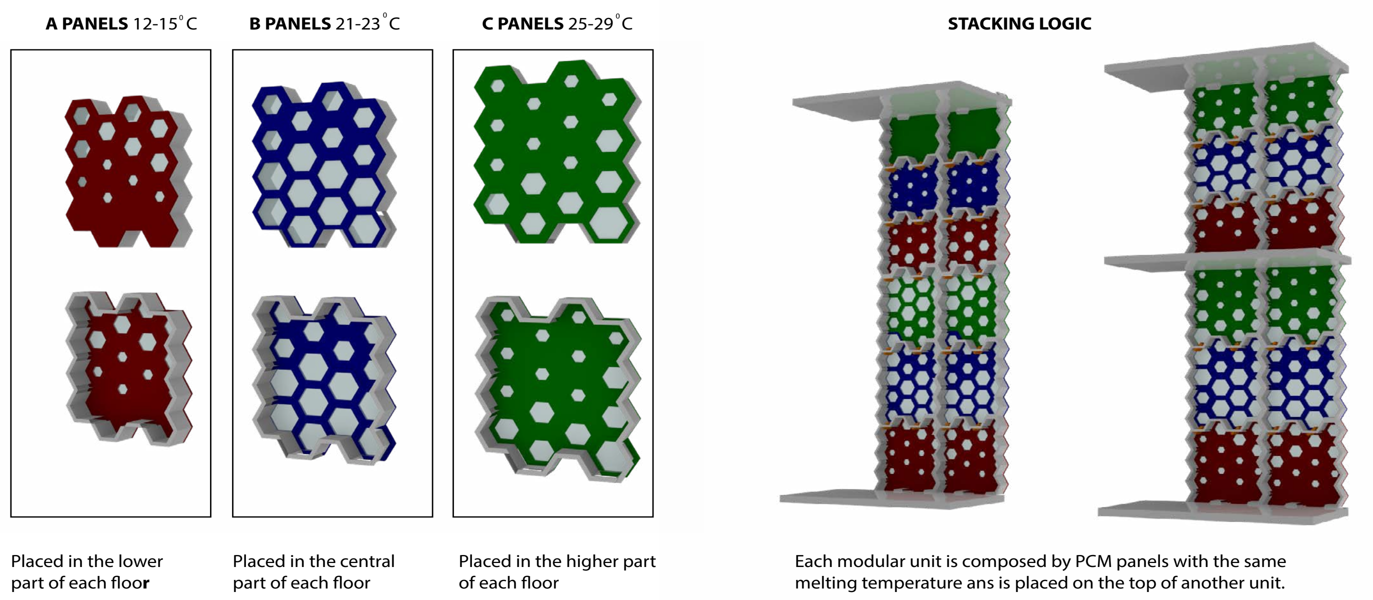


Figure 5.5: Modular units with multiple panels

2ND LOGIC
EACH MODULE CONTAIN MULTIPLE PANELS

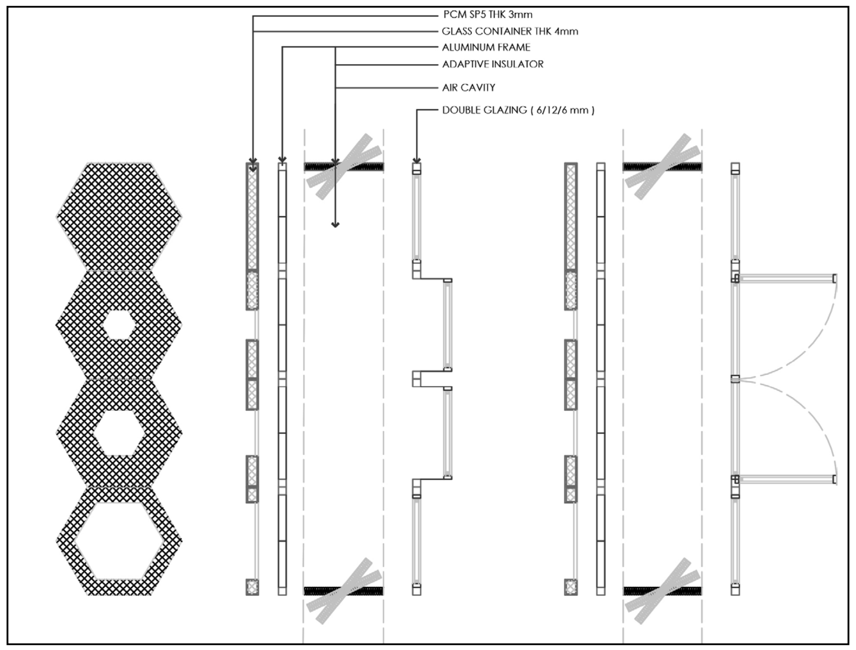


Figure 5.6: A single modular unit with multiple panels

DESIGN CONCEPT | HEXAGONAL VS SQUARE GRID

The initial motivation to use hexagonal grids was based on aesthetics. However, the lack of data on fixed construction details regarding the inter connection of modular units made it difficult to stick to hexagonal grids. Also, hexagons are more complicated in shape and design compared to square grids. For conventional designs such as the latter, the operation windows are easier. Furthermore, the presence of more sides on a hexagon means more connection points, making it a more expensive option. Lastly, the inner layer of the façade is usually not seen with hexagonal double glazed units. These are the reasons why square grids are preferred in façade design.

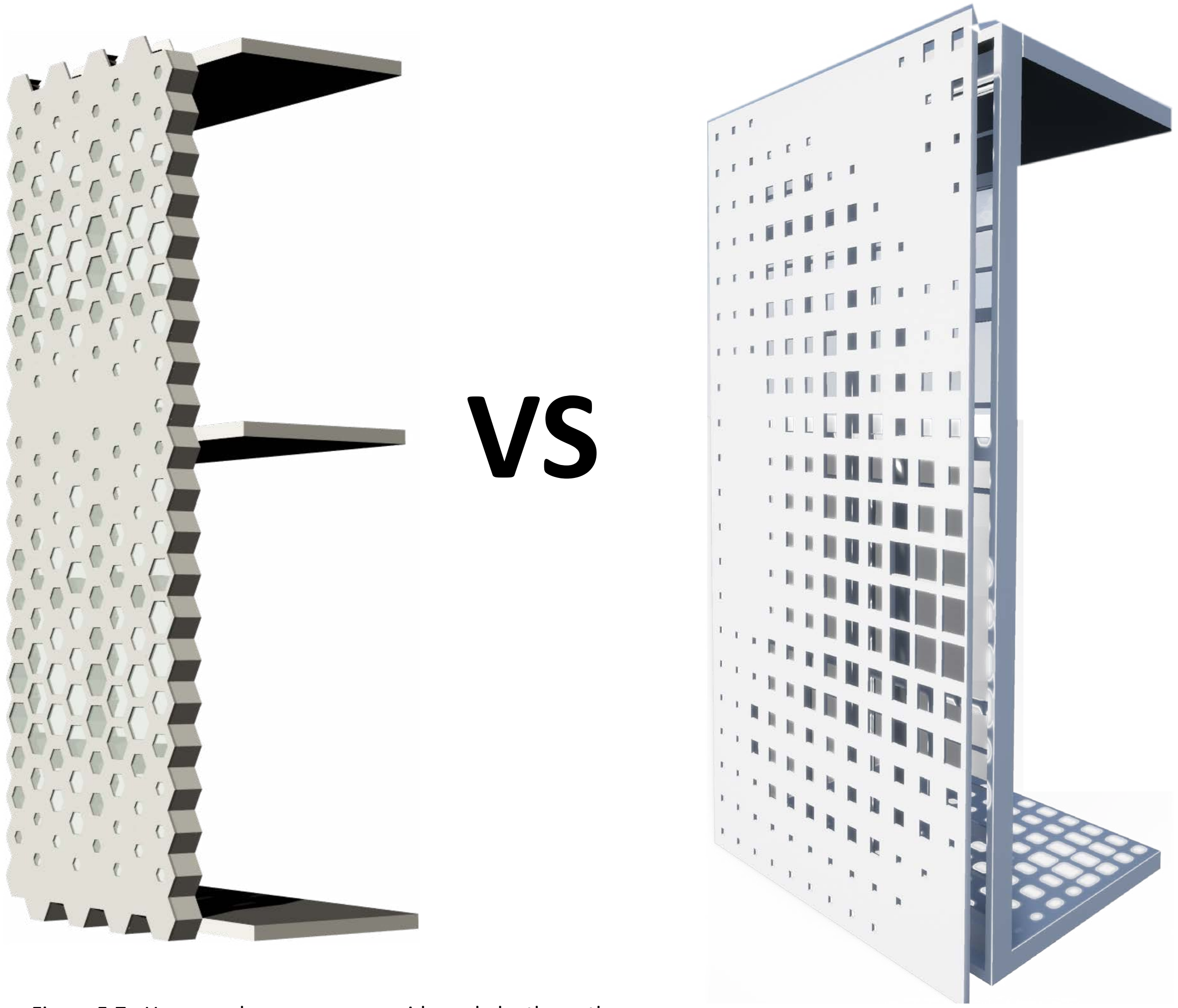


Figure 5.7: Hexagonal versus square grid, made by the author

6

computational design

DESCRIPTION

For the realization of the facade design based on PCM a parametric logic using Rhino along with the grasshopper is applied.The grasshopper definition is used
in order to design the construction components of the facade (main skeleton , window frames, modular units) ,to help the designer experiment with different facade patterns under specific restrictions, to check different facade operations for the external skin of the facade and make calculations for the glazing and the PCM percentage that is used for each design separately.Furthermore, another main function of the grasshopper definition is to separate the facade segment into smaller parts and place into them different PCMs (with different melting temperatures) by grouping the PCM panels into categories .

DIFFERENT COMMAND GROUPS

In this definition there are different groups of commands that facilitate different functions.The groups are separated into 7 categories as it is shown in the following flowchart. Through the command tools they are created different aspects of the facade system:
1) the structure (slabs,columns,main facade frame)
2) internal facade skin
3) Facade pattern
4) external facade skin
5) grouping of the facade into different PCM panel groups
6) creation of modular units
7) glazing/ pcm percentage measurements

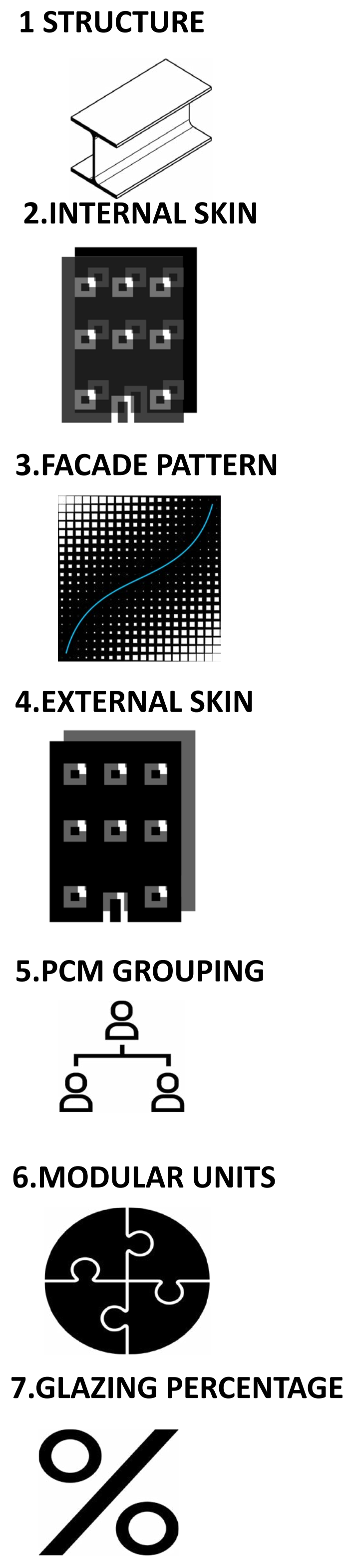
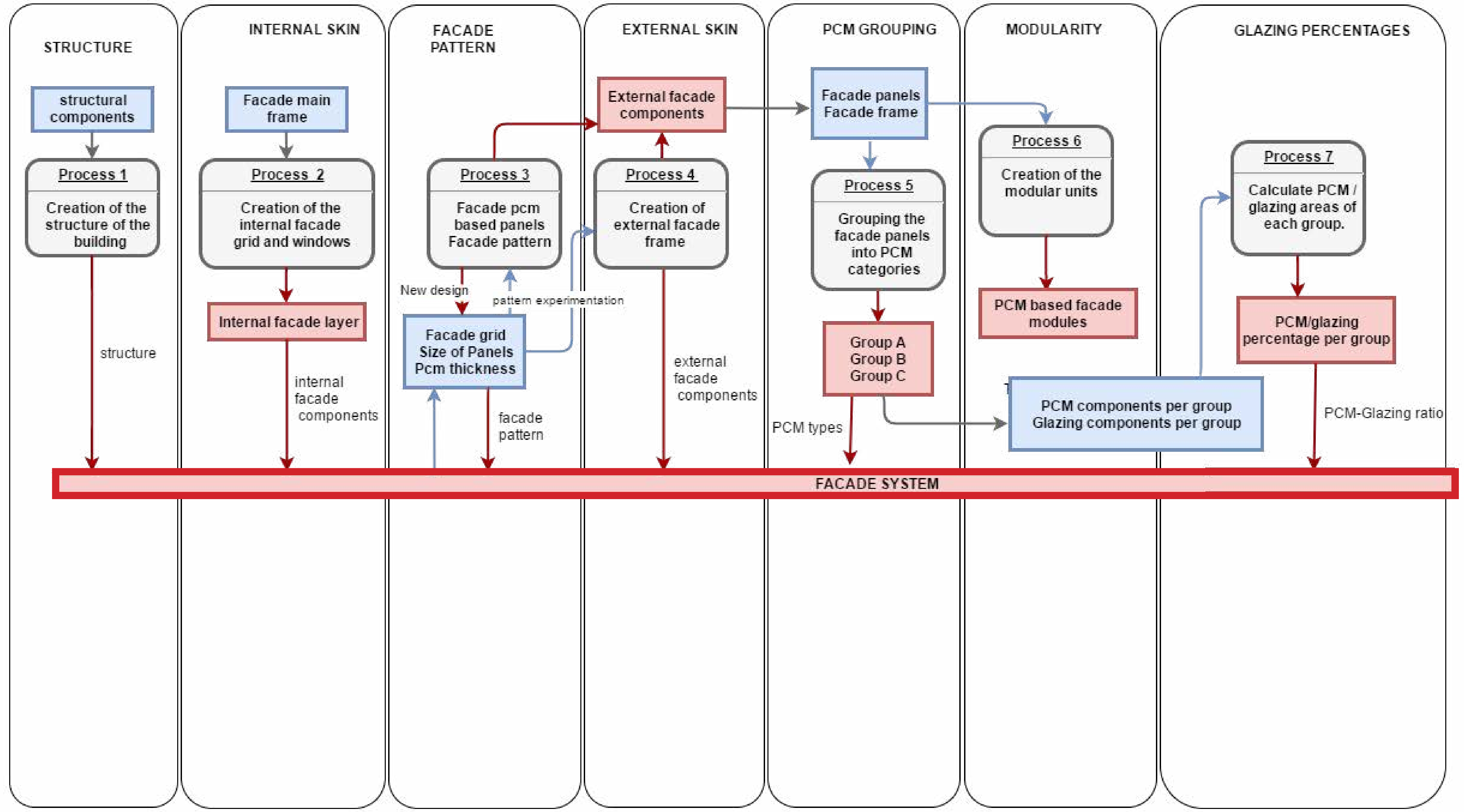


Figure 6.1: Components of the Grasshopper definition of computational design

FLOWCHART: THE GENERAL GRASSHOPPER



Flowchart 6.1: Main commands of the Grasshopper definition of computational design

STRUCTURAL ELEMENTS

In order to create the indoor space of the library, all the structural elements of the building should be added. This is translated to slabs and columns. The columns has a circular cross section with radius 0.2 m and the slabs have thickness of 0.2m.The distance between the columns is 4.8 m.

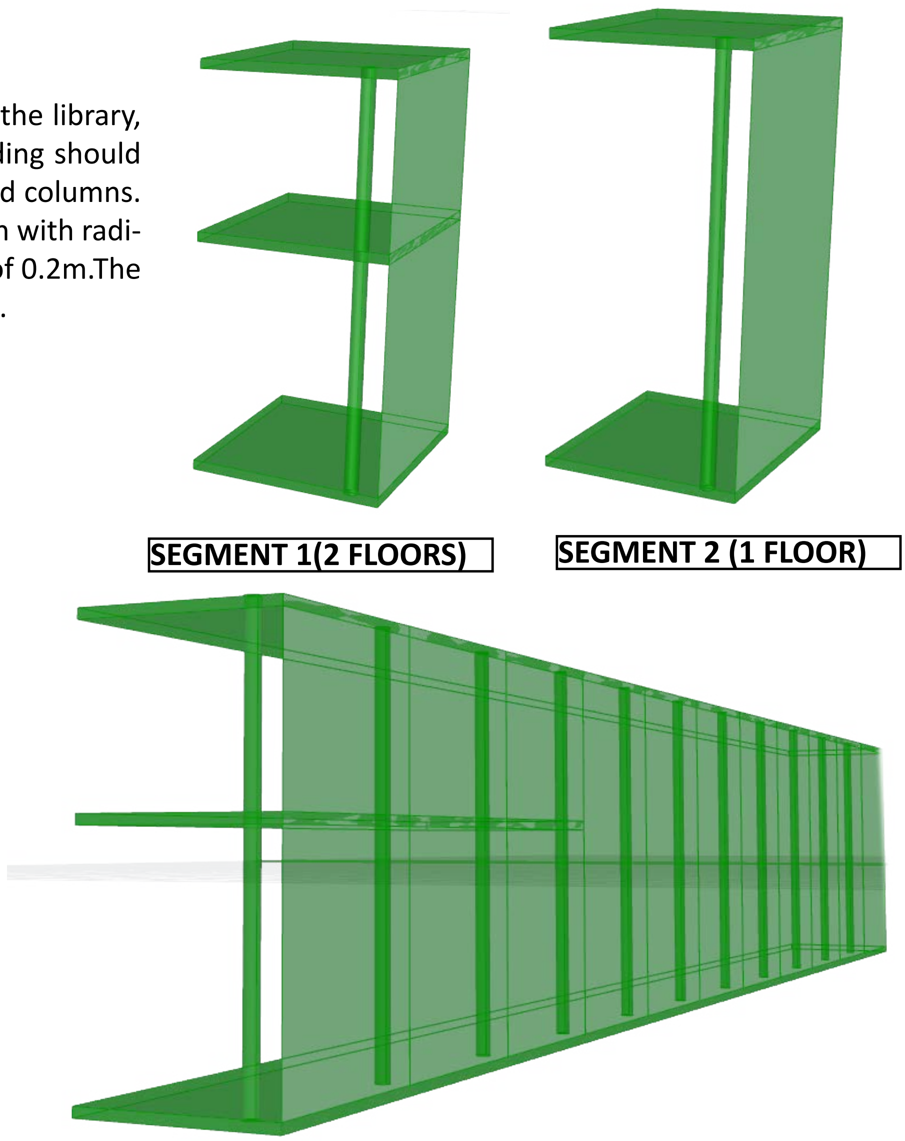
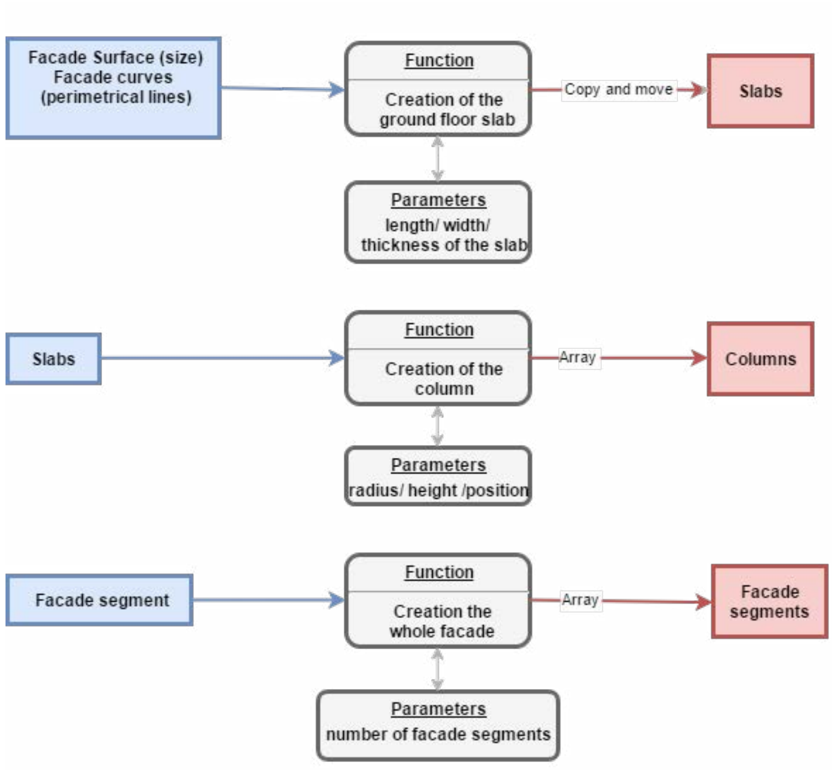


Figure 6.2: Structural components of the system



Flowchart 6.2: Commands leading to the structure of the building

FACADE PATTERN

What is an algorithm?

An algorithm is a procedure used to return a solution to a question - or to perform a particular task - through a finite list of basic and well-defined instructions. Algorithms follow the human aptitude to split a problem into a set of simple steps that can be easily computed, and although they are strongly associated with the computer, algorithms could be defined independently from programming languages. For example, a recipe can be considered as something similar to an algorithm. We can set a procedure for cooking a chocolate cake, based on a simple list of instructions:

1. Mix ingredients
2. Spread in Pan
3. Bake the cake in the oven
4. Remove the cake from oven
5. Cool (Tedeschi,2014)

Like the preparation and the cooking of the chocolate cake is also the algorithm (grasshopper) that is created in order to terminate a specific façade pattern for the PCM based double skin façade. The "ingredients" in this case were all the inputs for the creation of the façade pattern: a) the attractor curve , b) the surface where the pattern will be applied , c) the square grid which is going to be scaled. In order " the mixture of the ingredients" to lead in an ideal result, specific boundary conditions should be applied. The facade pattern was created with the use of a an attractor curve and the basic command of the algorithm is scaling the square cells of the grid. The square cells represent the glazing parts of the façade and the rest is the PCM proportion. The boundary conditions have to do with the distance of the square cells from the attractor curve. When the distance is <= 0.40 m then all the square cells are deleted from the pattern. The closer they are the smaller they are in size. The scaling factors that were used for the façade patterns were different for Greece and Netherlands. However, in both cases specific numbers are applied to the algorithm so as to determine how much the square cells will be scaled or not. After importing the boundary conditions, the façade pattern is already designed and is ready to be "baked" as it happens with the cake. After the baking process, the façade pattern is exported and ready to be used in the envelope's design.

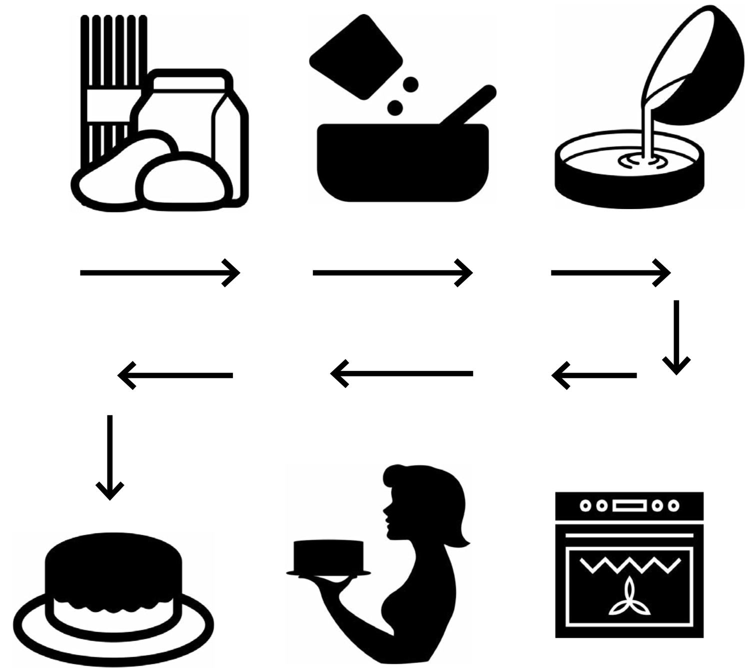


Figure 6.3: Sample algorithm

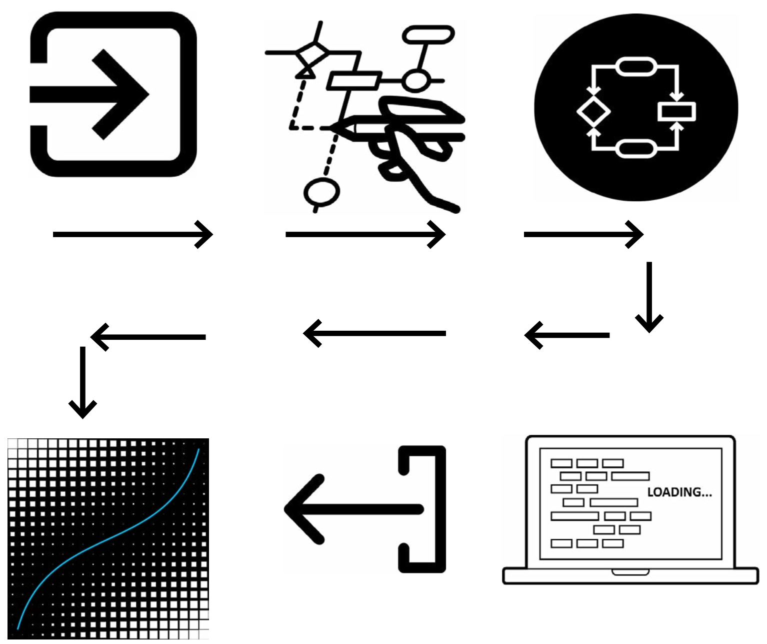
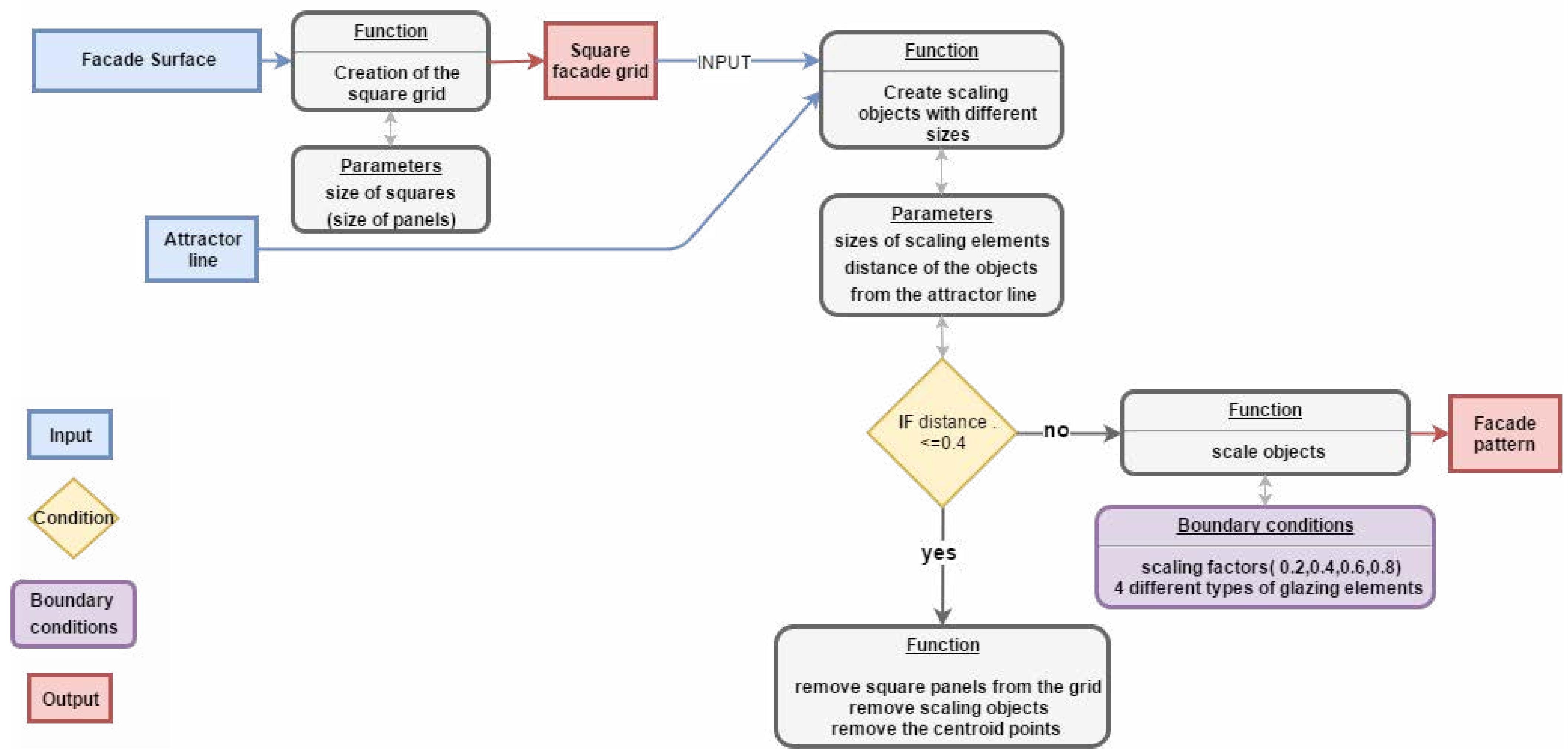


Figure 6.4: Algorithm of the facade pattern

FLOWCHART_FACADE PATTERN (applied in square grid_case Athens)



Flowchart 6.3: Commands leading to the facade pattern for Athens

ATTRACTORS|SET UP OF THE SCALE FACTORS

The component Remap Numbers (Maths > Domain) evaluates a list of numbers ranging from A to B, and resizes them proportionally to a new numeric domain A' to B'. The Remap component requires a list to remap (V= the list of square cells of the grid), a source domain (S), and a target domain (T). The source domain of the numerical sequence can be found using the component Bounds (Maths > Domain), while the target domain is specified using the Construct Domain component. For example, the list of numbers (0.1,0.2,0.3,0.4,0.5,0.6 ,0.7,0.8,0.9,1) can be remapped to a new domain [start domain= 0.2 ,end domain = 0.8], yielding the list of values (0.2,0.3 ,0.4, 0.5,0.6, 0.7, 0.8).All the last numbers are the potential scale factors that can be used for the pattern.

The values used for each façade pattern are affected by the climate of the area. In Greece it is needed 20% of glazing in the façade and as a result some intermediate and some large values of the total list should be erased so as the total area of the scaling objects to be 20%.More specifically, the list of scaling factors used for Athens are (0.2,0.4,0.6,0.8) ,leading to 4 different scaling objects.On the other hand, in Amsterdam it is needed more glazing in the façade in order to be energy efficient.(30%- 40%).This means, that high values as 0.9 or 1 should be included in the new domain and also intermediate values of the list are not needed to be erased. Then, the list of the scaling factors can be (0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1).

CULLING SCALING OBJECTS OUT OF THE DOMAIN LIST

The larger the value is ,the larger glass elements and less PCM proportion in the panel are appeared. However, another design choice is also the usage of panels filled with PCM and with no glazing exactly in the areas where the distance of the scaling square cells is <=0.4.The attractor curve is a variable of the algorithm and its curvature or shape in general can change according to the façade designer. In this case, it is always placed in front of the slabs and the columns and this means that these are the areas where I want to erase the scaling objects of the pattern ,representing the glazing elements of the façade. This happens, as in front of the slabs and the columns less transparency is needed. Taking everything into account the final decision is that in front of the attractor line are not used at all scaling objects(culling objects of the pattern) and near the attractor line the scaling objects with the lower value could be used (little proportion of glazing).This area represents the parapet zone of the façade system and for this reason, no transparency is needed. As for the rest of the panels(larger glazing elements) , they are placed in the working area height till the daylight zone so as to ensure optical contacts of the occupants of the space with the outside and natural daylighting.

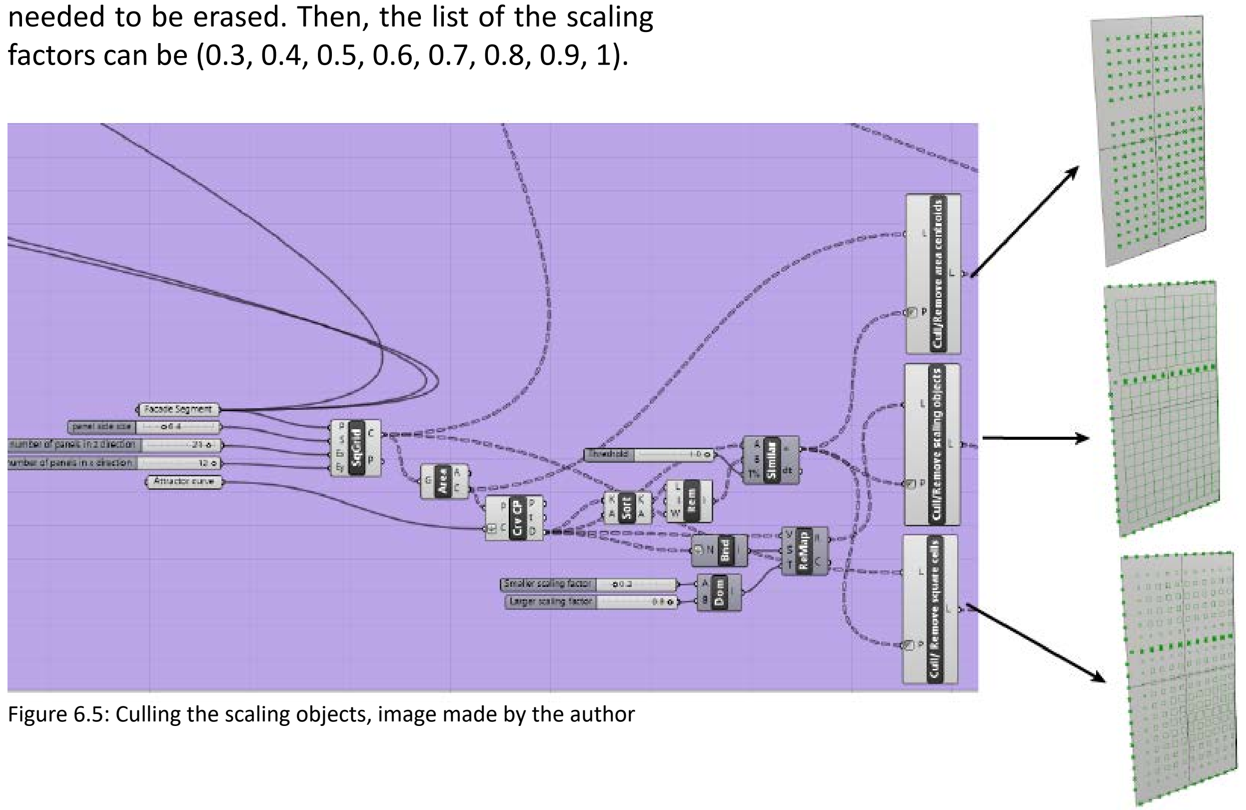


Figure 6.5: Culling the scaling objects, image made by the author

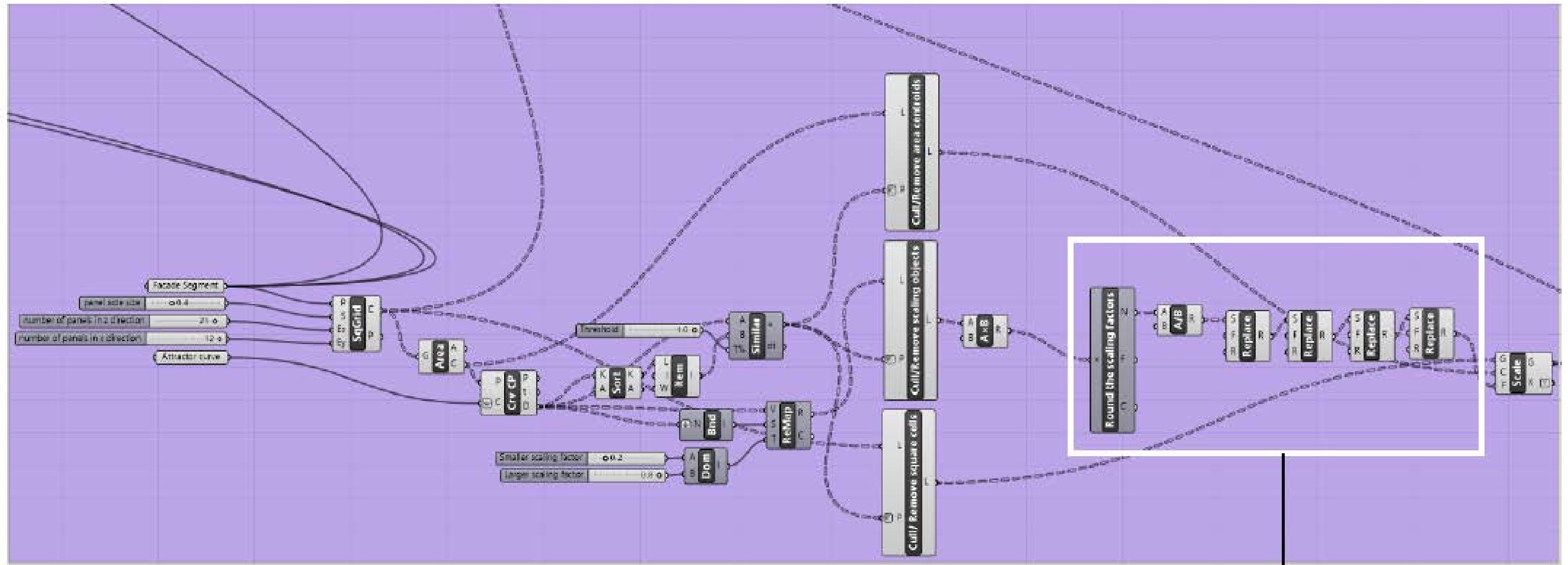


Figure 6.6: Setting up the scaling factors, snapshot taken from the Grasshopper definition

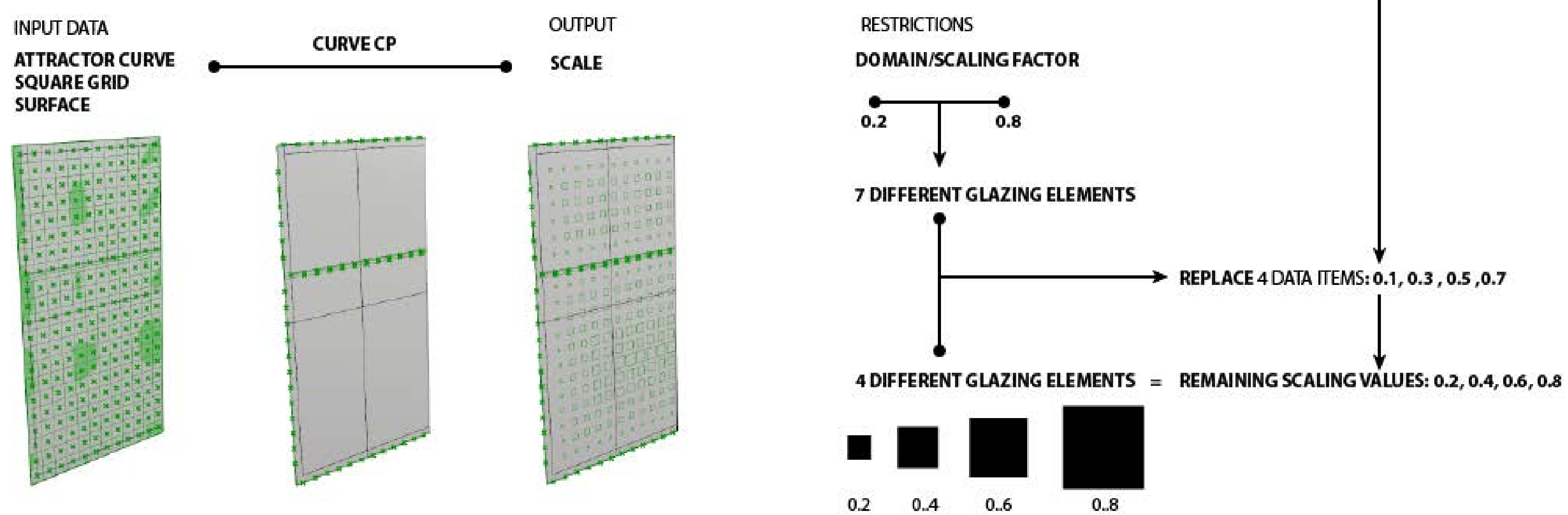


Figure 6.7: Setting up restrictions in the types of panels (Athens case)

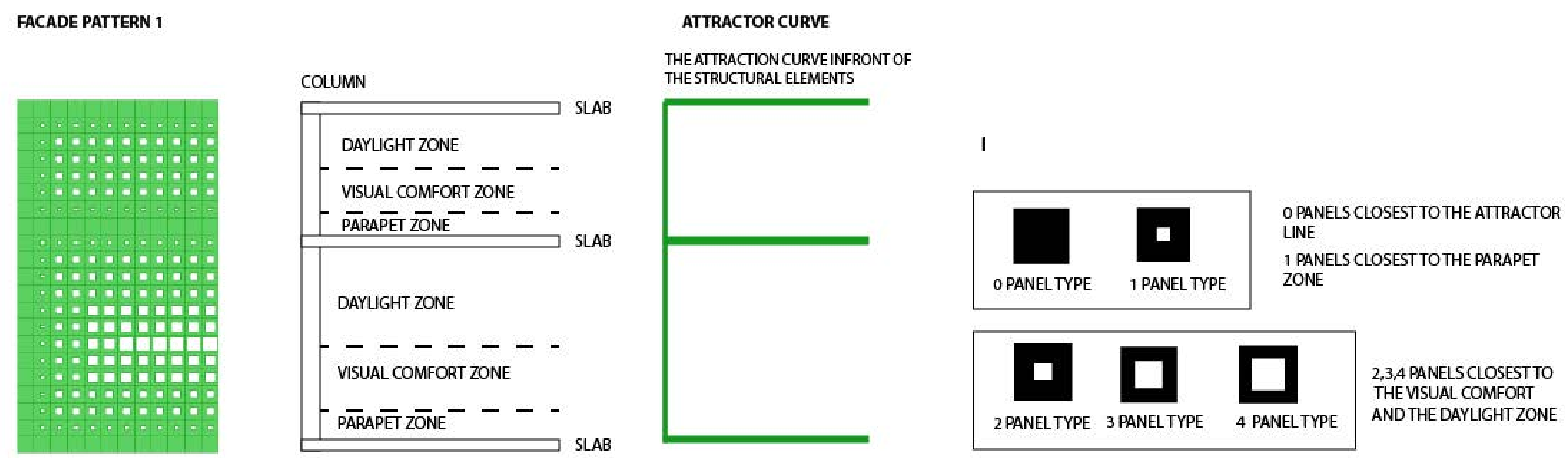


Figure 6.8: Creation of the attractor curve and placement of the panels, based on the optical contact with the exterior space

FACADE COMPONENTS

As it is referred before the façade system is a double skin façade. In the algorithm both the exterior and the interior skin have been designed. The exterior skin is composed of the façade with the parametric pattern (PCM panels with the glazing parts) ,the modular units (consisted of a number of PCM based panels) and their frames. The interior skin is composed by some operable windows and some fixed opening without being able to operate and also the parts where insulation boards are placed (in front of the slabs).The cavity between the two skins is defined with a depth of 0.3 m(this corresponds also to the width of the main frame of the façade. The façade is separated into 11 pieces with areas 4.8* 8.4 m(dimensions of each façade segment).

INNER LAYER

The internal facade layers consists of 3 sublayers : the general unitized system frame of the facade, the large window frames where fixed or operable glazing parts are applied and the series of lamella windows which are operable for natural ventilation.

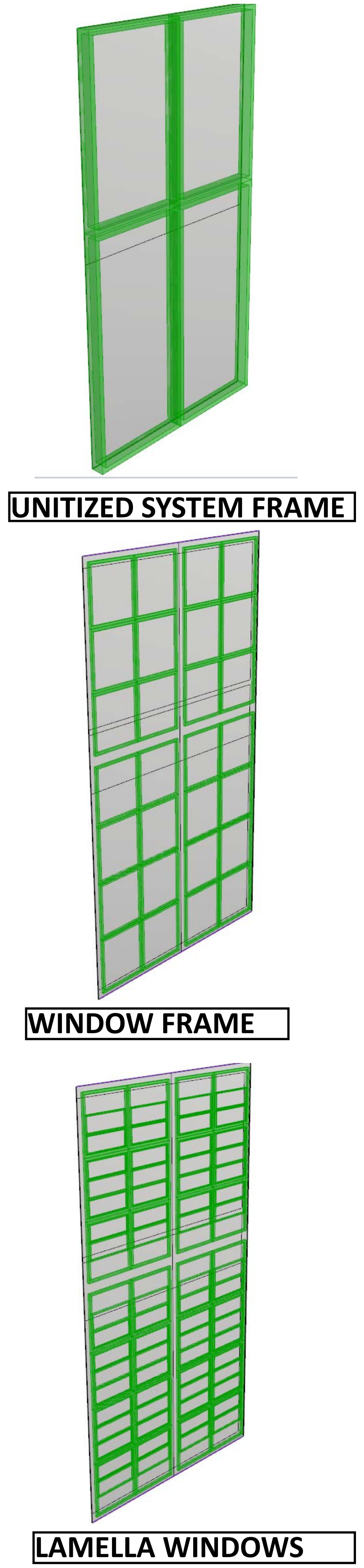
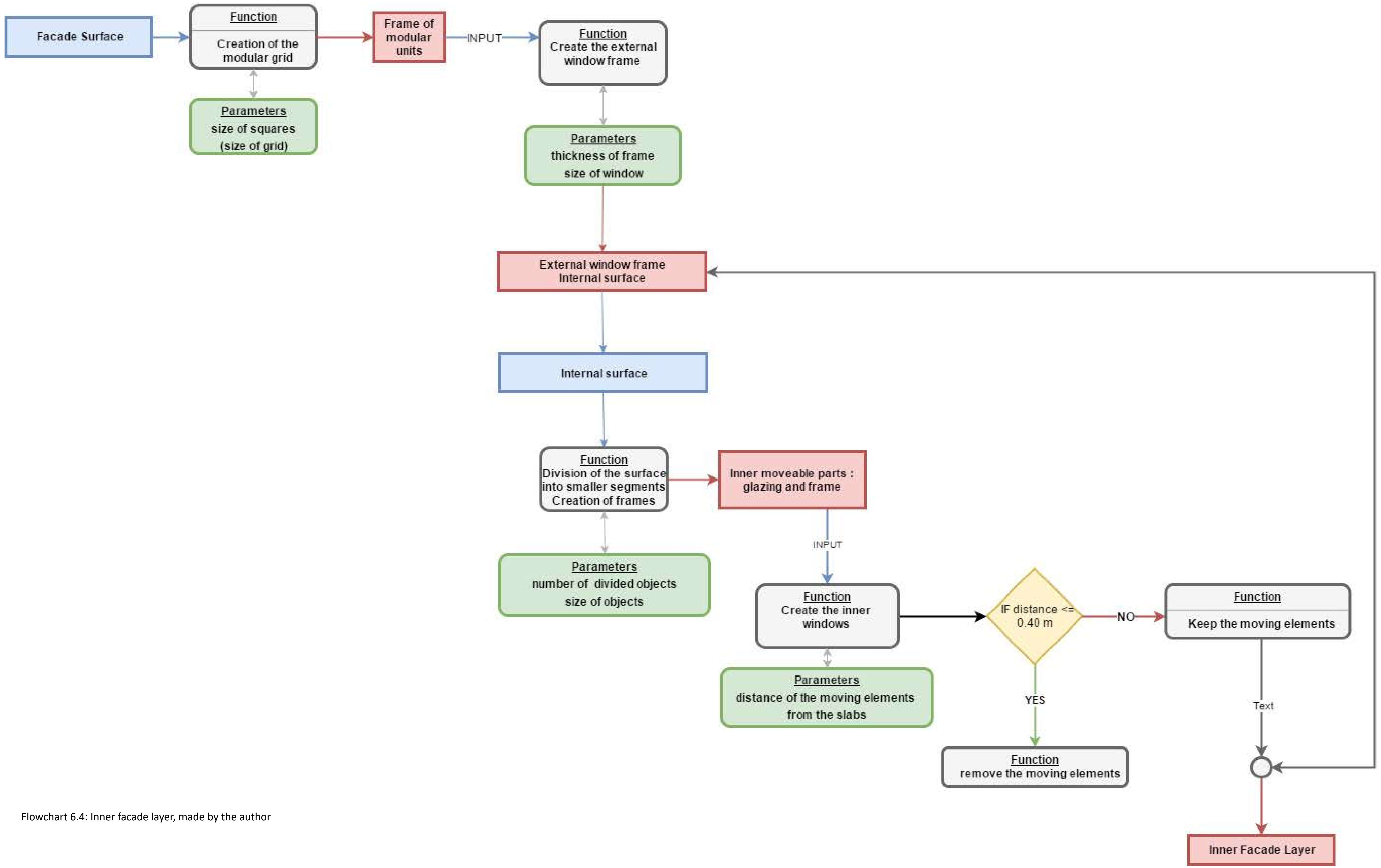


Figure 6.9: The components of the inner facade layer, made by the author

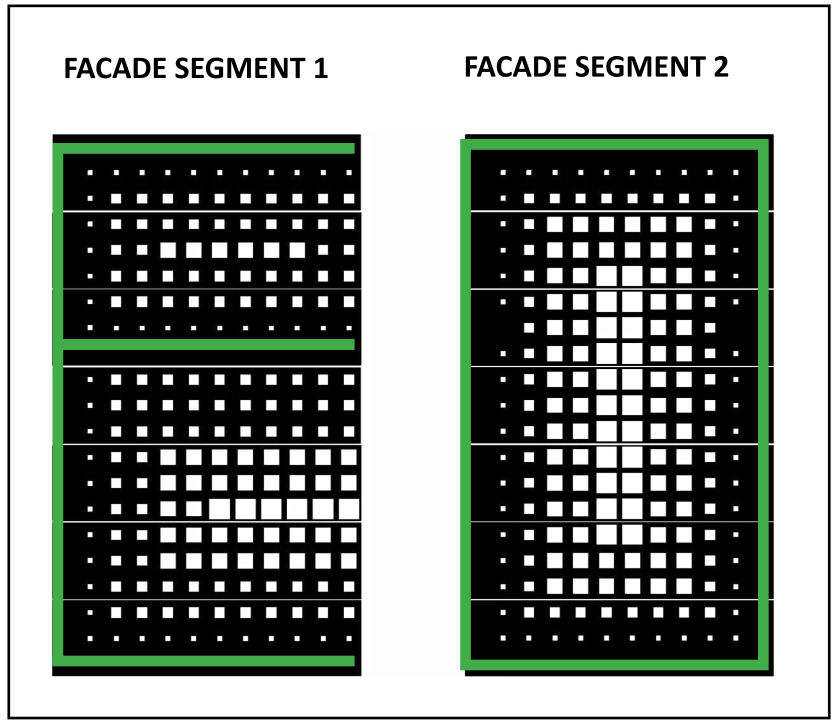
FLOWCHART _INNER FACADE LAYER



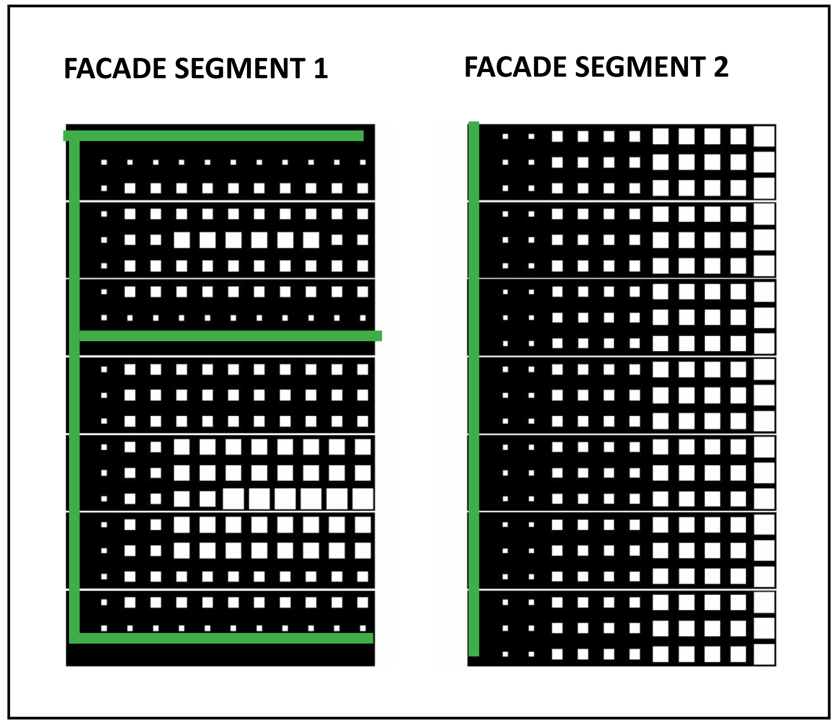
Flowchart 6.4: Inner facade layer, made by the author

FACADE PATTERN | ALTERNATIVE DESIGNS

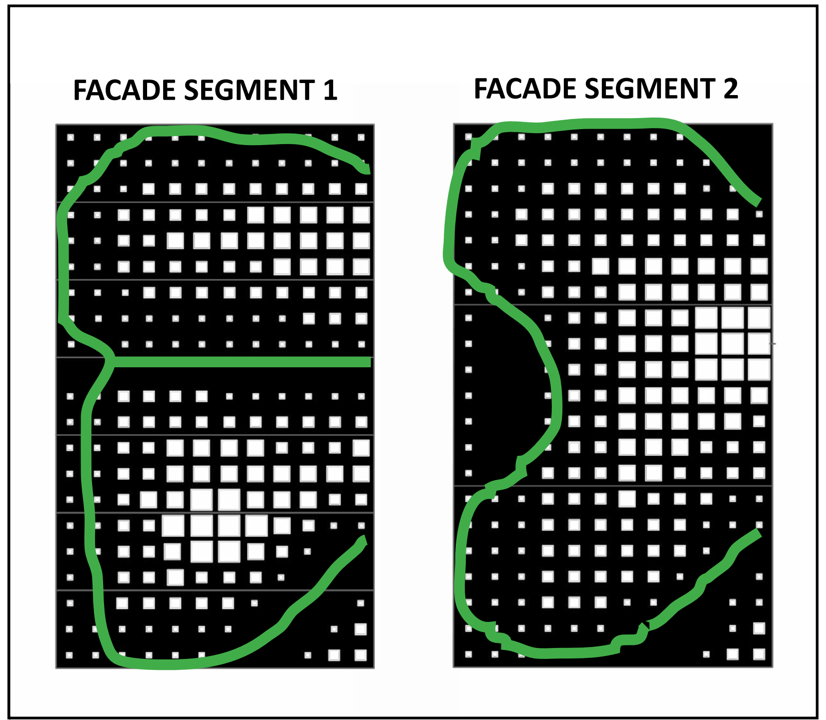
ATHENS



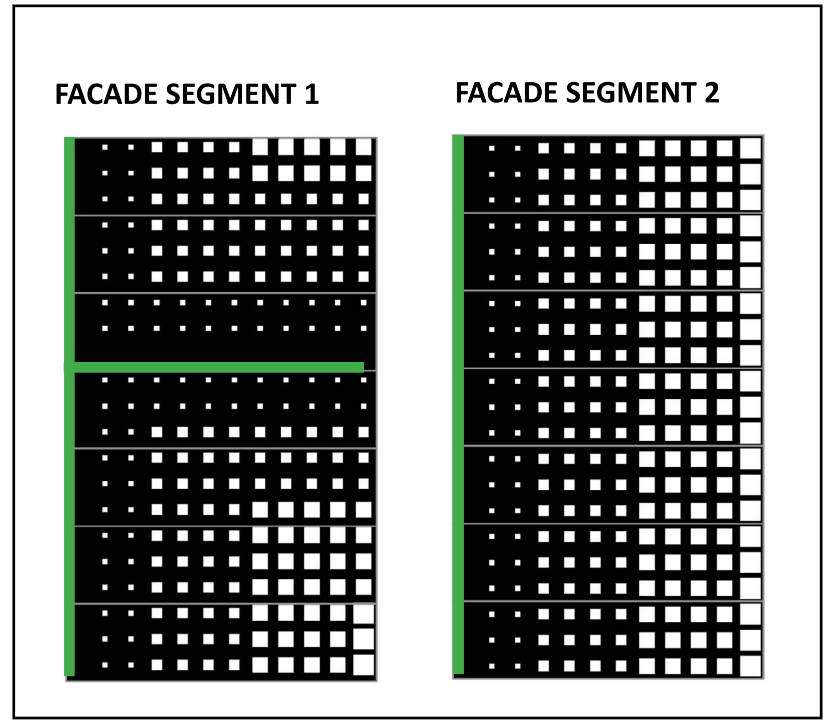
FACADE PATTERN 1



FACADE PATTERN 2



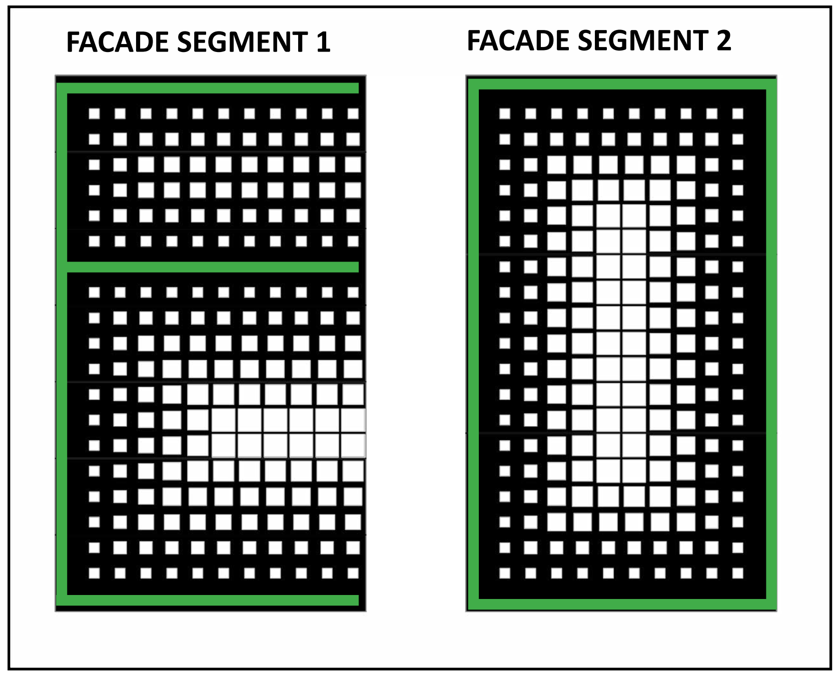
FACADE PATTERN 3



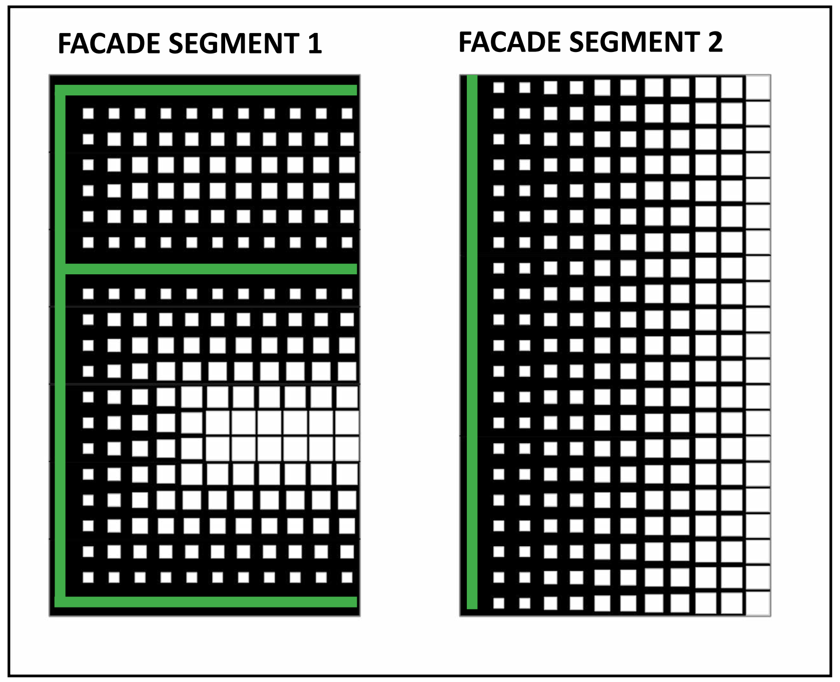
FACADE PATTERN 4

Figure 6.10: Facade patterns for Athens, made by the author

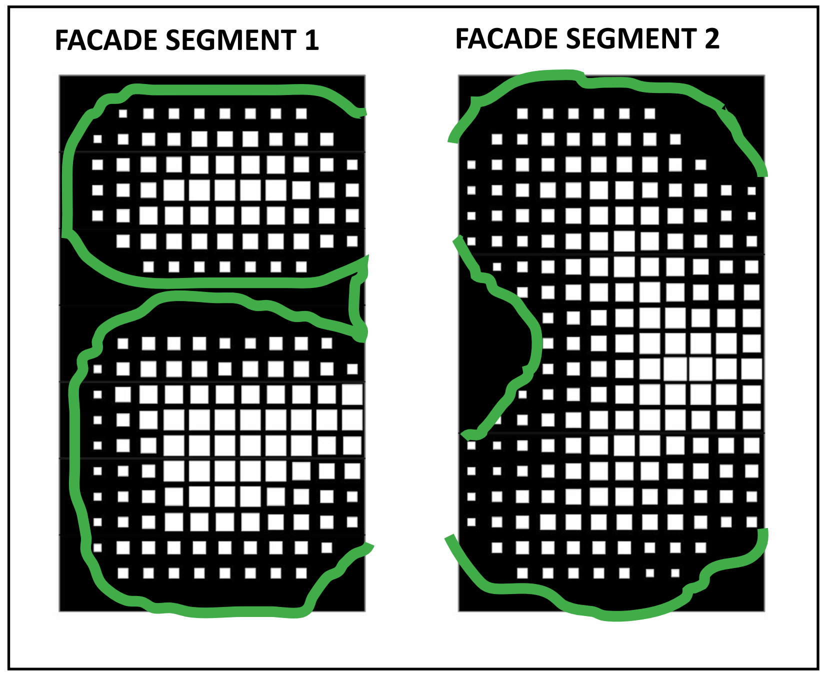
AMSTERDAM



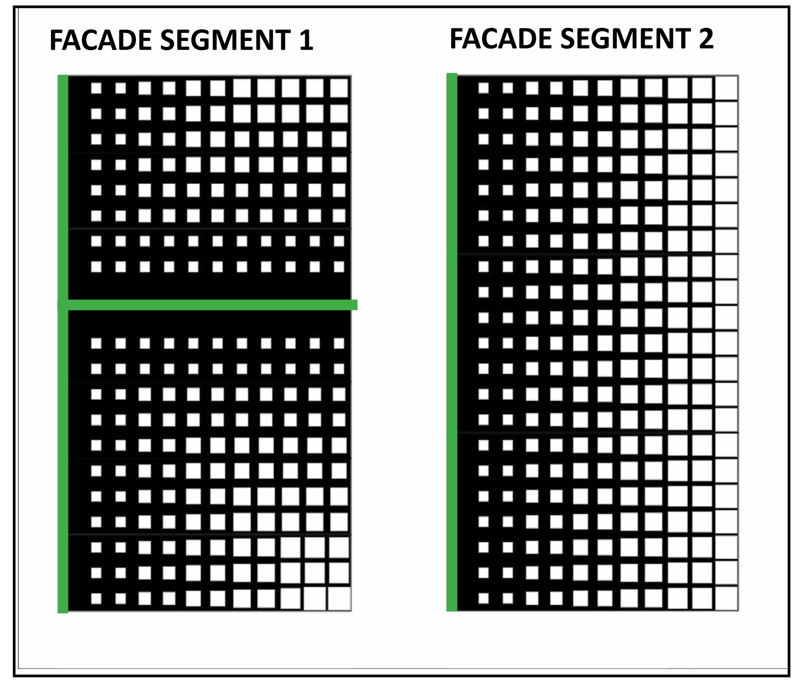
FACADE PATTERN 1



FACADE PATTERN 2



FACADE PATTERN 3



FACADE PATTERN 4

Figure 6.11: Facade patterns for Amsterdam, made by the author

PCM INTEGRATION

BOUNDARY CONDITIONS

PCM placement

First of all, the different panel types (A,B,C) are placed in a specific way in the façade. In order to take advantage of the stack effect for the natural ventilation of the indoor space of the libraries and the ventilation of the cavity , the panels(A panels) with the lower melting temperature are placed in the bottom part of the façade and the panels with the highest melting temperature (C Panels). The façade is divided into 11 segments where 3 of them belong to the façade segment 1 and 8 of them to the façade segment 2.The pattern is applied to the segments and it is different for each segment as the first segment represents a two floor system façade and the second segment a single (double height) floor façade

PCM grouping

Through the algorithm, each one of the segments is divided into three groups which refer to different PCM types (A panels, B panels, C panels).For the specific design specific limitations like the number of the panels of each groups , which is translated to 3 rows of items of the list per group for the segment 1 and 7 rows of items of the list per group for the segment 2.The number of rows can vary if the designer wants to make smaller or larger modular units per panel group. More specifically, in this occasion for the segment 1 each group contains two subgroups of each type of panels and each subgroup contains 3 rows per 12 columns (this corresponds to 3*12=36 panels per subgroup).On the other hand in the segment 2 we do not have subdivision of each group .There are just 3 groups with 7*12= 84 panels per group.

PCM –Glazing ratio

In order to calculate the PCM –glazing ratio in-the whole segment ,in each group separately and in the whole façade, the glazing percentages per panel group and the total glazing percentage of the segment should be calculated. After the initial energy calculations so as to find out the optimal PCM glazing ratio for each city ,it is concluded that in Athens it is required approximately 20% glazing percentage and Amsterdam 30-40% glazing percentage. Of course, except for the energy percentage it plays an important role how much is the glazing percentage per panel group. From the energy simulations it was shown that for Greece the A and B type of panels have positive impact on the energy performance of the façade and for Netherlands the B type of PCM is the most energy efficient. This means that when the A and B panel groups in Athens and the A panel groups in Amsterdam contain more PCM than glazing then the design will be more energy efficient. Also when these specific types are appeared in a larger area than the other types of PCM which is less energy efficient then also the design will lead to better energy performance.

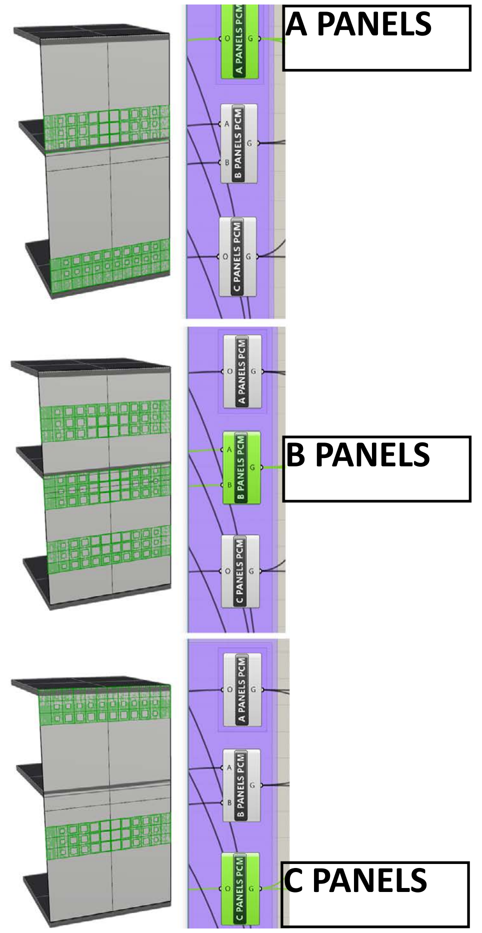
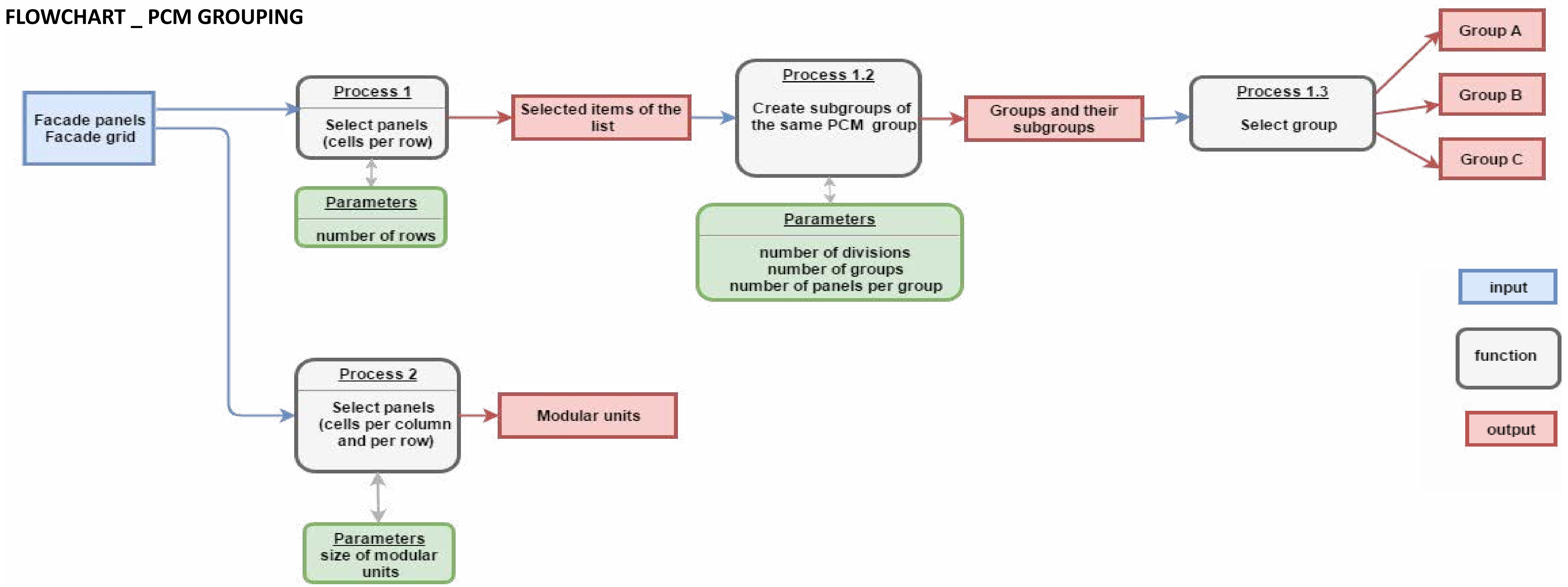


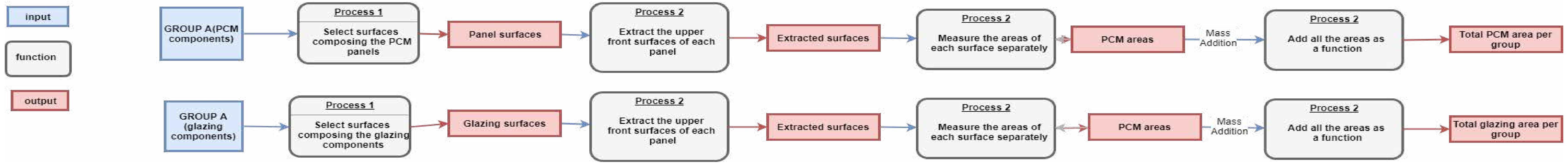
Figure 6.12: Grouping logic for segment 1, made by the author

FLOWCHART _ PCM GROUPING



Flowchart 6.5: PCM grouping, made by the author

FLOWCHART _ PCM -GLAZING AREA MEASUREMENTS (example for group A)

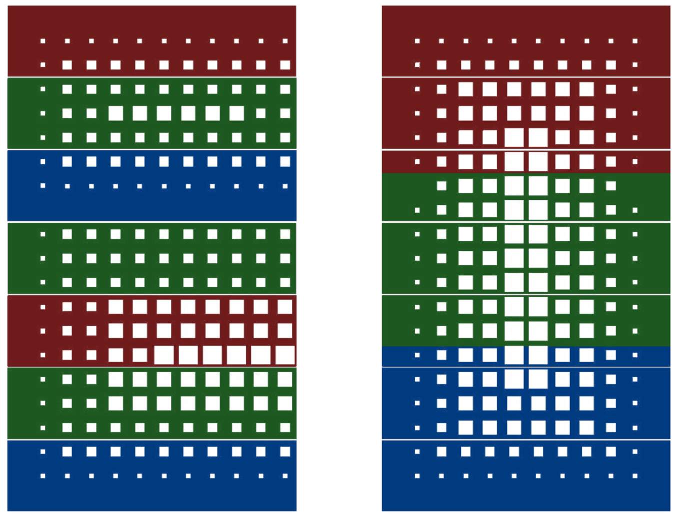


Flowchart 6.6: PCM glazing area measaurements, made by the author

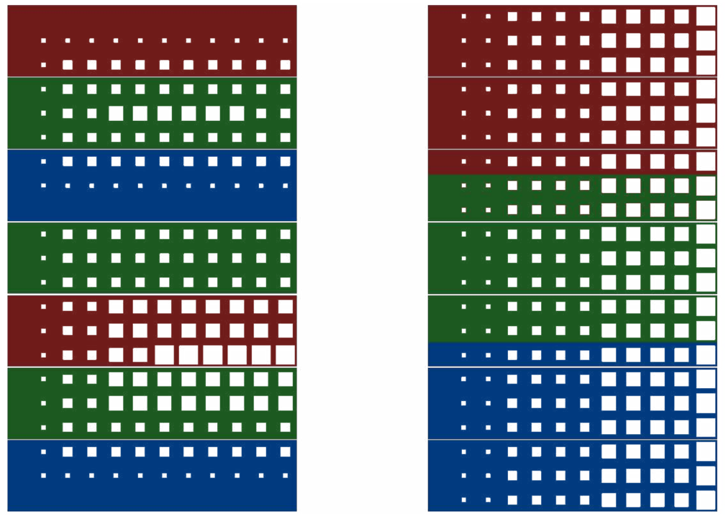
PCM GROUPING IN THE DIFFERENT PATTERNS

ATHENS

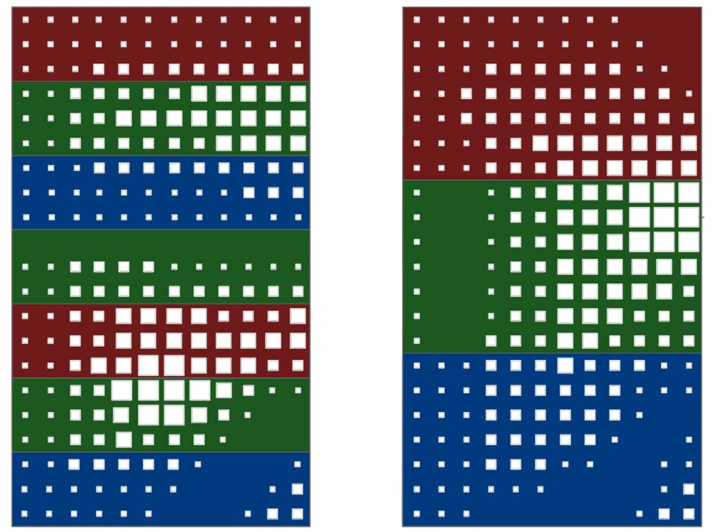
FACADE SEGMENT 1 FACADE SEGMENT 2



FACADE SEGMENT 1 FACADE SEGMENT 2



FACADE SEGMENT 1 FACADE SEGMENT 2



FACADE SEGMENT 1 FACADE SEGMENT 2

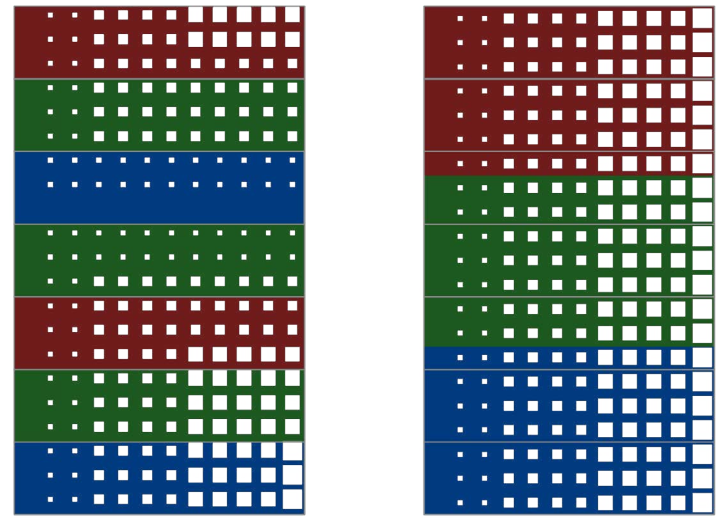


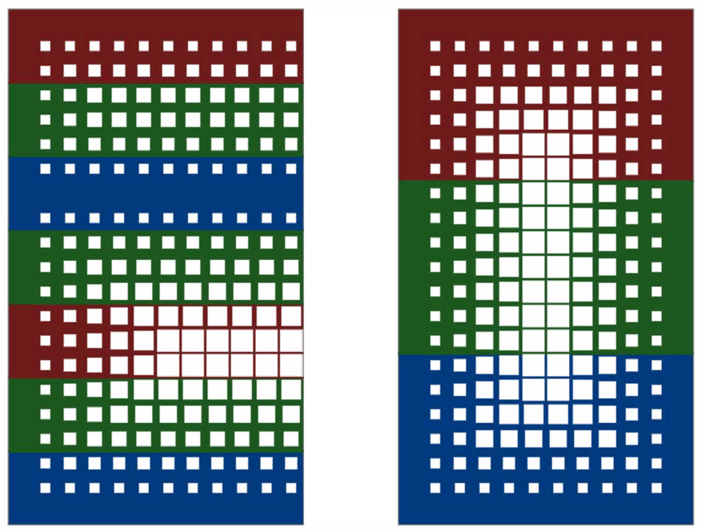
Figure 6.13: PCM grouping patterns for Athens, made by the author

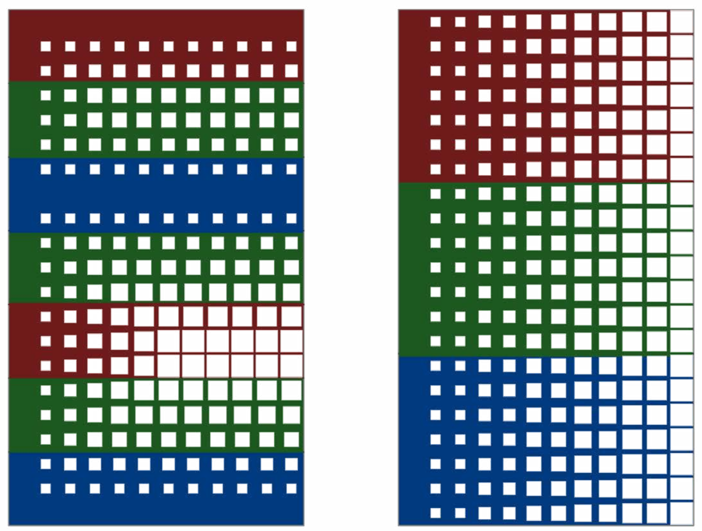
SP21

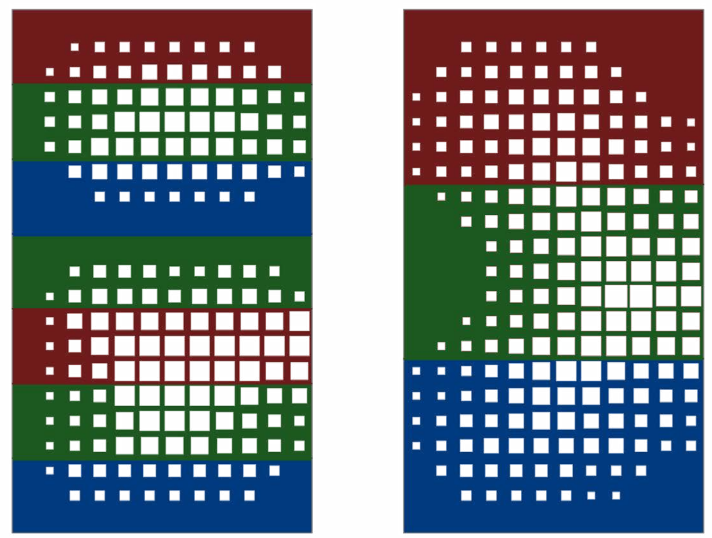
SP25

SP29 or SP31

AMSTERDAM







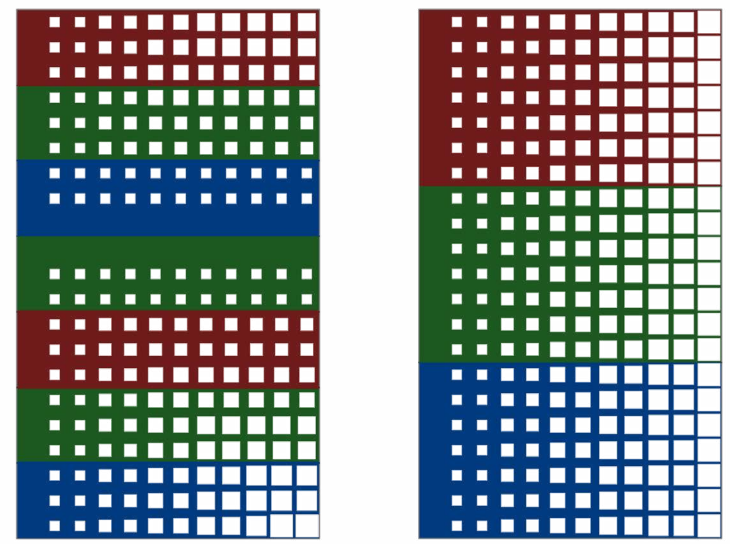


Figure 6.14: PCM grouping patterns for Amsterdam, made by the author

SP11

SP21

SP25 or SP29

INPUT DATA FOR ENERGY SIMULATIONS

All the glazing area measurements per PCM group and the total glazing of the facade will be an input in order for the energy simulations to take place.
More specifically, the glazing and the PCM percentages and the total energy percentage will be imported to the Design Builder Software as window to wall ratio, where the windows represent the glazing parts and the wall the pcm components.

Without these data the energy simulations could not be done and consequently the research could not base its aspects to scientific background in terms of evaluating the system's energy performance through software tools.

The grasshopper definition was not the central and the most important part of the research but it was the most critical piece of the puzzle in order the total research to be based in valid results through energy simulations.

The input data are referred to 8 facade patterns: 4 for Athens and 4 for Amsterdam.However, a negative aspect of the parametric model was the fact that it could not be imported as a 3d model to the Design Builder software and consequently the 3d was not used for the energy simulations in a immediate way (as a 3d model). It was used in a mediate way importing the calculated results (glazing and PCM percentages) as an input data in the contruction components of the facade system(show next chapter).

DISCUSSION | FURTHER IMPROVEMENTS

The parametric design in general is a very useful and efficient strategy when it comes to a kinet climate responsive facade design.
This research focuses in a climate responsive facade design based on phase change materials.For this reason a grasshopper definition with dynamic parameters and variables (facade pattern, facade operation, facade panel size, glazing element's size, PCM thickness) can be a really useful tool for a facade design who wants to use it in a simple facade model (parametric model design by the author) .
By using the grasshopper definition the facade designer can experiment with different facade patterns (using different attractor curves) and different facade components (changing the facade modular units, the lamella window's size, the PCM based facade panels size).
After ending up in a specific design, the facade design can have useful information about the glazing percentages per PCM group and the PCM quantity of the facade(thickness of PCM based panels, PCM to glazing ratio).
All these data can be an input for energy simulations that can be done either through Grasshopper(not in this case) or through energy softwares like the Design Builder Software.
The last improvement of this grasshopper definition is its ability to operate the facade with parameters like rotation axis and rotation angle of the operable parts.
However, these data were not used in the energy simulations because of time limitation.A CFD analysis took place using specific parameters of the grasshopper model (100% opening of the lamella windows in the inner facade skin and 20% opening of the PCM based panels in a parallel projection movement.On the other hand, the grasshopper definition provides alternative movement methods of the panels and they can also be simulated in further studies.

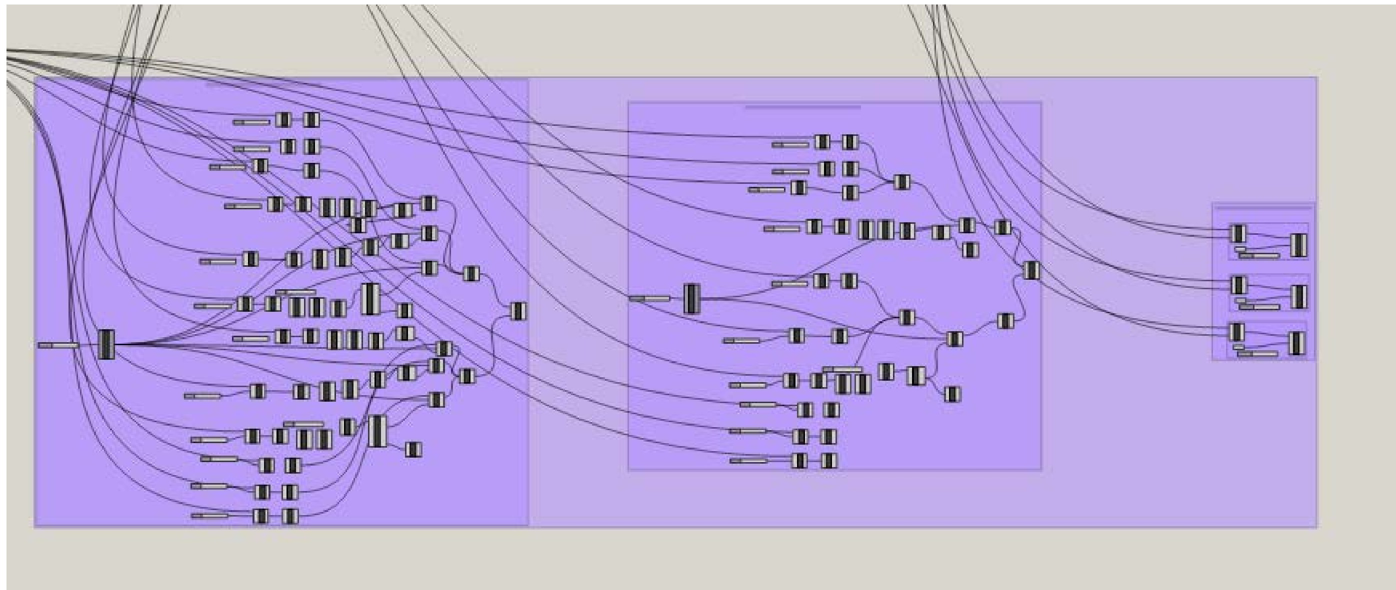


Figure 6.15: Commands for using alternative movement methods of the PCM based panels.

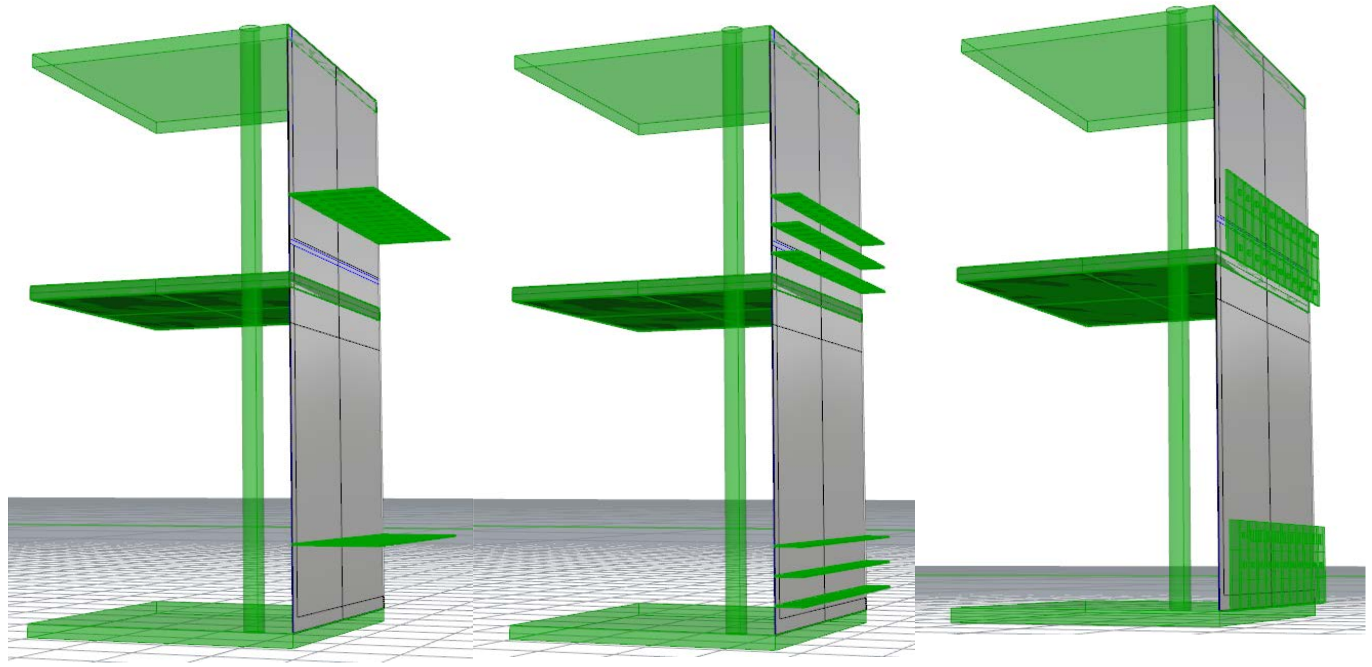


Figure 6.16: The alternative movement methods of the facade panels.

7

energy performance

ENERGY SIMULATIONS

THE SOFTWARE: DESIGN BUILDER

In order to gain a general insight on how the PCM affects the energy performance of the facade a simulation model was designed in Design Builder Software (Version 4.7.0.027).

CALCULATIONS

In order to assess the energy performance of the facade system experimenting with different facade designs energy calculations were done to calculate the energy demands of the indoor space for heating, cooling and artificial lighting.
In first steps, initial calculations in multiple simulation models with different glazing-PCM percentages and different types of PCM used so as to obtain a general knowledge on how the type of the PCM used and the PCM-glazing ratio in the facade can affect the total energy demands of the indoor space.
Later,specific designs were created with the contribution of the grasshopper definition in which it was provided all the input data about the glazing percentages of each design separately and the PCM combinations (PCM percentages of each pcm team applied in the facade.)

SIMULATION MODEL _SET UP

Several simplifications needed to be used in the simulation model in order to save time in the set up and the simulation.

a)Location

First of all,the location is implemented through importing weather data for Athens (Ellinikon Airport) and for Amsterdam (Sciphol airport relatively).The aim of this set up is to end up in comparative data in order to end up in conclusions on how the system can perform in two climates(mediterranean and temperate).

b)Building Construction

The simplifications that were made have to do with the implementation of the openings of the southern facade where the parametric facade pattern (scaling glazing objects) is now translated only to window -to wall ratio.The windows represent the glazing objects and consist of double glazing Low -e and the wall is made out of 3 layers : float glass 6mm, PCM (0.03Mm) and float glass 6mm.

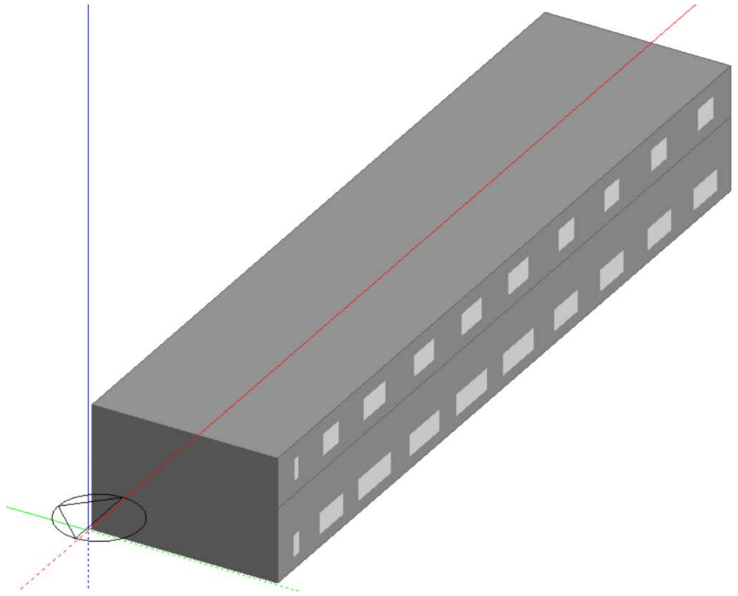


Figure 7.1: The simulation model, exported from Design Builder

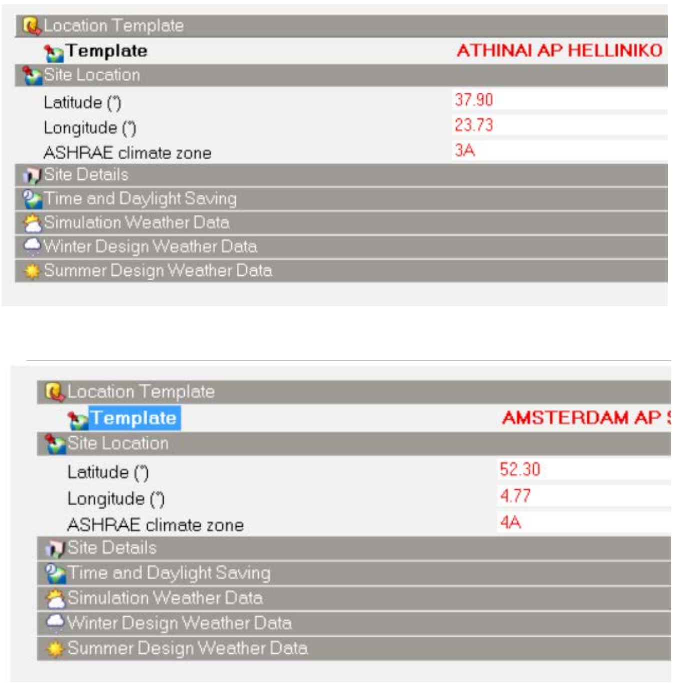


Figure 7.2: The location settings, exported from Design Builder

More specifically,the southern facade is a double skin facade in which the outer layer is composed of the glass elements filled with PCM and then the cavity of 0.3 m depth and again the innerd facade layer mde out of double low e glazing.
The other external walls are simply given a default material (Project wall) consisted of 4 layers:
1)Brickwork_Outer leaf (0.1m)
2)XPS extruded polystyren(0.07m)
3)Concrete block (0.1m)
4)Gypsum plastering (0.01m).
The northern wall has exactly the same composition with the other walls but the big difference is that the insulation layer is much thicker (0.7m). This happens as the wall in reality is not an external wall but an internal wall of the building.

c)Orientation

The orientation of the facade where the PCM based system is applied is always southern.The PCM should take full advantage of the sun and for this reason the southern orientation seems to be the most preferable choice.

d)Calculation method

It is used the explicit finite difference method to calculate the transient heat transfer of the system investigated.This happened because PCM s are integrated in the facade. The phase change process was implemented for each PCM as temperature-dependent heat capacity with a parabolic peak distribution and a melting range of 1°C.The enthalpy curve was applied in each PCM used by using 16 points in the curve.

e)Thermal zones

The simulation model is made out of two building blocks representing the 2 floors of the library room.The ground floor is separated into 8 thermal zones.6 of them represent the south facade zones where each zone represent different type of PCM (a panels, b panels, c panels) or different ratio og glazing -PCM (a panels, a panels 1).The other two zones represent two different rooms divided by a glass partition wall from each other.
In the first floor we have again 6 zones for the southern facade and one thermal zone for the indoor space.

f)Activity

Cavity Activity was applied in the zones where the double skin PCM based facade is applied and standard activity refered to Library buildings (stud-ying areas) is applied to the zones representing the indoor space.

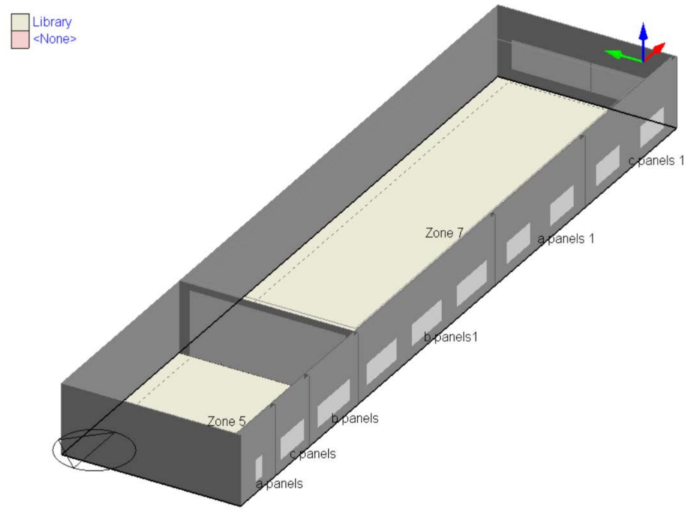


Figure 7.3: The ground floor and the thermal zones, exported from Design Builder

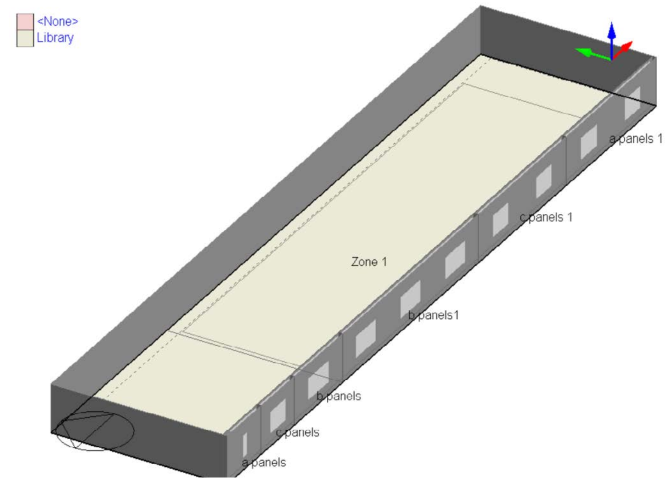


Figure 7.4: The first floor and the thermal zones, figure exported from Design Builder

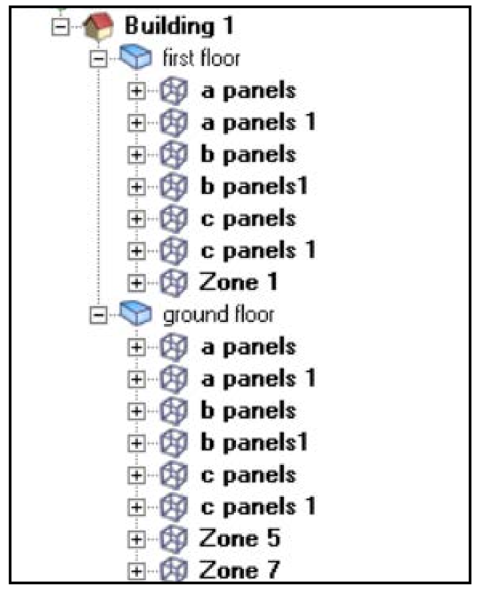


Figure 7.5: The separation into different thermal zones, figure exported from Design Builder

INITIAL SIMULATIONS

GENERAL DATA

Initial energy simulations are done checking the total energy demands of the building when one type of PCM (11,21,25,29,31) is applied in different glazing-pcm ratios.These kind of calculations give guidelines for the facade designers about which PCM type is more energy efficient and which PCM-glazing ratio is the most optimal in terms of energy performance.

AMSTERDAM

The PCM types that applied in the facade are SP11,SP21,SP25,SP29,SP31.These materials applied in the facade in different ratios in every measurement (50% PCM , 40% PCM, 30% PCM, 20% PCM).

RESULTS

The bar graphs show that the SP21 is the most energy efficient PCM type as it has the lowest values in energy consumption in every measurement which is applied independedly of the PCM-glazing ratio.

As far as the glazing percentage of the facade is concerned, the optimal glazing percentage in terms of energy performance is 30% and then follows 40%.

The least efficient PCM type is the SP 31.This is logical as the temperature in the Netherlands is not really high (average high temperature 24 ºC).The melting temperature of the SP31 is 31ºC which is a temperature that can be reached only in a sunny day with intense solar irradiation.On the other hand,the SP21 which is appeared to be the most energy efficient covers a large temperature range which is refered to the Netherlands and 21 ºC is a melting temperature that can be reached easily not only in the summer but also in the spring and the autumn.

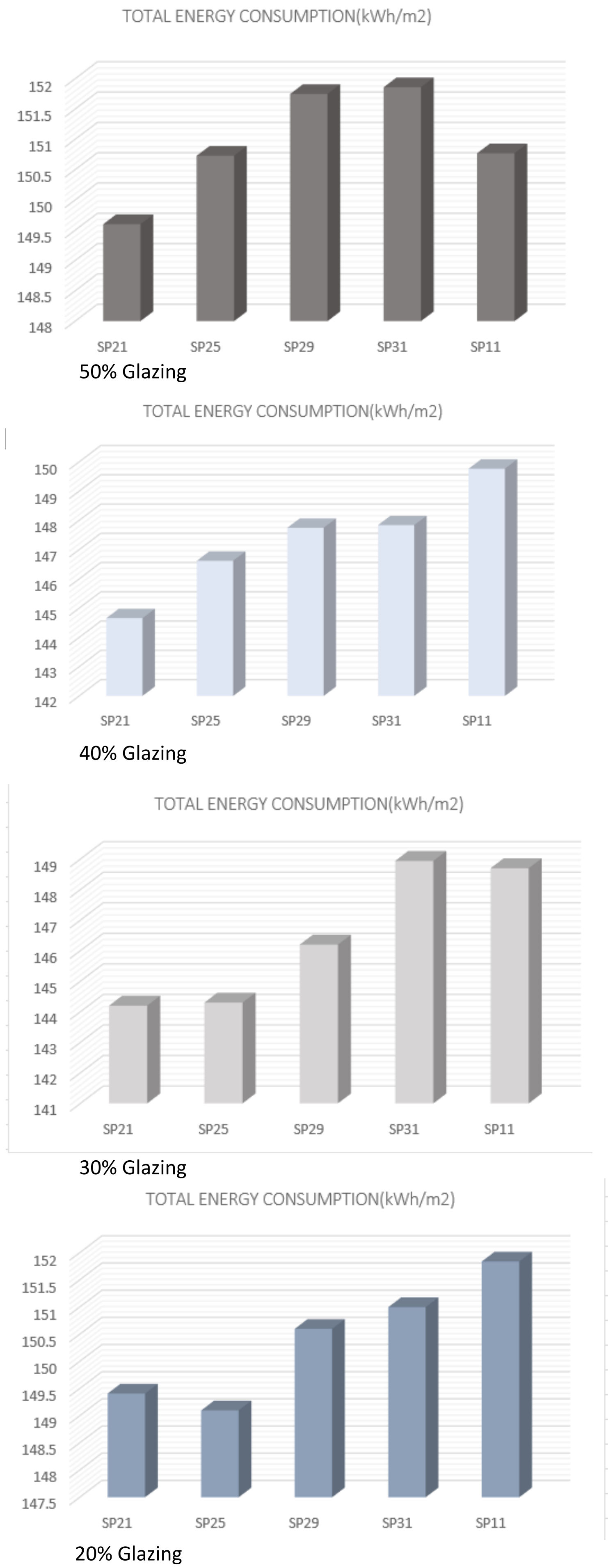


Figure 7.6 (a) to (d): Total energy consumption for PCMs with different glazing percentages in Amsterdam

ATHENS

The PCM types that applied in the facade are SP21,SP25,SP29,SP31.These materials applied in the facade in different ratios in every measurement (50% PCM , 40% PCM, 30% PCM, 20% PCM).

RESULTS

The bar graphs show that the SP21 is the most energy efficient PCM type as it has the lowest values in energy consumption in every measurement which is applied independedly of the PCM-glazing ratio.

As far as the glazing percentage of the facade is concerned, the optimal glazing percentage in terms of energy performance is 20% and the least oreferable is 50%.This is logical as the more glazing percentage means more energy demands for cooling.The least efficient PCM type is the SP 31 along with the SP 29.

DISCUSSION

Taking into account the measurements done with different glazing percentages and different PCM in Amsterdam,it is concluded that 30-40% of glazing is the optimal glass proportion in the facade. Whereas, in Athens the need for glazing is less and consequently 20% glazing is adequate and more energy efficient compared to other higher glazing percentages.

In Amsterdam it is needed more glass percentage in the facade because in general the heating loads are high due to its climate.More specifically, increased solar heat gains through the glazing are beneficial as they can decrease the energy demands for heating during the winter.Moreover, the artificial lighting loads are decreased with the integration of glazing in the facade as it can be done exploitation of daylight.

On the other hand, in Greece it can be used less glazing than in Netherlands in order to achieve energy savings for cooling.In Athens,because of the climate,overheating problems appear during the summer and as a results, solar heat gains should be limited so as to decrease the cooling loads.

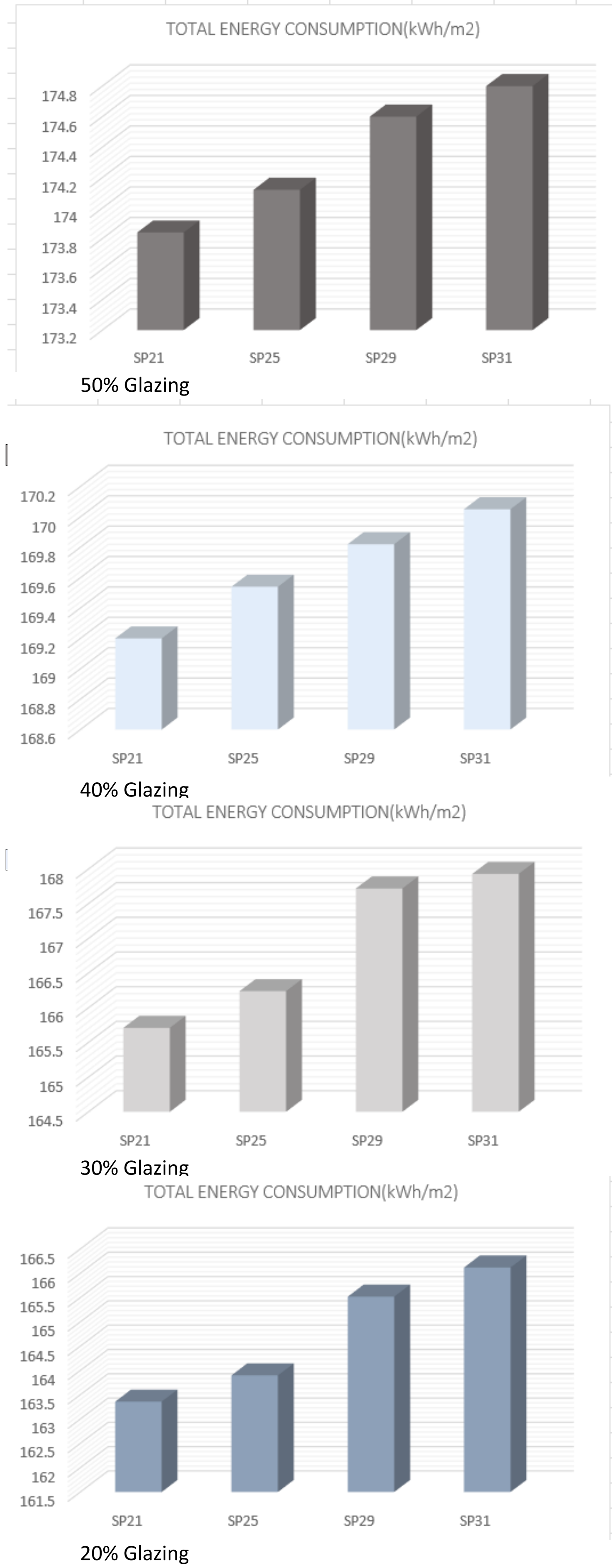


Figure 7.7(a) to (d): Total energy consumption for PCMs with different glazing percentages in Athens

ENERGY SIMULATIONS BASED ON ALTERNATIVE DESIGNS

THE AIM

In order to visualize the glazing percentages into a facade design a computational design logic (parametric approach) is used so as to explore different facade patterns and their impact in the energy performance of the envelope system.
Another objective of these energy simulations is to find out the optimal combination of different PCMs in both Amsterdam and Athens and the PCM percentages of each type separately.

INPUT DATA

As it is refered in previous chapter, the grasshopper definition made, has the ability to create facade segments with different glazing percentages and different PCM types. 3 Different types are used and as a result the combination of 3 different PCMs will be integrated in the simulation model in design builder with specific pcm percentages (input data from grasshopper.

PCM Types

In these simulations 5 different types of PCMs will be used in multiple combinations so as to end up in an optimal combination for both Amsterdam and Greece.
More specifically, in Amsterdam the PCM combinations that will be checked are :
1) SP11(A panels), SP 21(B panels), SP25(C panels)
2) SP11(A panels), SP 21(B panels), SP29(C panels)

In Athens the PCM combinations that will be applied in the simulations model are:
1) SP21(A panels), SP 25(B panels), SP29(C panels)
2) SP21(A panels), SP 25(B panels), SP31(C panels)

Facade patterns

Different facade patterns will be explored for Amsterdam and Athens separately.For the Amsterdam case the total glazing percentage will range from 30-40% whereas for Athens the total glazing percentage will be between 15 and 22 %.

RESTRICTIONS

In terms of simplification the input data coming from the grasshopper file are refered to 2 facade segments that are distributed in a different way in the facade.
The first facade segment is appeared three times in the facade and the whole facade area that covers has double height and facilitates 2 floors.
On the other hand, the second facade segment is appeared 8 times in the facade and the whole area that covers has double height consisting of one floor.

The facade pattern is translated to PCM -glazing ratio per PCM group(window to wall ratio).As a result,the actual facade pattern is not integrated in the simulation and the distribution of the glazing elements is different.

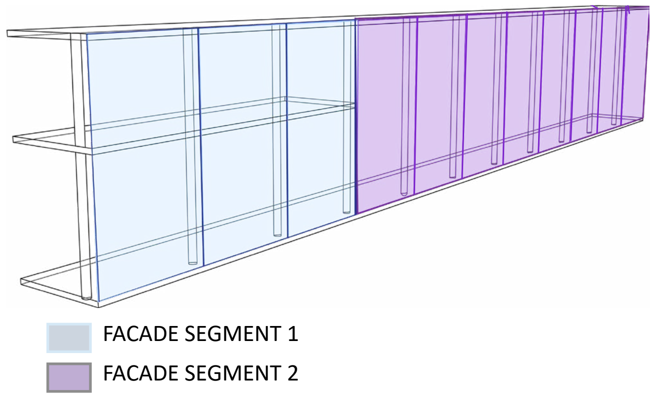


Figure7.8: The segmentation of the facade, sketch made by the author

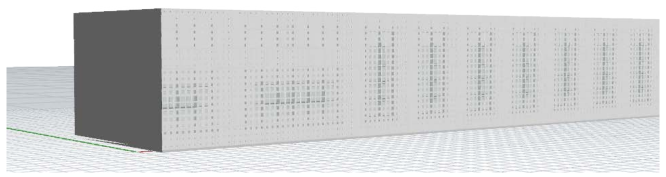


Figure 7.9: The actual facade pattern designed in Grasshopper,made by the author

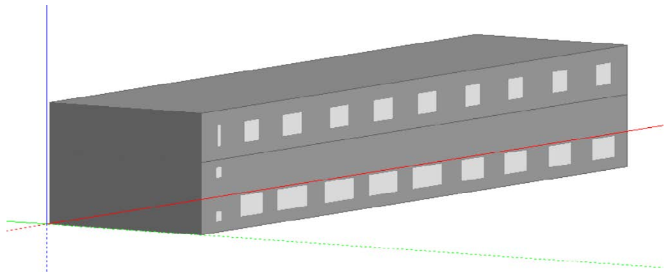


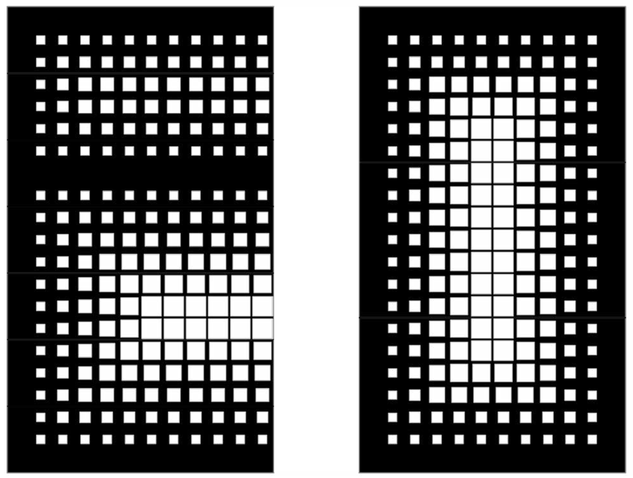
Figure 7.10: The simplified version of the 1st Design for Athens,exported from Design Builder

CASE 1 | AMSTERDAM

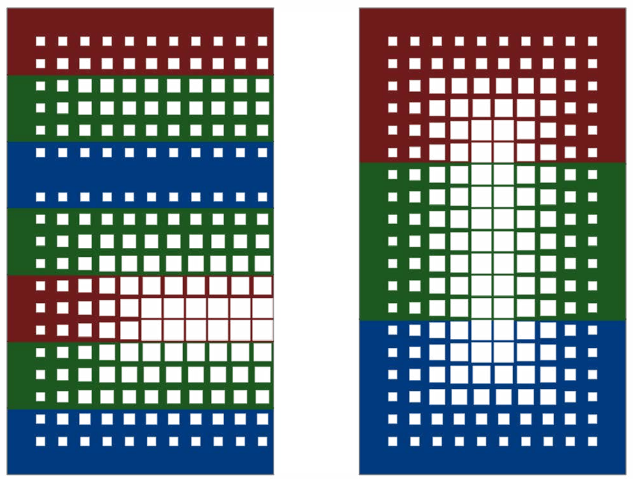
FACADE PATTERN 1

The percentage of the area that covers each PCM group is the same for A and C panels and higher for B panels.
For the energy simulations,the facade pattern is translated to PCM -glazing ratio per PCM group(window to wall ratio).The glazing percentage of each PCM group are presented in the table. The total glazing percentage of the facade is 30.73%.

FACADE SEGMENT 1 FACADE SEGMENT 2



PCM
GLAZING



A PANELS
B PANELS
C PANELS

Possible PCM combinations
1)11,21,25
2)11,21,29

Figure 7.11: The facade patterns of both facade segments,design made by the author through Grasshopper

INPUT DATA	
PATTERN 1	
TOTAL GLAZING PERCENTAGE	30.73%
FAÇADE SEGMENT 1	
TOTAL PERCENTAGE A PANELS	26.55%
TOTAL PERCENTAGE B PANELS	46.90%
TOTAL PERCENTAGE C PANELS	26.55%
GLAZING PERCENTAGE A PANELS	11%
GLAZING PERCENTAGE B PANELS	32.44%
GLAZING PERCENTAGE C PANELS	32.80%
FAÇADE SEGMENT 2	
TOTAL PERCENTAGE A PANELS	33.30%
TOTAL PERCENTAGE B PANELS	33.30%
TOTAL PERCENTAGE C PANELS	33.30%
GLAZING PERCENTAGE A PANELS	31.21%
GLAZING PERCENTAGE B PANELS	33.88%
GLAZING PERCENTAGE C PANELS	31.21%
TOTAL GLAZING PERCENTAGE (SEGMENT 1)	26.45%
TOTAL GLAZING PERCENTAGE (SEGMENT 2)	32.28%

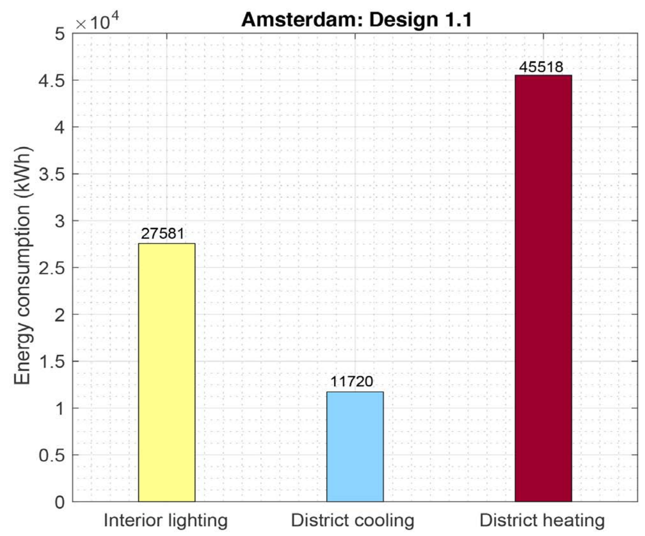
Table 7.1: Input data for Pattern 1

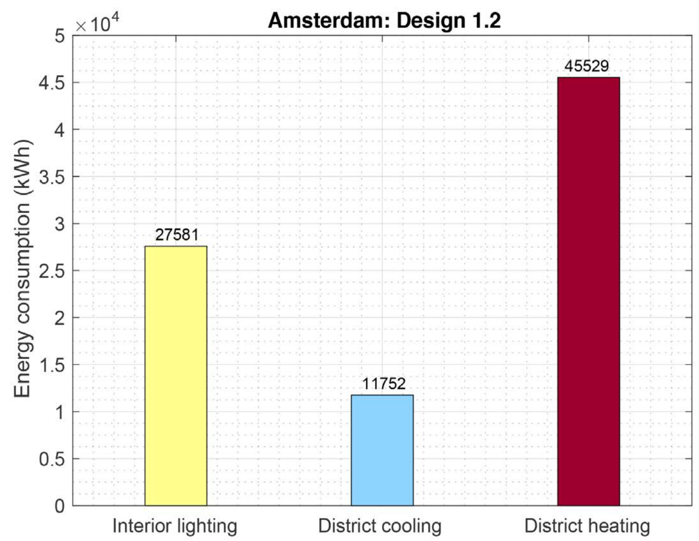
RESULTS

DESIGN 1.1	SP11, SP21, SP25		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	45518
Cooling	0	11720	0
Interior lighting	27581	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	48620.43	11720	49451.64
Energy Per Total Building Area	[kWh/m^2]		
	147.1		

DESIGN 1.2	SP11, SP21, SP29		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	45529
Cooling	0	11752	0
Interior lighting	27581	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	48620.43	64390	49462.64
Energy Per Total Building Area [kWh/m2]	[kWh/m^2]		
	147.5		

Table 7.2: Results for Design 1.1 and 1.2

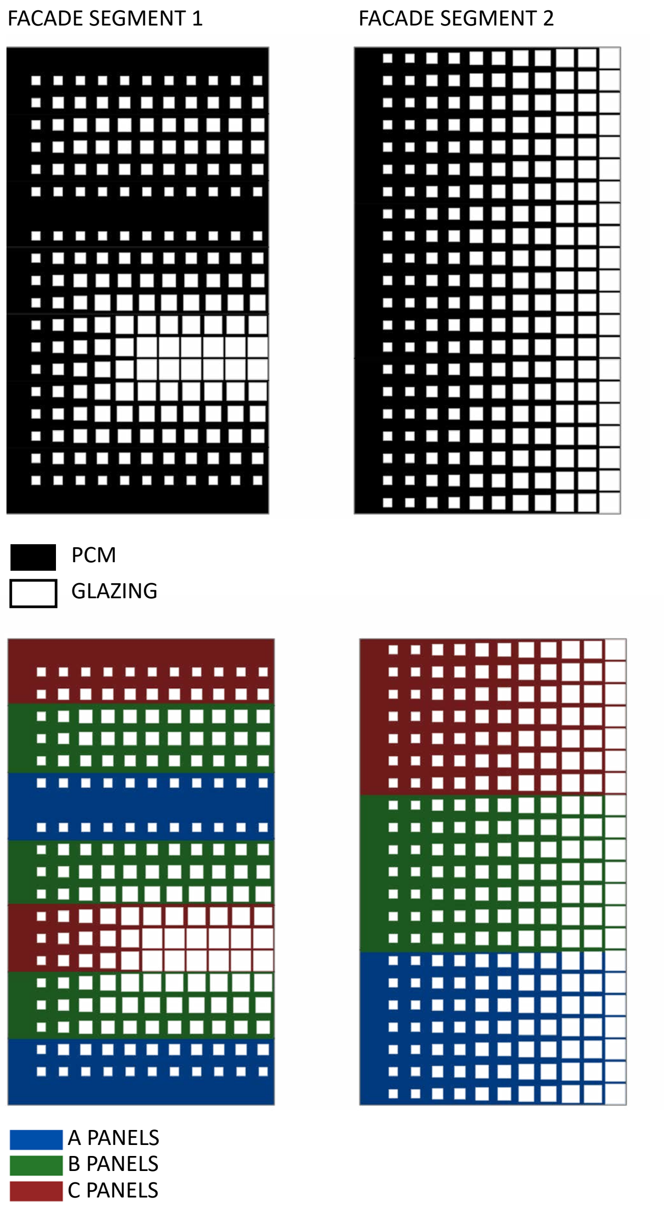




Graphs 7.1 (a), (b): Design 1.1 and 1.2 for Amsterdam

FACADE PATTERN 2

The glazing percentage of each PCM group are presented in the table.
The total glazing percentage of the facade is 35.73%.



Possible PCM combinations
1)11,21,25
2)11,21,29

Figure 7.12: The facade patterns of both facade segments,design made by the author through Grasshopper

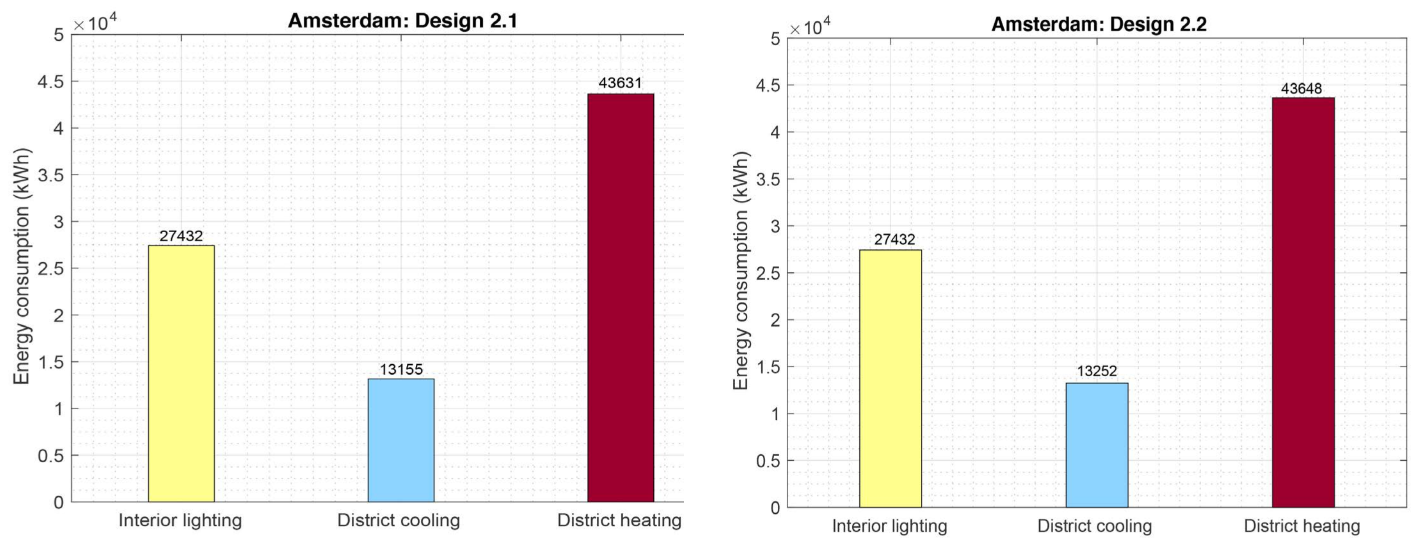
INPUT DATA	
PATTERN 2	
TOTAL GLAZING PERCENTAGE	35.73%
FAÇADE SEGMENT 1	
TOTAL PERCENTAGE A PANELS	26.55%
TOTAL PERCENTAGE B PANELS	46.90%
TOTAL PERCENTAGE C PANELS	26.55%
GLAZING PERCENTAGE A PANELS	11%
GLAZING PERCENTAGE B PANELS	32.44%
GLAZING PERCENTAGE C PANELS	32.80%
FAÇADE SEGMENT 2	
TOTAL PERCENTAGE A PANELS	33.30%
TOTAL PERCENTAGE B PANELS	33.30%
TOTAL PERCENTAGE C PANELS	33.30%
GLAZING PERCENTAGE A PANELS	39.16%
GLAZING PERCENTAGE B PANELS	39.16%
GLAZING PERCENTAGE C PANELS	39.16%
TOTAL GLAZING PERCENTAGE (SEGMENT 1)	25.46%
TOTAL GLAZING PERCENTAGE (SEGMENT 2)	39.16%

Table 7.3: Input data for Pattern 2

RESULTS

DESIGN 2.1	SP11, SP21, SP25		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	43631
Cooling	0	13155	0
Interior lighting	27432	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	48471.43	13155	47564.64
Energy Per Total Building Area	[kWh/m2]		
	146.14		
DESIGN 2.2	SP11, SP21, SP29		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	43648
Cooling	0	13252	0
Interior lighting	27432	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	48471.43	13252	47581.64
Energy Per Total Building Area [kWh/m2]	[kWh/m2]		
	146.69		

Table 7.4: Results for Design 2.1 and 2.2

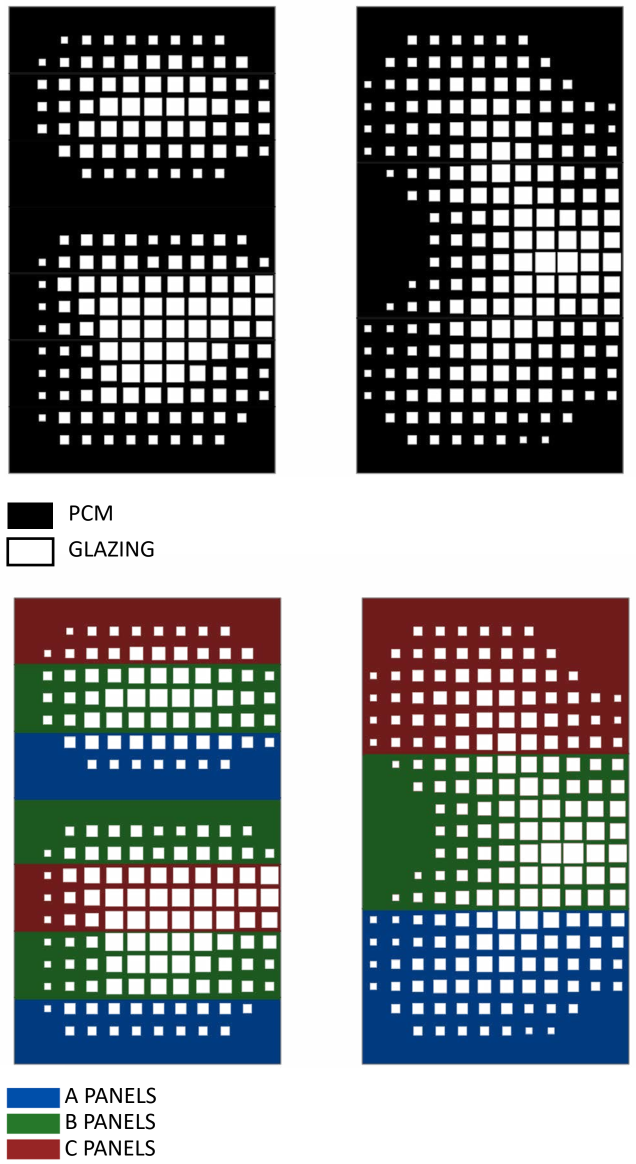


Graphs 7.2 (a), (b): Design 2.1 and 2.2 for Amsterdam

FACADE PATTERN 3

The glazing percentage of each PCM group are presented in the table.
The total glazing percentage of the facade is 27.45%

FACADE SEGMENT 1 FACADE SEGMENT 2



INPUT DATA	
PATTERN 3	
TOTAL GLAZING PERCENTAGE	27.45%
FAÇADE SEGMENT 1	
TOTAL PERCENTAGE A PANELS	26.55%
TOTAL PERCENTAGE B PANELS	46.90%
TOTAL PERCENTAGE C PANELS	26.55%
GLAZING PERCENTAGE A PANELS	16%
GLAZING PERCENTAGE B PANELS	32.80%
GLAZING PERCENTAGE C PANELS	31.88%
FAÇADE SEGMENT 2	
TOTAL PERCENTAGE A PANELS	33.30%
TOTAL PERCENTAGE B PANELS	33.30%
TOTAL PERCENTAGE C PANELS	33.30%
GLAZING PERCENTAGE A PANELS	25.00%
GLAZING PERCENTAGE B PANELS	30.00%
GLAZING PERCENTAGE C PANELS	24.80%
TOTAL GLAZING PERCENTAGE (SEGMENT 1)	27.87%
TOTAL GLAZING PERCENTAGE (SEGMENT 2)	27.25%

Table 7.5: Input data for Pattern 3

Possible PCM combinations
1)11,21,25
2)11,21,29

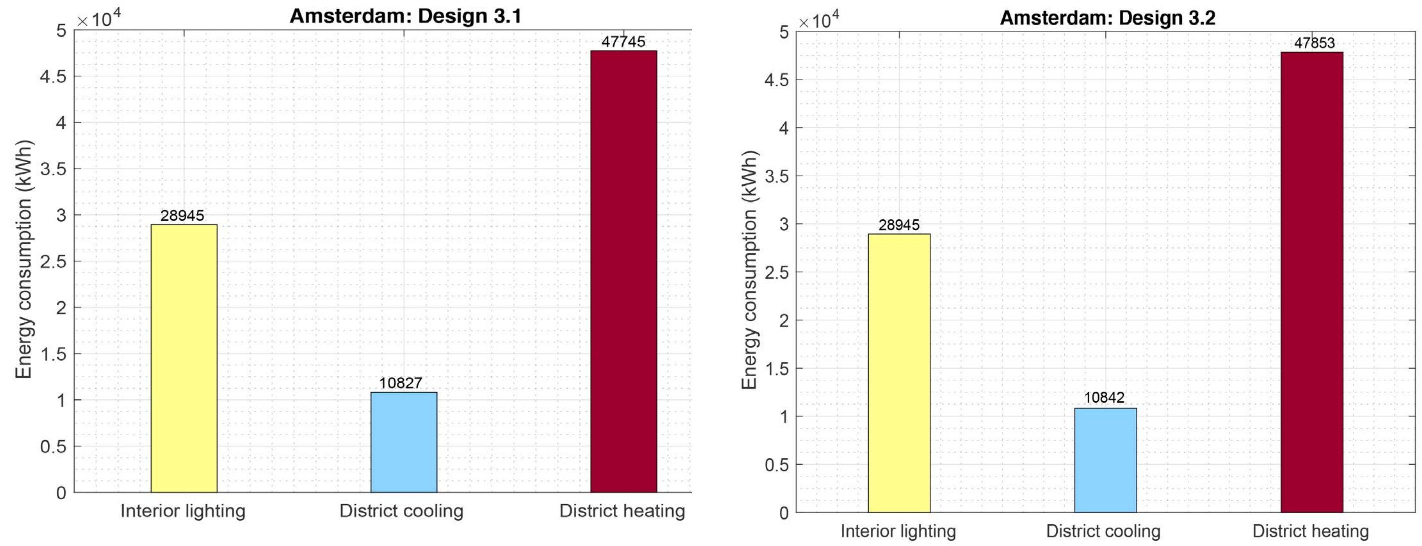
Figure 7.13: The facade patterns of both facade segments,design made by the author through Grasshopper

RESULTS

DESIGN 3.1	SP11, SP21, SP25		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	47745
Cooling	0	10827	0
Interior lighting	28945	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	49984.43	10827	51678.64
Energy Per Total Building Area	[kWh/m^2]		
	150.58		

DESIGN 3.2	SP11, SP21, SP29		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	47853
Cooling	0	10842	0
Interior lighting	28945	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	49984.43	10842	51786.64
Energy Per Total Building Area [kWh/m2]	[kWh/m^2]		
	150.91		

Table 7.6: Results for Design 3.1 and 3.2

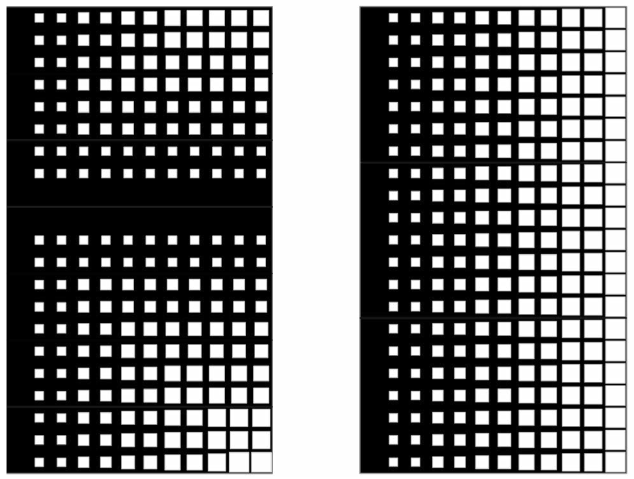


Graphs 7.3 (a), (b): Design 3.1 and 3.2 for Amsterdam

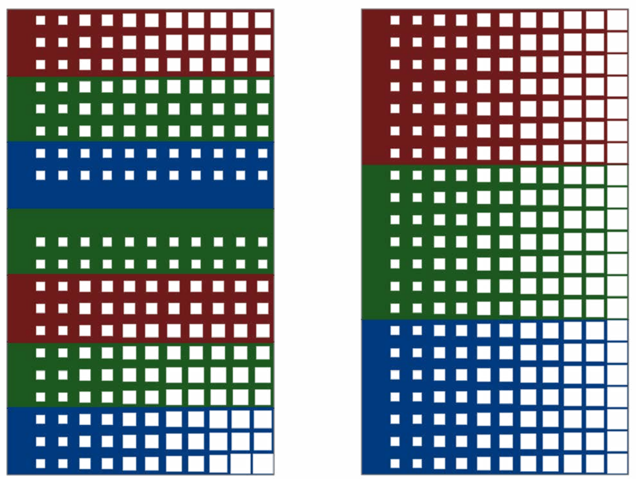
FACADE PATTERN 4

The glazing percentage of each PCM group are presented in the table.
The total glazing percentage of the facade is 35.45%

FACADE SEGMENT 1 FACADE SEGMENT 2



PCM
GLAZING



A PANELS
B PANELS
C PANELS

Possible PCM combinations
1)11,21,25
2)11,21,29

Figure 7.14: The facade patterns of both facade segments,design made by the author through Grasshopper

INPUT DATA	
PATTERN 4	
TOTAL GLAZING PERCENTAGE	35.45%
FAÇADE SEGMENT 1	
TOTAL PERCENTAGE A PANELS	26.55%
TOTAL PERCENTAGE B PANELS	46.90%
TOTAL PERCENTAGE C PANELS	26.55%
GLAZING PERCENTAGE A PANELS	22%
GLAZING PERCENTAGE B PANELS	26.49%
GLAZING PERCENTAGE C PANELS	24.40%
FAÇADE SEGMENT 2	
TOTAL PERCENTAGE A PANELS	33.30%
TOTAL PERCENTAGE B PANELS	33.30%
TOTAL PERCENTAGE C PANELS	33.30%
GLAZING PERCENTAGE A PANELS	39.16%
GLAZING PERCENTAGE B PANELS	39.16%
GLAZING PERCENTAGE C PANELS	39.16%
TOTAL GLAZING PERCENTAGE (SEGMENT 1)	25.46%
TOTAL GLAZING PERCENTAGE (SEGMENT 2)	39.16%

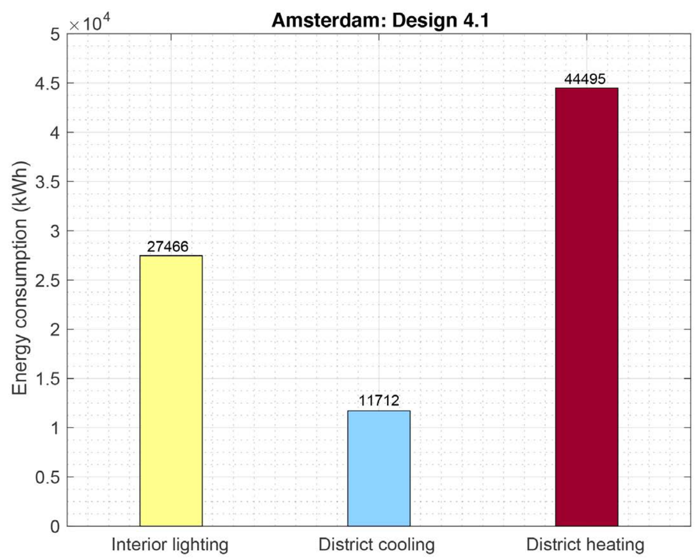
Table 7.7: Input data for Pattern 4

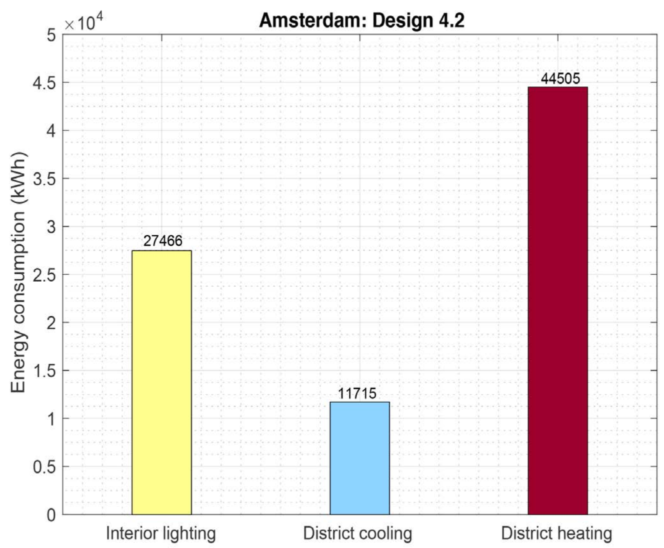
RESULTS

DESIGN 4.1	SP11, SP21, SP25		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	44495
Cooling	0	11712	0
Interior lighting	27466	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	48505.43	10827	48428.64
Energy Per Total Building Area	[kWh/m^2]		
	147.21		

DESIGN 4.2	SP11, SP21, SP29		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	44505
Cooling	0	11715	0
Interior lighting	27466	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	48505.43	10842	48438.64
Energy Per Total Building Area [kWh/m2]	[kWh/m^2]		
	147.26		

Table 7.8: Results for Design 4.1 and 4.2





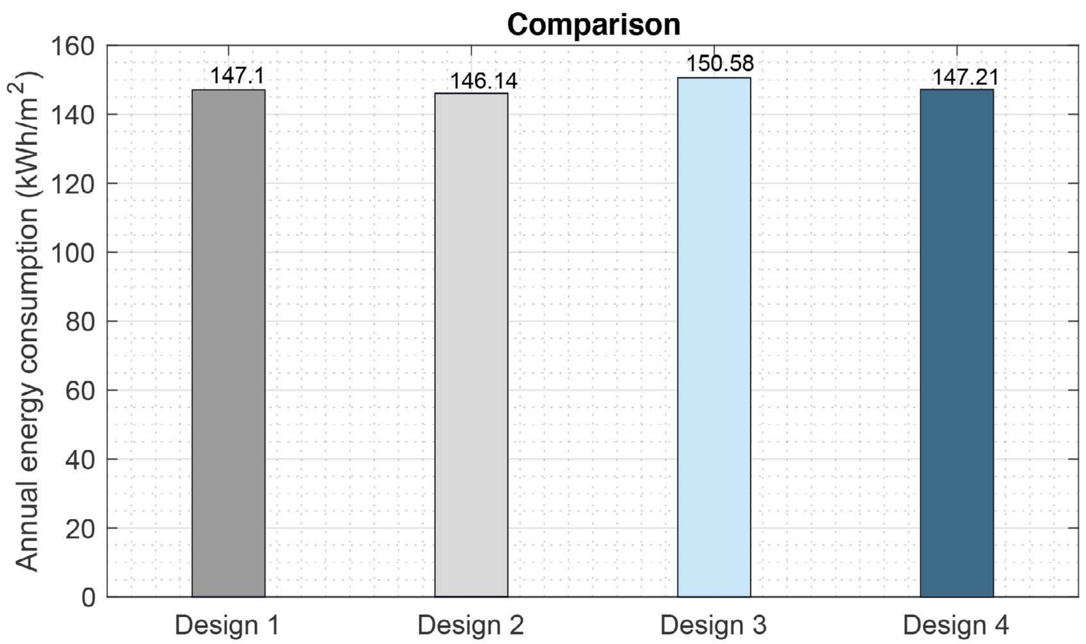
Graphs 7.4 (a), (b): Design 4.1 and 4.2 for Amsterdam

ANALYSIS OF THE RESULTS

Taking into consideration , the results of the simulations for the 4 alternative design,the second design is the most energy efficient in terms of minimizing the heating ,cooling and artificial lighting loads with a total energy consumption 146.14 kWh/m².(design 2.1)

This happens because in this case the total glazing percentage of the facade has the highest value of the other 3 designs.As a result,increased solar heat gains can contribute to decreazing the existing heating loads of the building .Moreover, the artificial lighting loads are also decreased because the facade is more exposed to the sun and more sunlight (natural lighting) is provided. However,in the 2nd design higher percentage in the glazing means more energy demands for cooling the building (in general the demands for mechanical cooling services are quite low because of the climate of the area.

As the combination of the PCM types is concerned,SP11-SP21-SP25 is more energy efficient than SP11-SP21-SP29,as in all the designs the results have shown less energy consumption with the first combination.However, the differences appeared between the two combinations are really minor and if we take into account the inaccuracy level of the program(Design Builder),it is like there is no difference between the 2 choices.



Graph 7.5: Comparisons for Designs 1 to 4 for Amsterdam

DISCUSSION

In order the facade designers to make the optimal choice of the PCM type or the PCM combination used in the facade in a temperate climate they should take into account several factors that can affect the efficiency of the PCMs and the energy performance of the system.

First of all, the climate is a really important factor to help a designer to choose the right PCM type. In the Netherlands in general the climate is temperate and this means quite cold winter and 25 °C as the highest temperature in the summer.Moreover,the high wind speed appeared in Netherlands contributes to maintain the facade temperature in logical values and not really high values during the summer.On the other hand,during the winter the air temperature is quite low and this lead that only materials with inthermediate melting temperature can melt during the day and complete their cycles.Thus, PCM with melting temperatures 11,21,25° can be used.

However, these materias have a specific maximum operative temperature and they are not allowed to exceed the temperature.However in the Netherlands the solar irradiation is not very high compared to Greece and extremely high temperatures cannot be developed in the facade.Thus,the use of shading system in order to protect the PCM from excessive heat exposure is not needed.

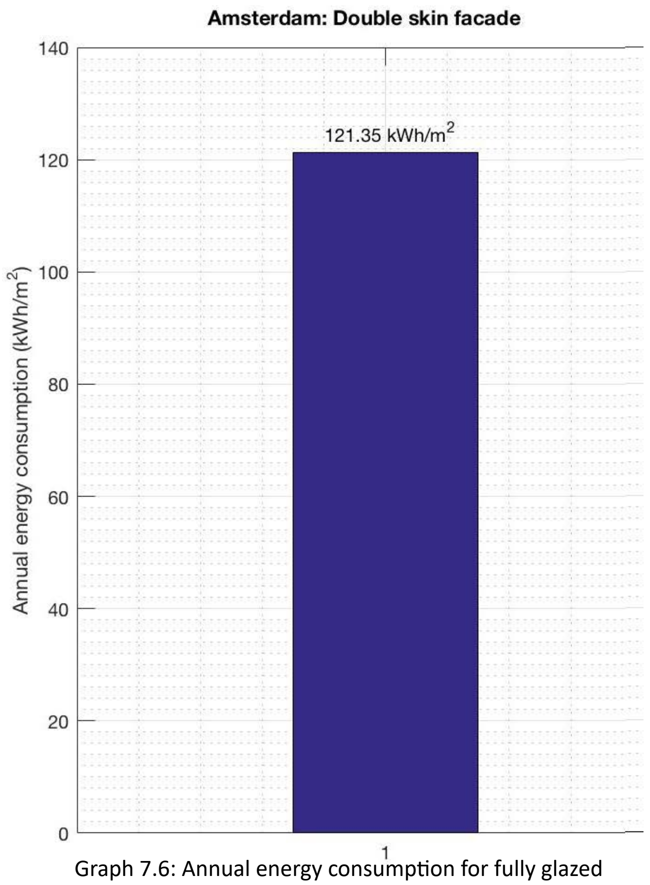
As far as the placement of the different PCM panels is concerned, it is important to take into advantage the direction of the airflow while natural ventilation takes place.When the different types of the PCM are located from the panels with the lower melting temperature (bottom) to the panels of the higher melting temperature , this means that the stack effect can be promoted and natral ventilation can take place by using the intake of fresh air from the lower parts of the facade and releasing the hot stale air from the upper operable windows of the facade.

COMPARISON WITH A DOUBLE SKIN FACADE

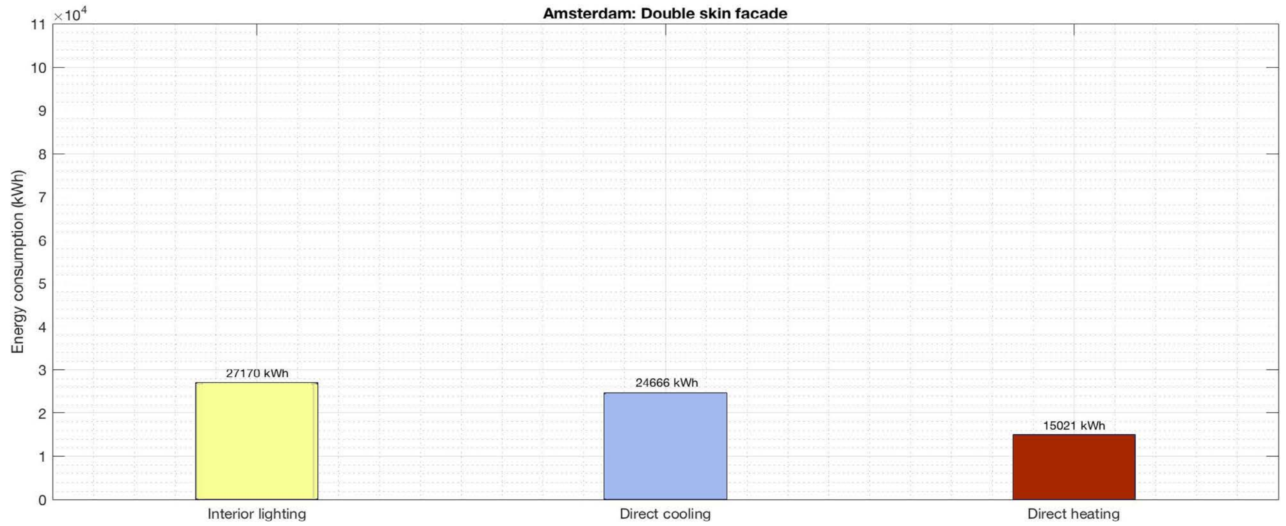
In order to be assessed the performance of the chosen and the most energy efficient design, a comparison with a fully glazed double skin facade will be done in terms of energy loads for heating, cooling and artificial lighting.

Taking into account the total energy consumption in annual basis and comparing this with the energy results for the fully glazed facade system, it is shown that the PCM based double skin is less energy efficient than a double skin facade with two skins prividing double glazing low-E .This happens because in the fully glazed double skin facade the heatng loads and the artificial lighting loads are lower than the one in the chosen PCM based design as the facade is fully exposed to the sun. However, the simulation in design builder does not take into account the optical properties of the PCMs and the fact that when they melt they become transparent and thus the heating and the artificial lighting can be decreased.

Another important aspect to be taken into account while doing this comparison is that the energy simulations made for the pcm based double skin facade does not represent exactly the performance of the system as it is designed (adaptive air flow control, natural ventilation aspects and adaptive behaviour according to the season).Of course, if more detailed calculations were done in another software and if the behaviour of the system was simulated in a more detailed model , then the results for the proposed facade design would be different. For example,if the adaptive control would be taken into consideration for the pcm based design then the calculated cooling loads would be lower than they are presented.



Graph 7.6: Annual energy consumption for fully glazed double skin facade (Amsterdam)



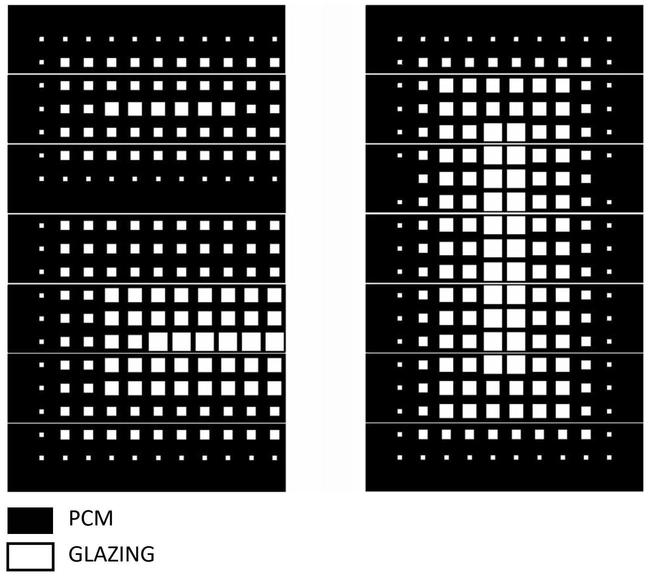
Graph 7.7: Energy consumption for fully glazed double skin facade (Amsterdam)

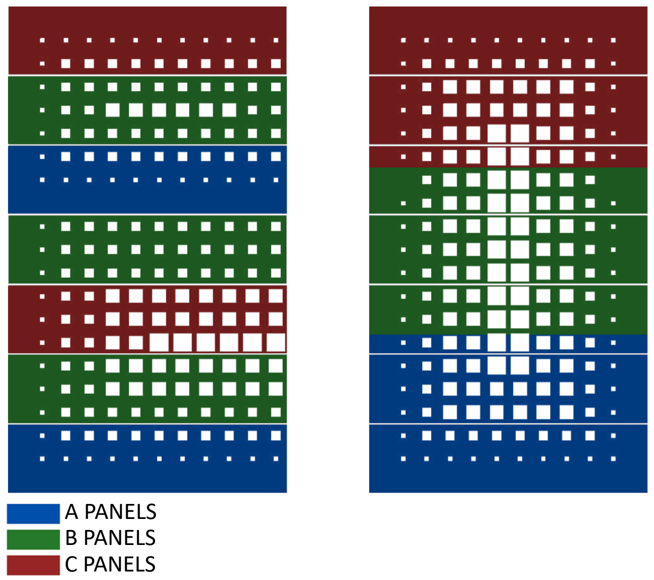
CASE 2 | ATHENS

FACADE PATTERN 1

The glazing percentage of each PCM group are presented in the table.
The total glazing percentage of the facade is 18.64%.

FACADE SEGMENT 1 FACADE SEGMENT 2





INPUT DATA	
PATTERN 1	
TOTAL GLAZING PERCENTAGE	18.64%
FAÇADE SEGMENT 1	
TOTAL PERCENTAGE A PANELS	26.55%
TOTAL PERCENTAGE B PANELS	46.90%
TOTAL PERCENTAGE C PANELS	26.55%
GLAZING PERCENTAGE A PANELS	6%
GLAZING PERCENTAGE B PANELS	20.00%
GLAZING PERCENTAGE C PANELS	22.00%
FAÇADE SEGMENT 2	
TOTAL PERCENTAGE A PANELS	33.30%
TOTAL PERCENTAGE B PANELS	33.30%
TOTAL PERCENTAGE C PANELS	33.30%
GLAZING PERCENTAGE A PANELS	16.00%
GLAZING PERCENTAGE B PANELS	26.00%
GLAZING PERCENTAGE C PANELS	16.00%
TOTAL GLAZING PERCENTAGE (SEGMENT 1)	15.00%
TOTAL GLAZING PERCENTAGE (SEGMENT 2)	20.00%

Table 7.9: Input data for Pattern 1 (Athens)

Possible PCM combinations
1)21,25,29
2)21,25,31

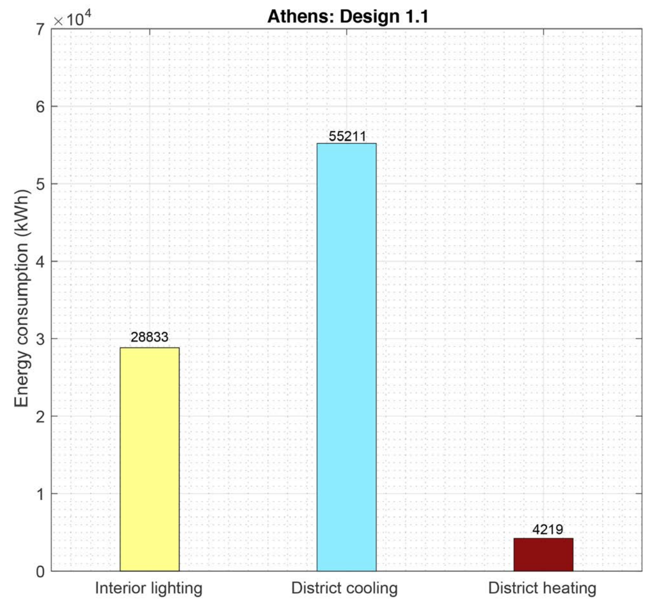
Figures 7.15:The facade patterns of both facade segments,design made by the author through Grasshopper

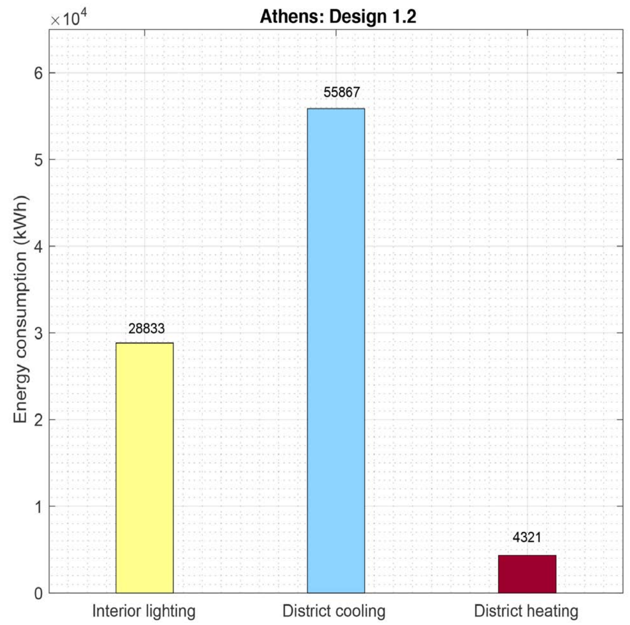
RESULTS

DESIGN 1.1	SP21, SP25, SP29		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	4219
Cooling	0	55211	0
Interior lighting	28833	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	49872.43	64278.95	8152.64
Energy Per Total Building Area [kWh/m2]			
	149.62		

DESIGN 1.2	SP21, SP25, SP31		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	4321
Cooling	0	55867	0
Interior lighting	28833	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	49872.43	64390	8254.64
Energy Per Total Building Area [kWh/m2]			
	149.98		

Table 7.10: Results for Design 1.1 and 1.2 (Athens)

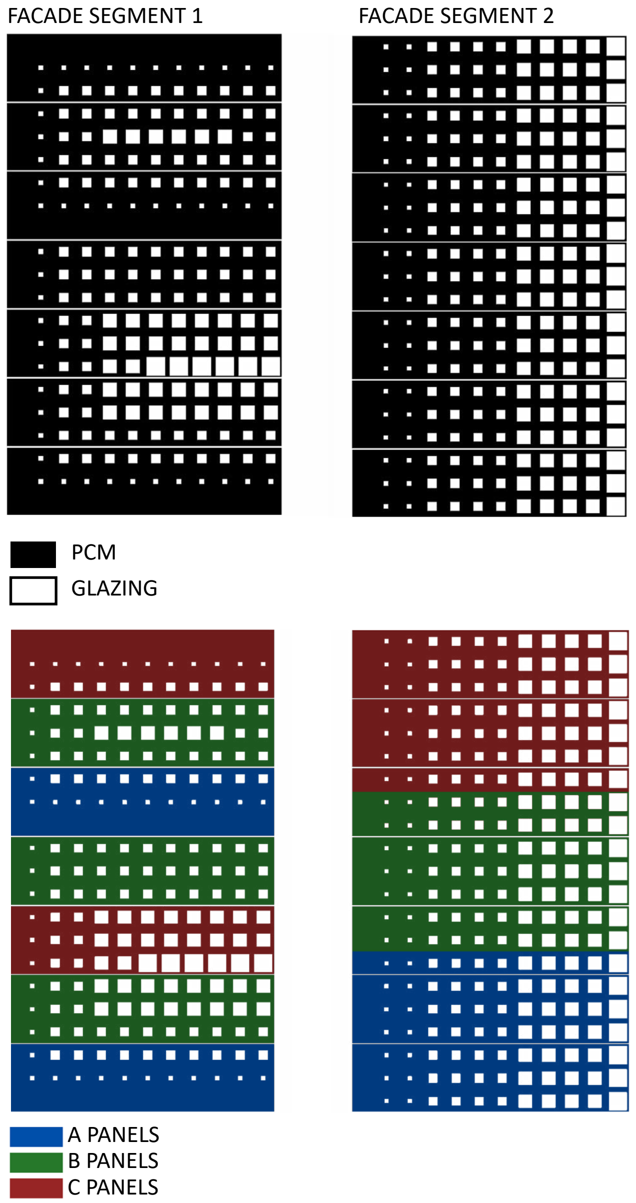




Graph 7.8: Energy consumption for Design 1.1 and 1.2 (Athens)

FACADE PATTERN 2

The glazing percentage of each PCM group are presented in the table.
The total glazing percentage of the facade is 21.55%.



Possible PCM combinations
1)21,25,29
2)21,25,31

Figure 7.16: The facade patterns of both facade segments,design made by the author through Grasshopper

INPUT DATA	
PATTERN 2	
TOTAL GLAZING PERCENTAGE	21.55%
FAÇADE SEGMENT 1	
TOTAL PERCENTAGE A PANELS	26.55%
TOTAL PERCENTAGE B PANELS	46.90%
TOTAL PERCENTAGE C PANELS	26.55%
GLAZING PERCENTAGE A PANELS	6%
GLAZING PERCENTAGE B PANELS	20.00%
GLAZING PERCENTAGE C PANELS	22.00%
FAÇADE SEGMENT 2	
TOTAL PERCENTAGE A PANELS	33.30%
TOTAL PERCENTAGE B PANELS	33.30%
TOTAL PERCENTAGE C PANELS	33.30%
GLAZING PERCENTAGE A PANELS	24.00%
GLAZING PERCENTAGE B PANELS	24.00%
GLAZING PERCENTAGE C PANELS	24.00%
TOTAL GLAZING PERCENTAGE (SEGMENT 1)	15.00%
TOTAL GLAZING PERCENTAGE (SEGMENT 2)	24.00%

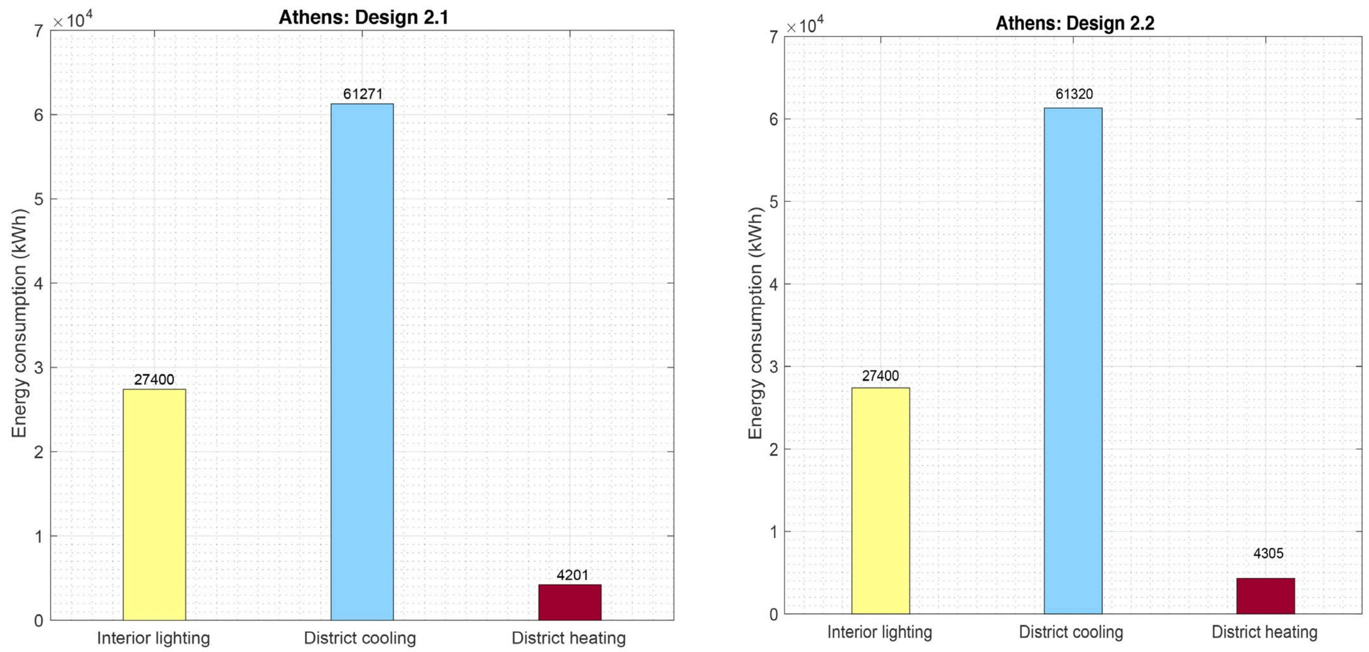
Table 7.11: Input data for Pattern 2 (Athens)

RESULTS

DESIGN 2.1	SP21, SP25, SP29		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	4201
Cooling	0	61271	0
Interior lighting	27400	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	48439.43	61271	8134.64
Energy Per Total Building Area [kWh/m2]			
	152.65		

DESIGN 2.2	SP21, SP25, SP31		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	4305
Cooling	0	61320	0
Interior lighting	27400	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	48439.43	64390	8238.64
Energy Per Total Building Area [kWh/m2]			
	152.97		

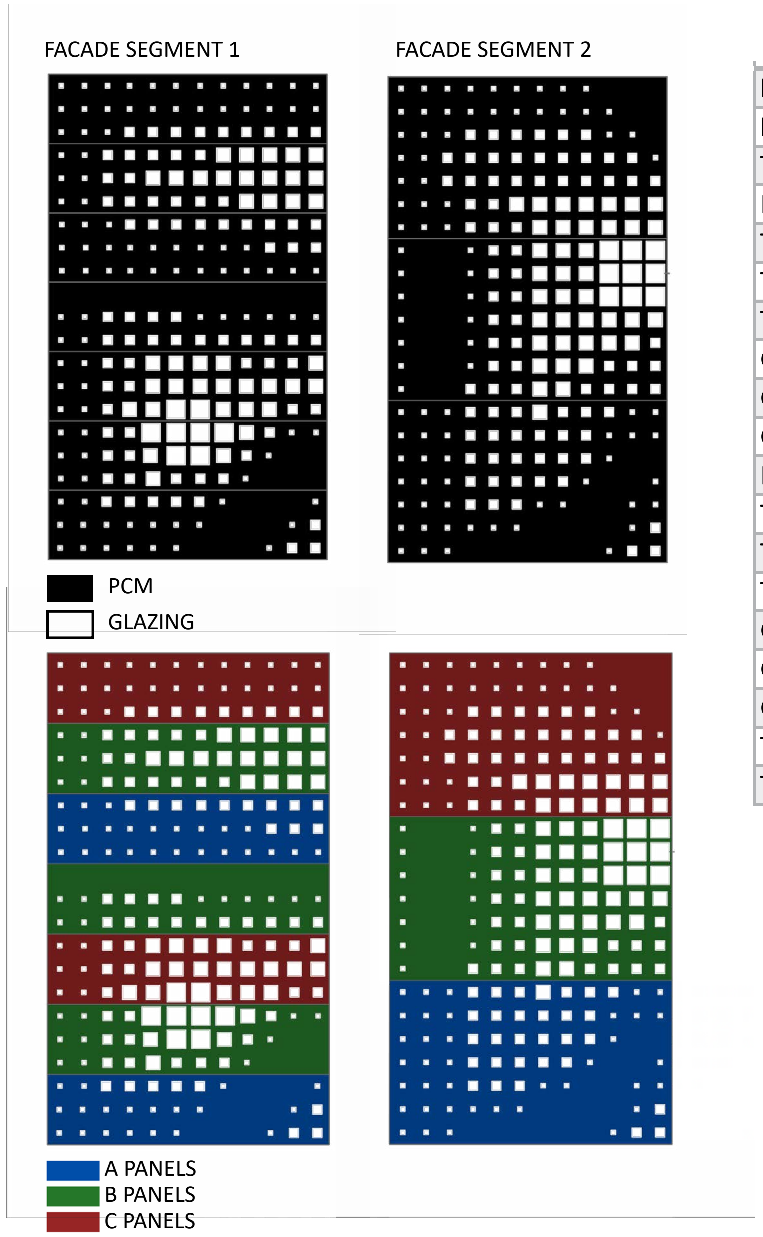
Table 7.12: Results for Design 2.1 and 2.2 (Athens)



Graph 7.9: Energy consumption for Design 2.1 and 2.2 (Athens)

FACADE PATTERN 3

The glazing percentage of each PCM group are presented in the table.
The total glazing percentage of the facade is 18.64%.



Possible PCM combinations
1)21,25,29
2)21,25,31

Figures 7.17: The facade patterns of both facade segments,design made by the author through Grasshopper

INPUT DATA	
PATTERN 3	
TOTAL GLAZING PERCENTAGE	17.60%
FAÇADE SEGMENT 1	
TOTAL PERCENTAGE A PANELS	26.55%
TOTAL PERCENTAGE B PANELS	46.90%
TOTAL PERCENTAGE C PANELS	26.55%
GLAZING PERCENTAGE A PANELS	10%
GLAZING PERCENTAGE B PANELS	21.00%
GLAZING PERCENTAGE C PANELS	20.00%
FAÇADE SEGMENT 2	
TOTAL PERCENTAGE A PANELS	33.30%
TOTAL PERCENTAGE B PANELS	33.30%
TOTAL PERCENTAGE C PANELS	33.30%
GLAZING PERCENTAGE A PANELS	15.00%
GLAZING PERCENTAGE B PANELS	20.00%
GLAZING PERCENTAGE C PANELS	18.00%
TOTAL GLAZING PERCENTAGE (SEGMENT 1)	17.50%
TOTAL GLAZING PERCENTAGE (SEGMENT 2)	17.66%

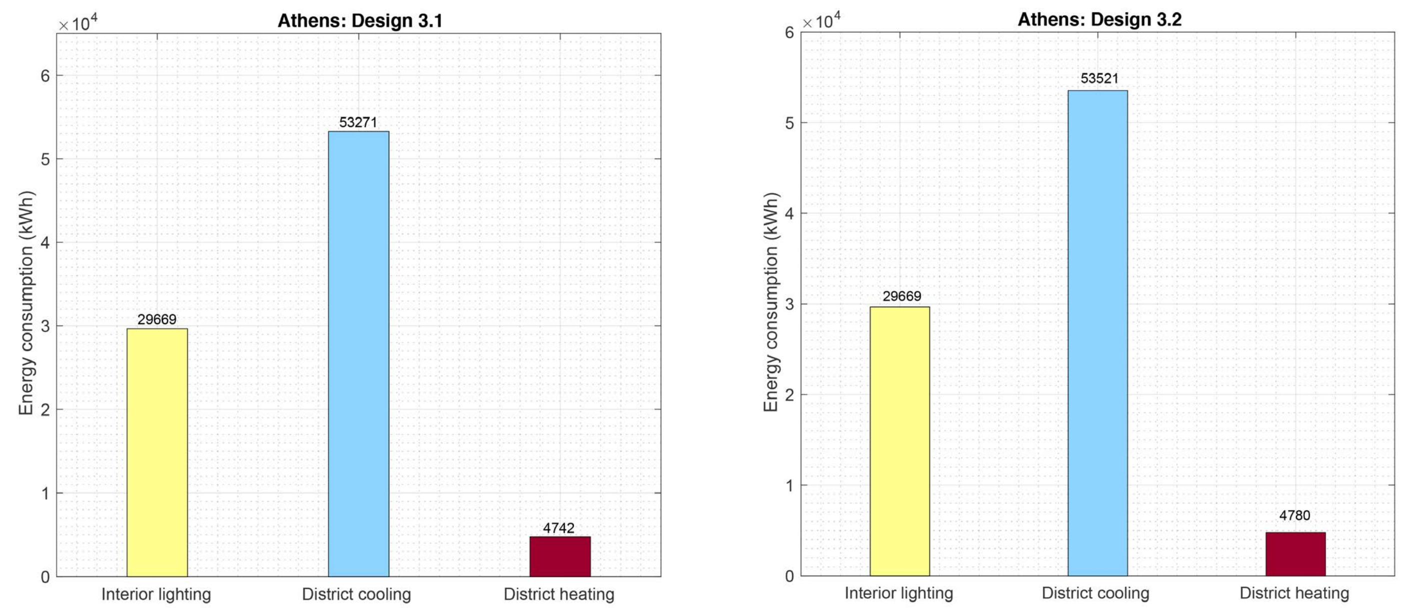
Table 7.13: Input data for Pattern 3 (Athens)

RESULTS

DESIGN 3.1	SP21, SP25, SP29		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	4742
Cooling	0	53271	0
Interior lighting	29669	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	50708.43	53271	8675.64
Energy Per Total Building Area [kWh/m2]			
	148.85		

DESIGN 3.2	SP21, SP25, SP31		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	4780
Cooling	0	53521	0
Interior lighting	29669	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	50708.43	53521	8713.64
Energy Per Total Building Area [kWh/m2]			
	149.2		

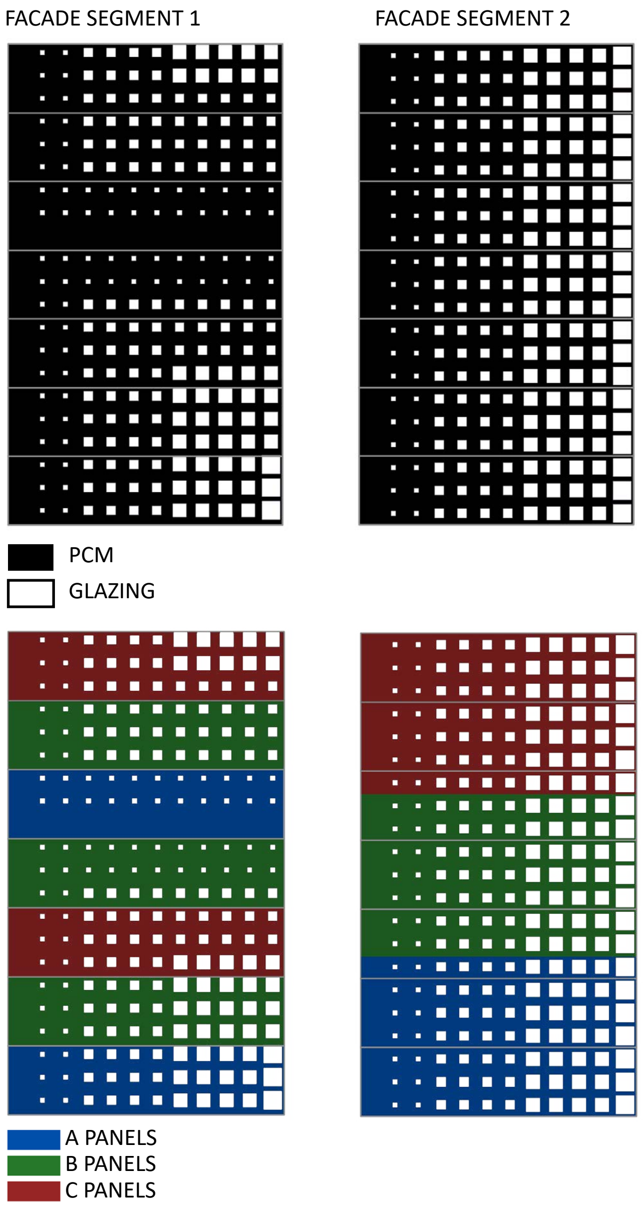
Table 7.14: Results for Design 3.1 and 3.2 (Athens)



Graph 7.10: Energy consumption for Design 3.1 and 3.2 (Athens)

FACADE PATTERN 4

The glazing percentage of each PCM group are presented in the table.
The total glazing percentage of the facade is 18.64%.



Possible PCM combinations
1)21,25,29
2)21,25,31

Figure 7.18: The facade patterns of both facade segments,design made by the author through Grasshopper

INPUT DATA	
PATTERN 4	
TOTAL GLAZING PERCENTAGE	21.8%
FAÇADE SEGMENT 1	
TOTAL PERCENTAGE A PANELS	26.6%
TOTAL PERCENTAGE B PANELS	46.9%
TOTAL PERCENTAGE C PANELS	26.6%
GLAZING PERCENTAGE A PANELS	12.5%
GLAZING PERCENTAGE B PANELS	18%
GLAZING PERCENTAGE C PANELS	17%
FAÇADE SEGMENT 2	
TOTAL PERCENTAGE A PANELS	33.3%
TOTAL PERCENTAGE B PANELS	33.3%
TOTAL PERCENTAGE C PANELS	33.3%
GLAZING PERCENTAGE A PANELS	24%
GLAZING PERCENTAGE B PANELS	24%
GLAZING PERCENTAGE C PANELS	24%
TOTAL GLAZING PERCENTAGE (SEGMENT 1)	16%
TOTAL GLAZING PERCENTAGE (SEGMENT 2)	24%

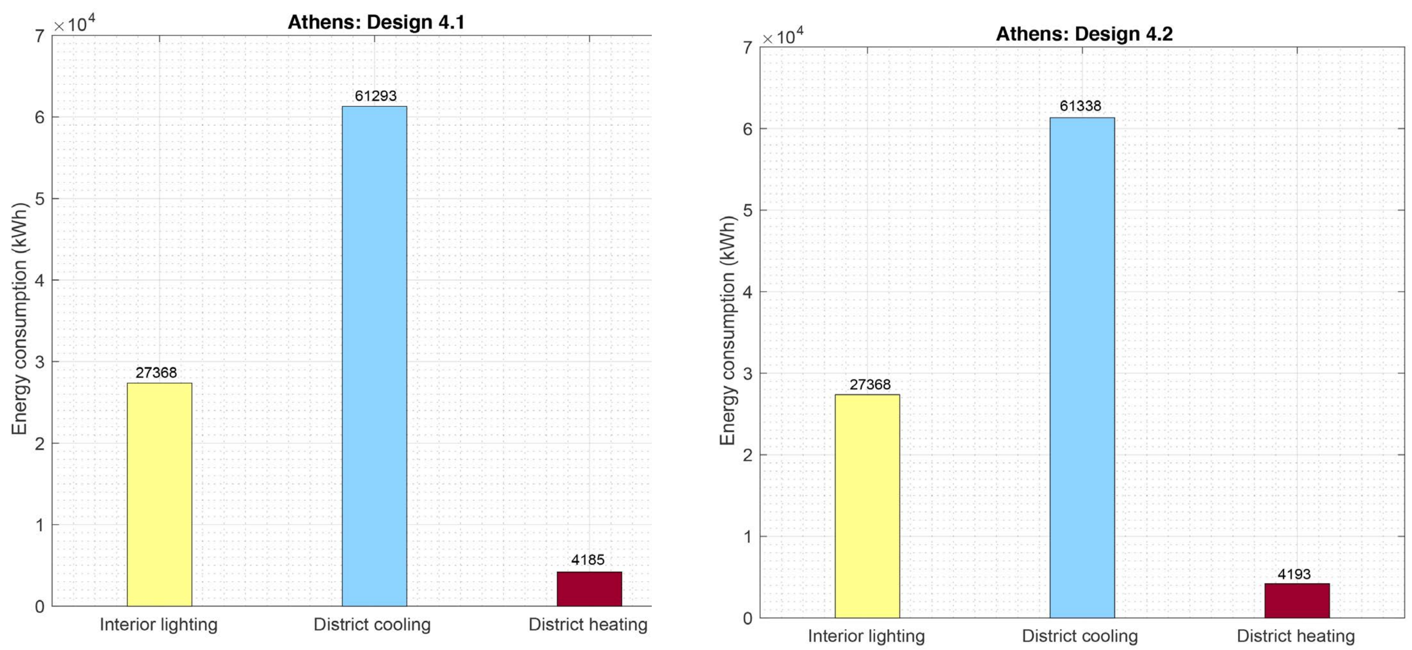
Table 7.15: Input data for Pattern 4 (Athens)

RESULTS

DESIGN 4.1	SP21, SP25, SP29		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	4185
Cooling	0	61293	0
Interior lighting	27368	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	48407.43	61293	8118.64
Energy Per Total Building Area [kWh/m2]			
	153.1		

DESIGN 4.2	SP21, SP25, SP31		
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	4193
Cooling	0	61338	0
Interior lighting	27368	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	48407.43	61338	8126.64
Energy Per Total Building Area [kWh/m2]			
	153.6		

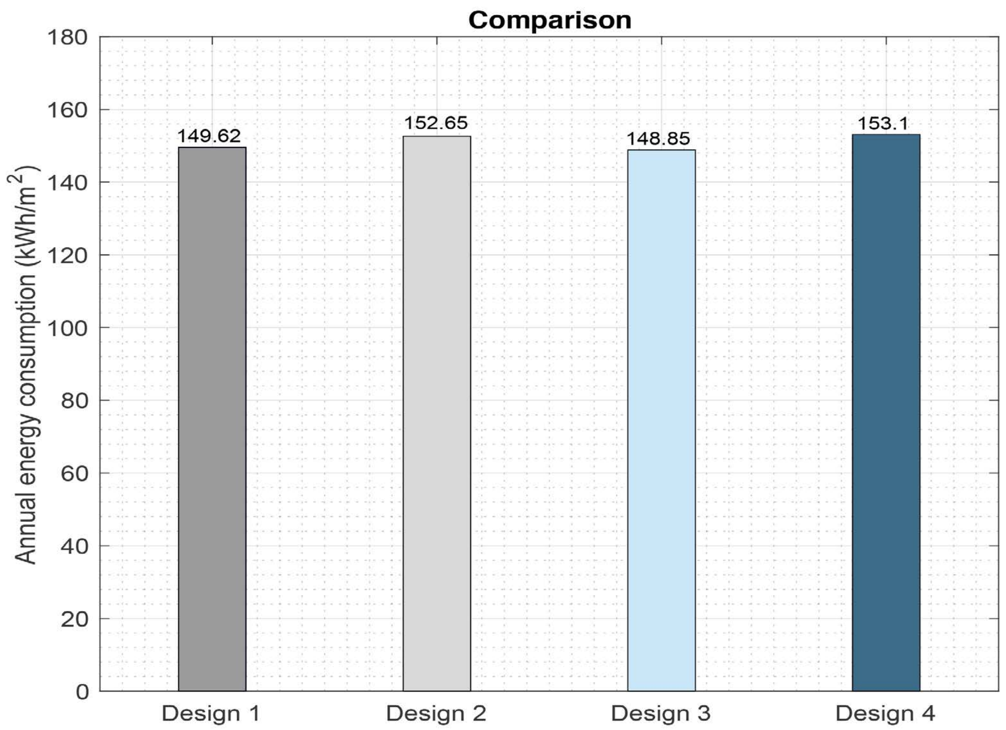
Table 7.16: Results for Design 4.1 and 4.2 (Athens)



Graph 7.11: Energy consumption for Design 3.1 and 3.2 (Athens)

ANALYSIS OF THE RESULTS

Taking account all the data collected by the energy simulations that are made for 4 alternative designs for Greece it is shown that the 3rd design is the most energy efficient since the annual energy consumption for heating,cooling and artificial lighting has the lowest value of all the other designs.
This happens because in this case the total glazing percentage of the facade has the lowest value of the other 3 designs.As a result,decreased solar heat gains and less cooling loads are appeared. However,in the 3rd design the low percentage in the glazing means more energy demands for artificial lighting in the building.
As the combination of the PCM types is concerned,SP21-SP25-SP29 is more energy efficient than SP21-SP25-SP31,as in all the designs the results have shown less energy consumption with the first combination.However, the differences appeared between the two combinations are really minor and if we take into account the inaccuracy level of the program(Design Builder),it is like there is almost no difference between the 2 choices.
A factor that seems to affect the results for each design is the proportion of SP21 in the facade or each one of the 4 designs.This specific type of PCM seems to be more energy efficient than the other types(show initial calculations) and consequently the least glazing (the more PCM proportion) we have in the A panels Group(SP21) the more energy efficient is the design.



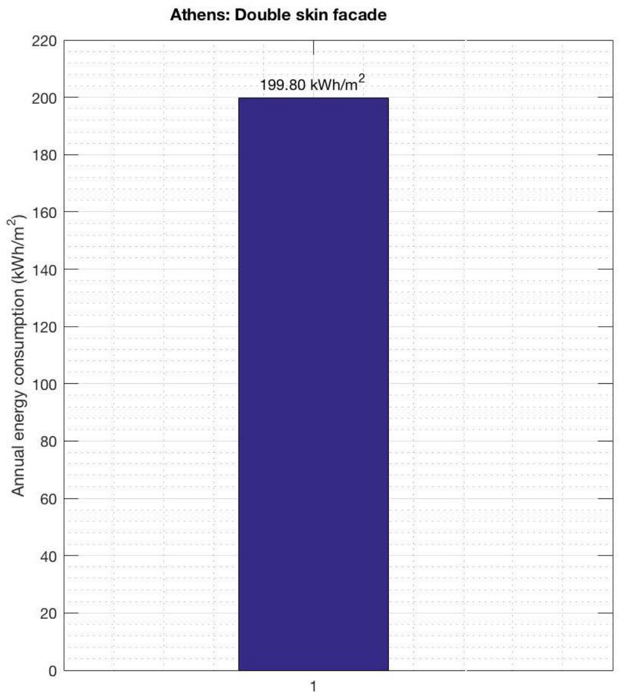
Graph 7.12: Comparisons for Designs 1 to 4 for Athens

DISCUSSION

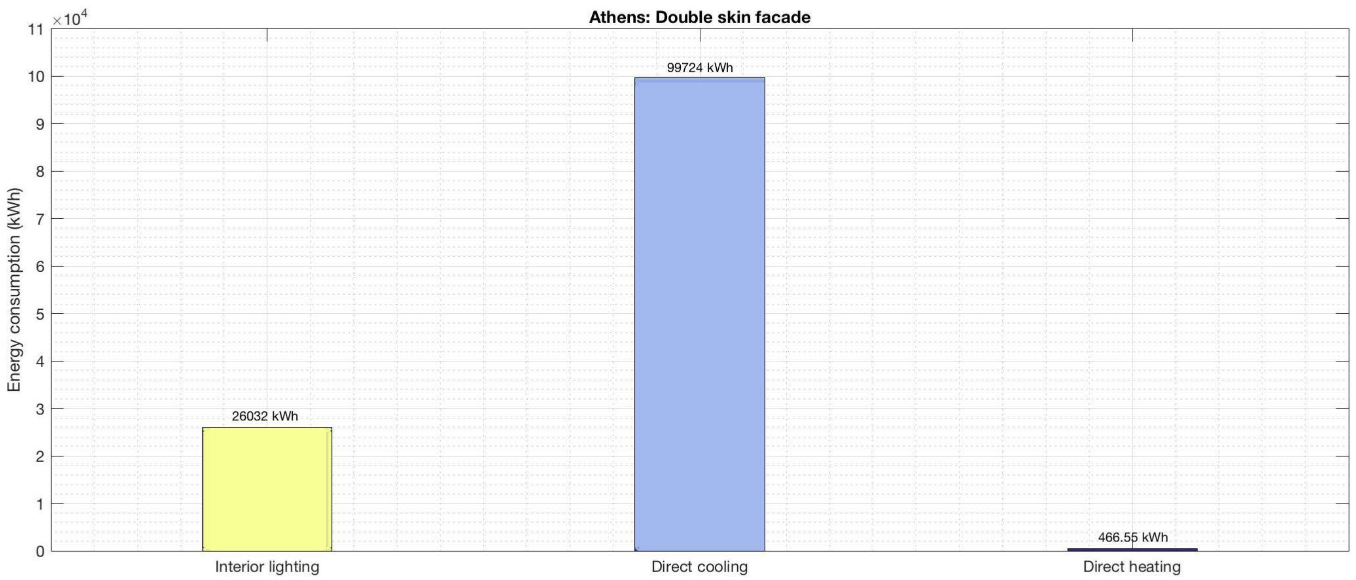
In order the facade designers to make the optimal choice of the PCM type or the PCM combination used in the facade in a mediterranean climate they should take into account several factors that can affect the efficiency of the PCMs and the energy performance of the system.
First of all, the climate is a really important factor to help a designer to choose the right PCM type.When the climate is mediterranean PCM with quite high melting temperatures can be used 21,25,29 or 31 °C.
However, these materias have a specific maximum operative temperature and it is preferable to be protected by the sun in the summer so as not to reach higher temperatures than the maximum operative one.This can be done with the use of shading systems applied to the facade in the summer. With this way not only the pcm will be protected by the high solar irradiation but also the cooling loads of the building in general will be decreased.
Another important factor is the combination of the PCM types that can be used.The melting temperatures of the PCMs used should follow the maximum and the average air temperatures of the area where the facade system is applied.
Another point of attention should be focused on the wind speed because the higher the wind speed in a district the lower the temperatures that will be appeared in the facade.

FULLY GLAZED DOUBLE SKIN FACADE

In order to be assessed the performance of the 3rd design ,a comparison with a fully glazed double skin facade will be done in terms of energy loads for heating,cooling and artificial lighting.
Taking into account the previous result of the 3rd design as far as the total energy consumption is concerned and comparing this with the energy results for the fully glazed facade system ,it is shown that the PCM based double skin is 25.5% more efficient than the fully glazed facade.
This happens because in the fully glazed double skin facade the cooling loads are much higher than the ones appeared in the PCM based double skin facade.



Graph 7.13: Annual energy consumption for fully glazed double skin facade (Athens)



Graph 7.14: Energy consumption for fully glazed double skin facade (Athens)

APPLICATION OF THE SHADING SYSTEM

As it was discussed before, a shading system can be integrated in the facade design in order to furthr decrease the cooling loads during the summer and prevent the PCM from exceeding their maximum operative temperature(60°C).
Two simulation models with 2 different shading systems were designed and calculated in terms of energy performance.The results are presented in the folowing tables.

1st SHADING SYSTEM (HORIZONTAL LOUVERS 0.5m)

DESIGN 3 NEW WITH SHADING TYPE 1	Louver shading system	SP21, SP25, SP29	
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	5392
Cooling	0	49556	0
Interior lighting	30285	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	51324.43	64390	9325.64
Energy Per Total Building Area [kWh/m2]	145.6		

Table 7.17: 1st Shading system

2nd SHADING SYSTEM (OVERHANGS 1m)

DESIGN 3 NEW WITH SHADING TYPE 2	Overhangs	SP21, SP25, SP29	
End uses			
	Electricity [kWh]	Direct Cooling [kWh]	District Heating [kWh]
Heating	0	0	5372
Cooling	0	48709	0
Interior lighting	30199	0	0
Interior equipment	21039.43	0	0
Water systems	0	0	3933.64
Total End Uses	51238.43	64390	9305.64
Energy Per Total Building Area [kWh/m2]	144.35		

Table 7.18: 2nd Shading system

As it observed by the tabular data, both shading systems contribute to the decrease of the energy consumption for cooling. It was discussed before that the cooling loads are the higher energy loads appeared in the building located in Athens (mediterranean climate).For this reason there is a slight difference (but not really large difference) in the results of the chosen design when both shading systems are applied.Another design logic that would have a higher positive impact is to apply a self regulating adaptive system that will behave in a flexible way according to the season.

PERSONAL REFLECTION ON THE LIMITATIONS

PCM DOUBLE SKIN FACADE OR DOUBLE SKIN FACADE IN THE LIBRARIES ?

This question is going to be answered taking into account the results steming from the energy simulations in Amsterdam and Athens respectively.

Amsterdam

In temperate climates like in Amsterdam, it is shown that the proposed system is less energy efficient than the double skin facade.This happens as in a conventional fully glazed double skin facade the solar heat gains are fully exploited because there is full exposure to the sun during the day(100% glazing percentage).On the other hand, the proposed system can work almost equally good if we take into consideration the fact that in the software (Design Builder) there is not this level of accuracy to integrate the adaptive optical behaviour of the PCMs when the change phase from solid (fully opaque panels) to liquid (transparent panels).Moreover, in order the proposed system to function well in a library, the optimal glazing percentage should be approximately 30-40 %.

Athens

Unlike Amsterdam, the facade system which is proposed is 25.5% more energy efficient than the double skin facade system.This was a result coming from energy calculations that does not integrate the adaptive behaviour of the system according to the seasons (operable windows and specific natural ventilation strategies).If the energy calculations are applied in another more accurate software and if all the variables of the system are integrated in the simulation model,the efficiency of the pcm-based system is expected to reach higher values compared to the conventional double skin facade system.
Another point that should be taken into account is that in a mediterranean climate where the solar irradiation is quite high during the whole year, a shading system should be applied in order to protect the PCM that has a maximum operative temperature of 60 ^{o}C.

The answer to the question is that as a facade designer I would propose the integration of this specific facade system in Greece in the library buildings because the energy efficiency of the system is high compared to a double skin facade.Nevertheless, a shading system should be applied in order to protect the PCM from excessive solar exposure.As far as the shading system is concerned, an adative shading system being able to regulate the amoun of heat falling on the PCM based facade will be more beneficial and can take into advantage the changing rates of the solar irradiation during the whole year.

As far as the Amsterdam case is concerned, there are some limitations of the system as it seems that the double skin facade functions better because of the increased solar heat gains.However, if specific measurements are taken, like ventilation strategies and if the right PCM types of salt hydrates are used in order to ensure that the PCM will melt during the day (the panels will be cme transparent), then the energy efficiency of the system can rise in higher levels.

8

the experiment

THE EXPERIMENT

Lab tests are done in the Building Physics laboratory at TU Delft so as to get to know the thermal behaviour of 3 different PCM s undergoing the same climate conditions.Additionally, with these physical tests , it is given useful information about the thermal cycle of each PCM separately, the duration of the melting and the solidification process and the amount of heat which is accumulated in the PCMs over time.

More specifically, they are investigated three different kinds of PCMs for this application.All of them are salt hydrates from Rubitherm company SP21 ,SP25 and SP 31 with melting points of 21 °C ,25°C and 31°C relatively. Big advantages of the salt hydrates are high values for heat of fusion and density.This gives even thin salt hydrate layers a sufficient storage capacity. A disadvantage is the supercooling of the salt hydrates, which can be reduced by nucleating agents, though. Moreover, only this category of PCM is selected as it is the only option that can be integrated in the facade system.Paraffins were excluded from the research because they are flammable PCMs and they cannot provide fire safety in a facade system.The basic properties of the materials selected for the physical measurements are shown in the table below.

SP 21 / RUBITHERM	Column1
PROPERTIES	
Melting area °C	22-23
Congealing area °C	21-19
Heat storage capacity(kJ/kg)	180
Specific heat capacity (kJ/kg *K)	2
Density solid(kg/m^3)	1.5
Density liquid(kg/m^3)	1.4
Volume expansion(%)	3
Heat conductivity (W/ m*K)	0.6
Max. operation temperature °C	45
Heat stored in 0.03 thk container (J/m2)	7560000

SP 25 / RUBITHERM	Column1
PROPERTIES	
Melting area °C	24-26
Congealing area °C	24-23
Heat storage capacity(kJ/kg)	180
Specific heat capacity (kJ/kg *K)	2
Density solid(kg/m^3)	1.5
Density liquid(kg/m^3)	1.4
Volume expansion(%)	3
Heat conductivity (W/ m*K)	0.6
Max. operation temperature °C	45
Heat stored in 0.03 thk container (J/m2)	8100000

SP 31 / RUBITHERM	Column1
PROPERTIES	
Melting area °C	31-33
Congealing area °C	28-30
Heat storage capacity(kJ/kg)	210
Specific heat capacity (kJ/kg *K)	2
Density solid(kg/m^3)	1.35
Density liquid(kg/m^3)	1.3
Volume expansion(%)	3
Heat conductivity (W/ m*K)	0.8
Max. operation temperature °C	45
Heat stored in 0.03 thk container (J/m2)	8505000

Table 8.1: Specifications of PCMs

EXPERIMENT SET UP

THE SAMPLES

All three PCMs are encapsulated in transparent plexiglas containers with a thickness of 0.03 m as it is shown in the figure.In order the containers to be constructed 5 layers of plexiglass sheets were stuck on the top of each other by using chloroform.Then, because of leakage problems that were occured during the measurements the samples were coated with a resin mixture.All pcms had to be in liquid form so as to be encapsulated in the containers..

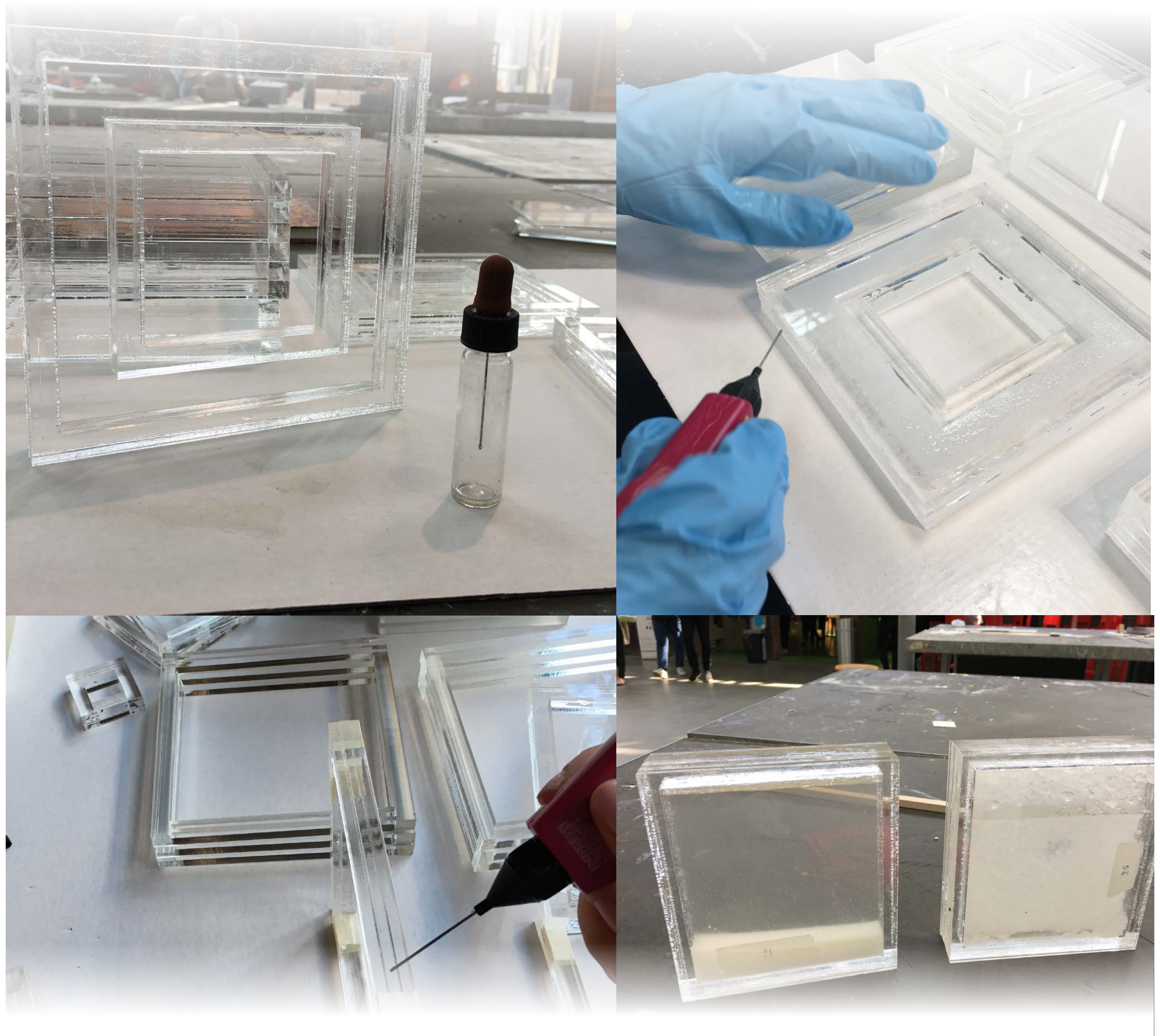


Figure 8.1: Creation of PCM based samples

THE CLIMATE BOX

The containers were placed inside a hole of a climate chamber in such a way so as the one surface to be exposed to the test room and the other to be inside the climate box.
Inside the climate chamber it is placed a bulb which is connected with a temperature regulator device , in order to be able to set up a specific temperature inside the box .For the melting process the PCM was placed(fully solidified) inside the hole of the climate box being exposed to 45°C till it melts completely. After melting, the bulb is switched off and the samples SP25 and SP 31 are placed out of box being exposed in room temperature (22.5 °C) so as to get solidified.A ventilator was also used in order to accelerate the solidification of the PCMs.
As far as th SP21 sample is concerned,unfortunately it was impossible to get it solidified and for this reason ,it is the only sample that contain measures of the half of the PCM sample (from solid to liquid state).

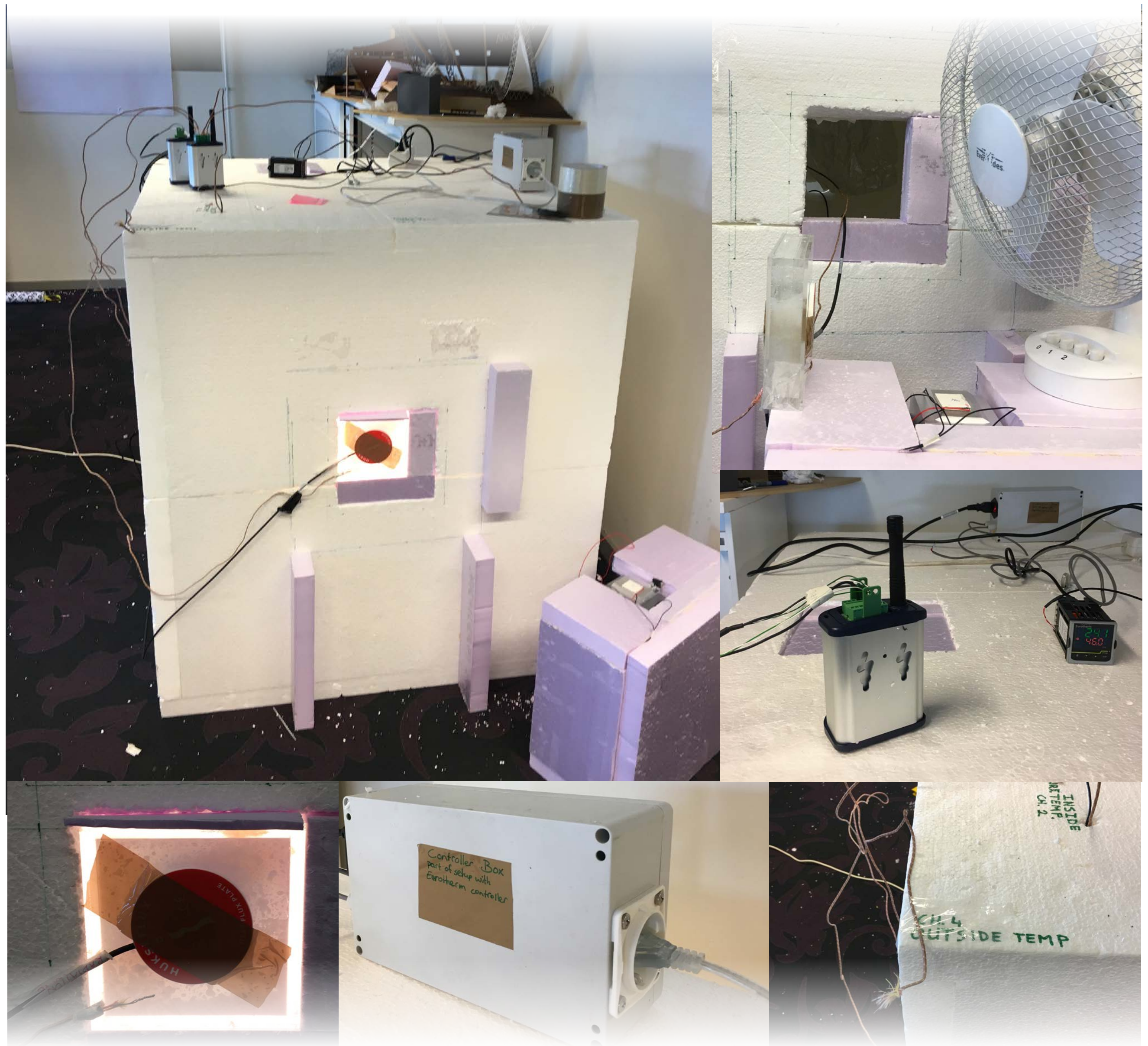


Figure 8.2: The conditions of the experiment, pictures taken by the author

PHYSICAL MEASUREMENTS

TEMPERATURE

The temperatures that are measured for the three samples are:

1. the temperature inside the climate box(the higher limit is 44 °C)
2. the room temperature (22.5°C approximately)
3. the temperature of the inside PCM surface (the surface facing the indoor space of the box)
4. the temperature of the outside PCM surface(the surface facing the room).

The meausurement of the temperature is realized by the use of a thermocouple device.(4 different channels representing the 4 different temperature measurements).
These specific measurement were done to give information about the duration of the melting and the solidification process of the PCM samples and the way of the heat storage which is done over the thermal cycle.The thermocouples are connected to a Eltek thermocouple transmitter, the heat flux sensors to a Eltek GS-44 transmitter. The data is recorded on a Squirrel RX250-AL, which sends the data to a laptop via the software Darca Plus.

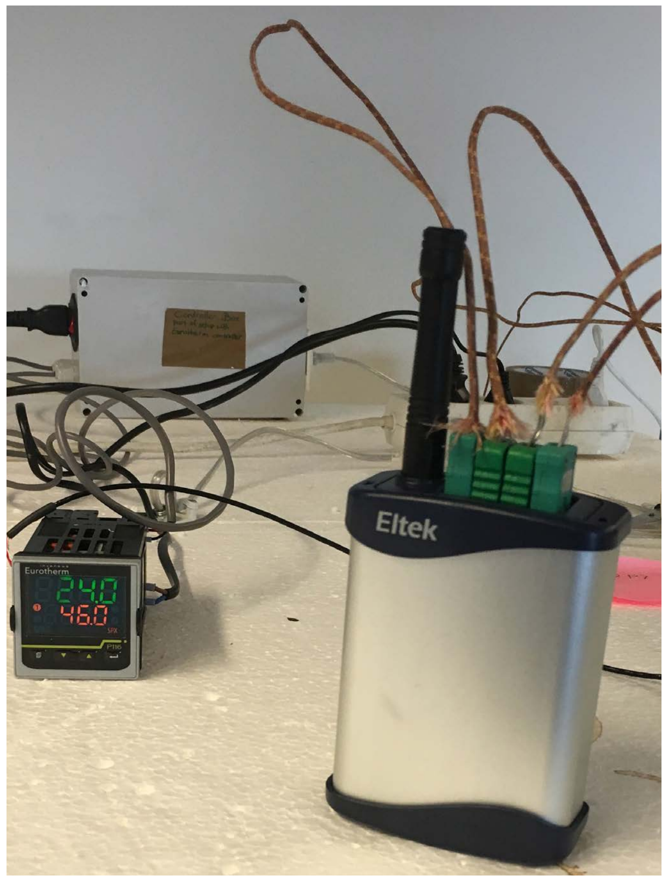


Figure 8..5:The thermocouple device

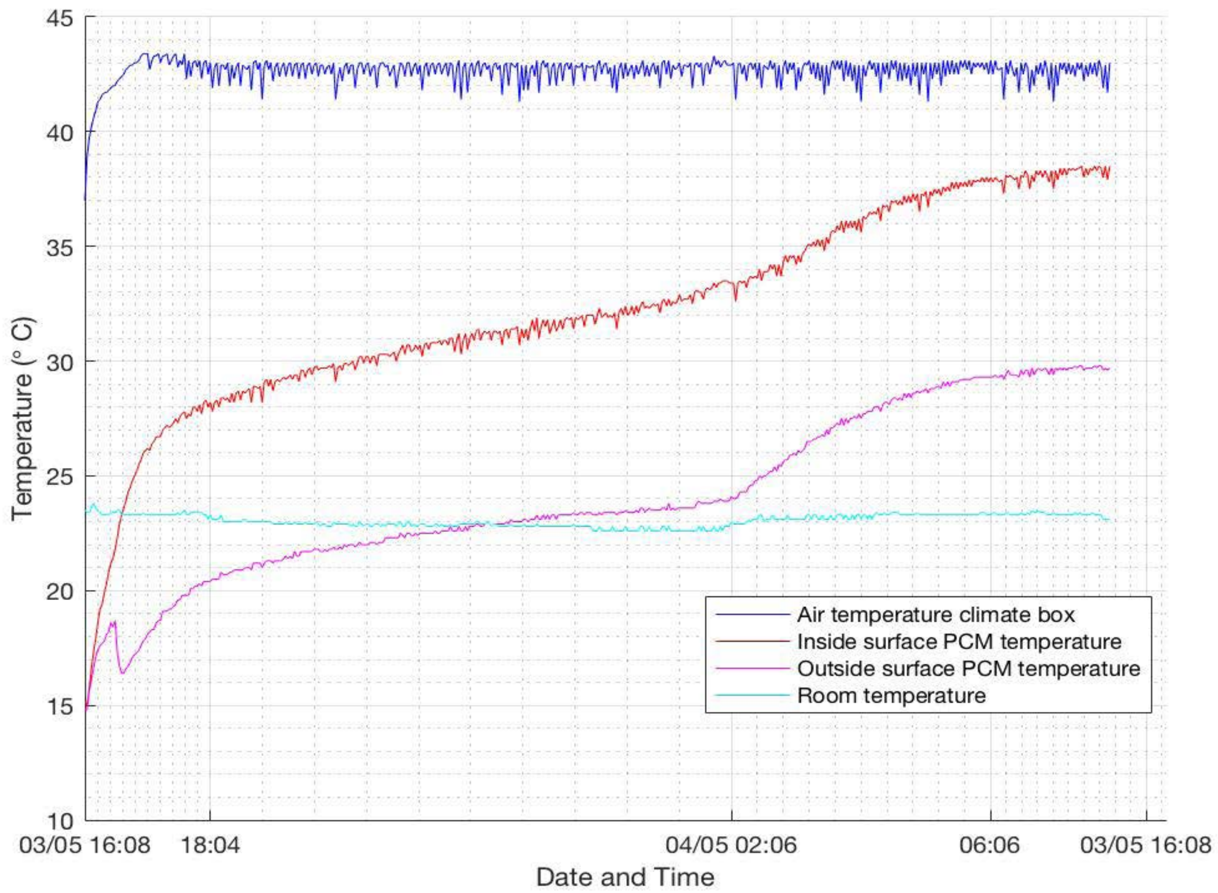
HEAT FLUX

Moreover, the heat fluxes of both the surfaces of the samples where measured with a pair of heat flux sensors.
The data exported by these tests indicate the way with which the heat is stored over the thermal cycle (sensible or latent heat storage) .Moreover,useful information about the maximum amount of heat which can be stored in the sample is given by these measurements.

Figure 8.3: Hukseflux heat flux plate.Reviewed from: http:// www.hukseflux.com/product_group/ heat-flux-sensors

Figure 8.4: The sensor in HFP01 is a thermopile. This thermopile measures the temperature difference across the ceramics-plastic composite body of HFP01. A thermopile is a passive sensor. Reviewed from: http://www.hukseflux.com/product_group/heat-ffflux ux-sensorswww. hukse ux.com/ product_group/heat-flux-sensors

SAMPLE 1: PCM 21 | TEMPERATURE MEASUREMENTS



Graph 8.1:Temperature measurements of the PCM 21. Graph exported from Eltec Darca Plus.

As it is shown from the graph the initial temperature of the sample SP21 is 15 ºC and the room temperature 22.5 ºC.In order the material to be in solid state , it was located in the fridge for a couple of hours.For the melting process it was required the sample to be exposed to 44ºC (temperature inside the box).In the first hour of the measurements,in both the surfaces of the sample there is a steep increase in the temperature till the temperature inside the box reaches and stabilizes to 44 ºC. From that time, the temperature in both surfaces of the sample continues increasing with a slower rate till it is almost stabilized for a little and then
it continues increasing in a stable way till both the temperatures of the sample are stabilized.The stabilization in the temperature indicates that the material has already been melted and it stores heat in a latent way.On the other hand, where temperature increase is observed this means that the material stores heat in a sensible way.By the time, that the temperature of the PCM is stabilized for a short time in the middle of the melting process, a transitional phase takes place between latent and sensible heat storage when heat is stored in a mixed- form.This means that the material is not fully melted and continues melting.By taking into account the data taken from the graph,the melting process duration is almost 14 hours.

TIME REQUIRED FOR MELTING ACCORDING TO ΔT

The duration of the melting process is also calculated by the equation below:

$$t=\frac{l * p * d}{h_i * (T_i - T_{pcm}) - h_e*(T_{pcm}-T_e)} \qquad (1)$$

where **t** is time (seconds)
l is heat storage capacity (J/Kg)
p is the density (kg/m$^{3)}$
d is the PCM thickness (m)
h_i is the heat transfer coefficient J/m^2*K(indoor space)
h_e is the heat transfer coefficient J/m^2*K(exterior)
T_{pcm} is the temperature of the PCM
T_i is the indoor temperature
T_e is the exterior temperature

Heat Capacity(kJ /kg)	Density(kg/m^3)	Thickness(m)	Heat transfer coef in	Heat transfer coef/o
PCM21				
180	1450	0.03	7.8	7.8
Tpcm(°C)	Tin(°C)	Tout(°C)	Time for melting(s)	Time melting (h)
21	45	22	43596.88	12.1

Table 8.1: The data given for the sample PCM 21 and the required hours for full melting of the PCM.

The duration of the melting process based on ΔT is 12.1 hours for the sample PCM 21. Compared to the physical measurements, the hand calculations indicate less time for melting (2 hours less).This deviation occurs because the initial temperature in the climate box is not 45 ºC .It is also required almost an hour till the box reaches this temperature.However, these results are not refered to real conditions because no solar irradiation is taken into account.

TIME REQUIRED FOR MELTING BASED ON SOLAR IRRADIATION

The duration of the melting process is also calculated by the equation below:

$$t=\frac{l * p * d}{\alpha * q_{sol}} \qquad (2)$$

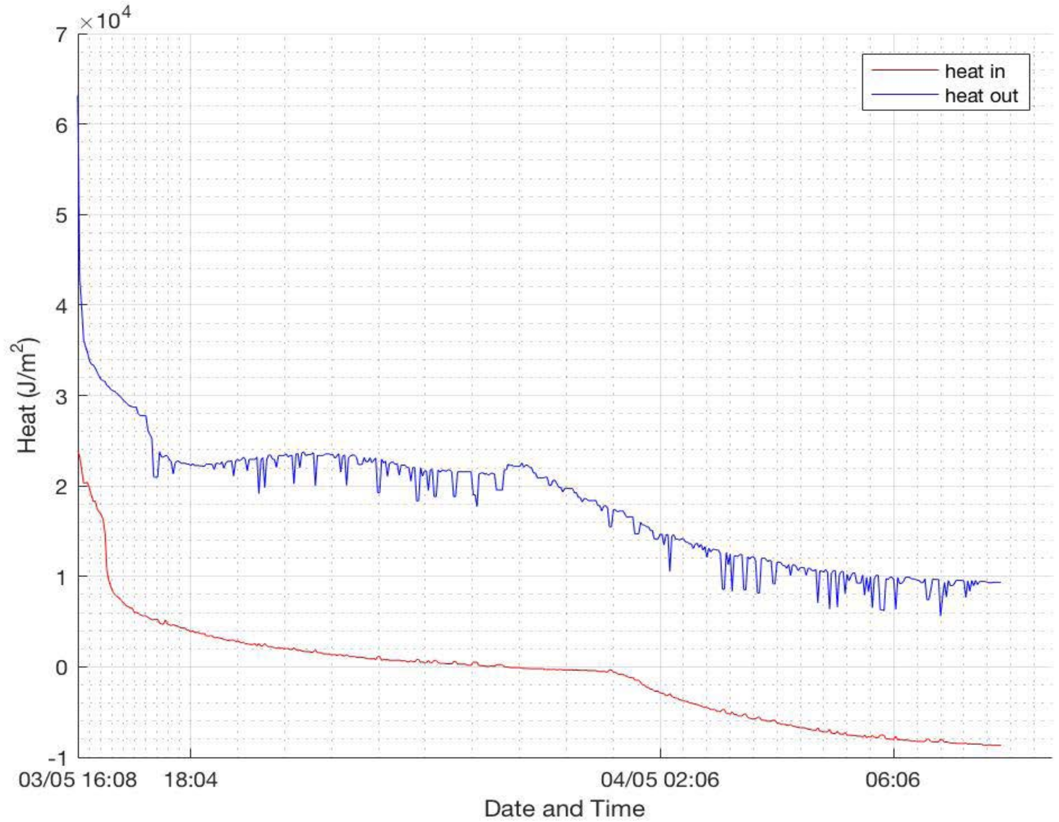
where **t** is time (seconds)
l is heat storage capacity (J/Kg)
p is the density (kg/m^{3})
d is the PCM thickness (m)
α is the absorption coefficient , assuming that α= 0.8
q_{sol} is the solar irradiation (W/m^2)

Heat Capacity(kJ /kg)	Density(kg/m^3)	Thickness(m)	Heat absorption coef	Solar irradiation(W/m2)	Time (h)
PCM21					
170	1400	0.03	0.8	300	8.56

Table 8.2: The data given for the sample PCM 21 and the required hours for full melting of the PCM.

If the solar irradiation is taken into consideration then the PCM21 needs almost the half of the duration that was measured before so as to get fully melted.This means that the material will be able to get melted during the day and get solidified at nighting providing passive heating during the winter.

SAMPLE 1: PCM 21 | HEAT FLUX MEASUREMENTS



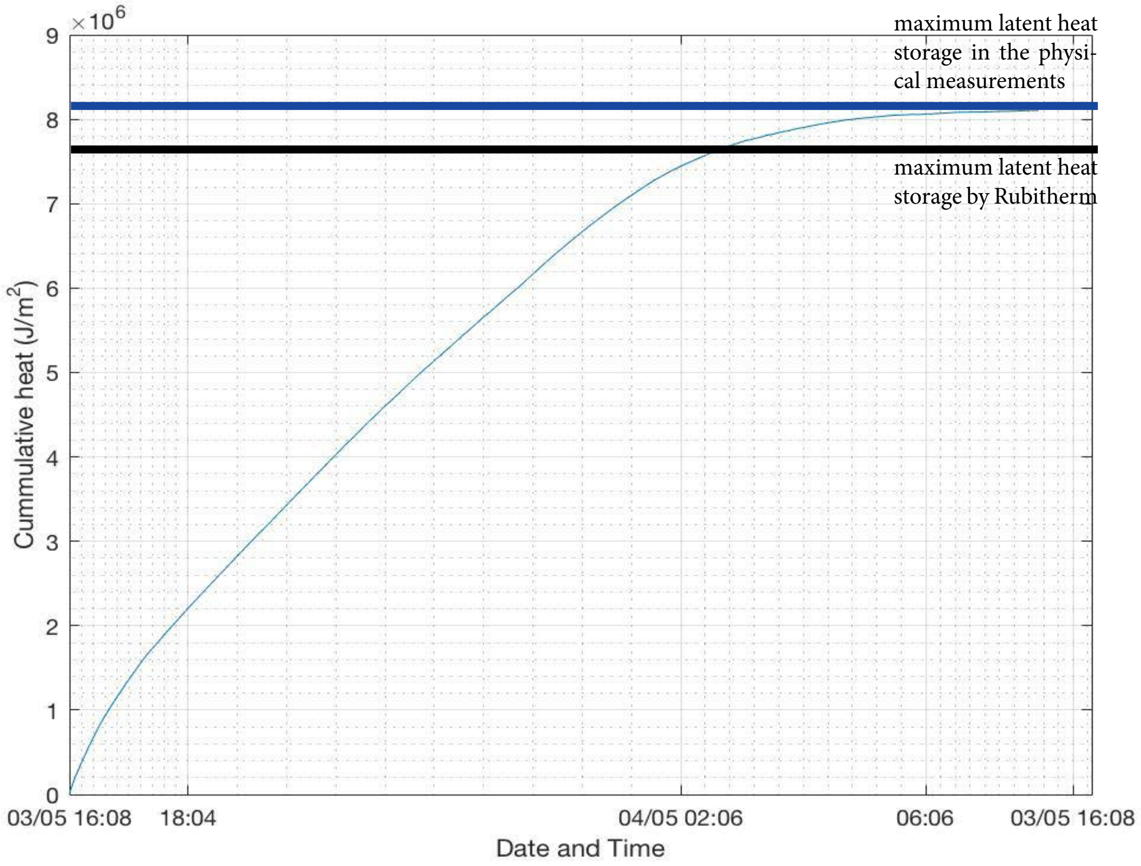
Graph 8.2:Heat transfer from the inside and the outside .Graph data exported from Eltec Darca Plus.Graph made by the author.

The heat flux measurements are helpful in order the cummulative heat to be calculated and information about the heat storage capacity of the system to be given. As it is data of the pcm 21 given by the manufacturer are shown in the table below:

SP 21 / RUBITHERM	Column1
PROPERTIES	
Melting area °C	22-23
Congealing area °C	21-19
Heat storage capacity(kJ/kg)	180
Specific heat capacity (kJ/kg *K)	2
Density solid(kg/m^3)	1.5
Density liquid(kg/m^3)	1.4
Volume expansion(%)	3
Heat conductivity (W/ m*K)	0.6
Max. operation temperature °C	45
Heat stored in 0.03 thk container (J/m2)	7560000

Table 8.3:Properties of SP 21 . Data reviewed from : https://www.rubitherm.eu/media/products/datasheets/Techdata_-SP21EK_EN_30092016.PDF, table redrawn by the author

SAMPLE 1: PCM 21 | CUMMULATIIVE HEAT MEASUREMENTS



Graph 8.3:The heat stored over time.Graph made by the author

As it is shown from the graph , the heat which is totally stored by the pcm 21 reaches the value calculated in the previous table based on the manufacturer's data about the specific phase change material.Moreover, when the heat is stored in a latent way , the increase is constant and the graph should represent a straight line in the graph with a uniform slope all along its length.The heat is calculated:

$$Q_{total} = q_{in} + q_{out}$$

where:
q_{in} is the heat transfered to the PCM from the inside
q_{out} is the heat transfered to the PCM from the outside

and $$q_{in} = h_{in} (T_{in} - T_{pcm})$$

$$q_{out} = h_{out}(T_{pcm} - T_{out})$$

where h_{in}= 7.8 (heat transfer coefficient)
$h_{out}=h_{in}$ (measurements are done inside a room and not outside)
T_{in} is the temperature inside the box
Tout is the room temperature
$T_{pcm}=21^oC$ (the temperature of the PCM/constant value)

When the latent heat storage takes place the Qtotal is a constant value as the temperature of the PCM remains stable.This is why the cumulative heat graph should represent a straight line showing the continuous and uniform increase of the heat stored over the time.

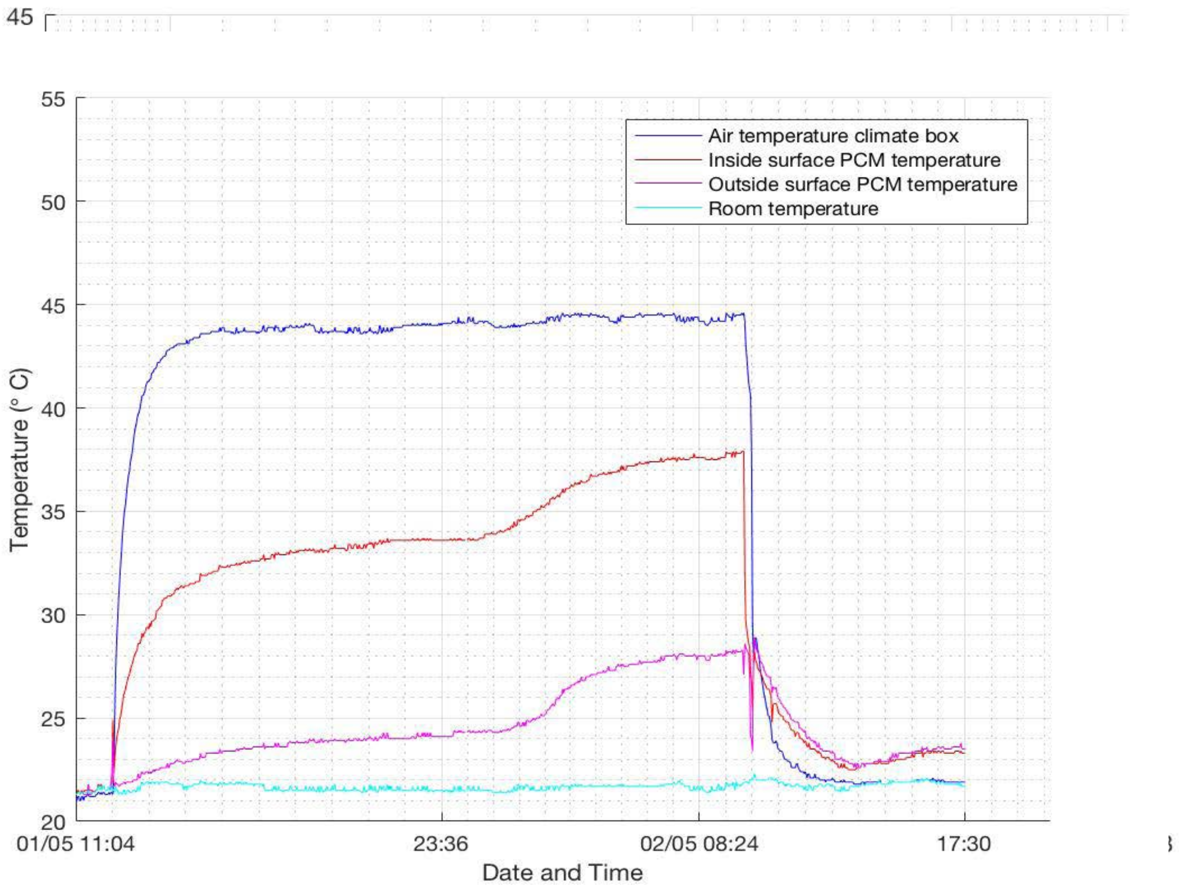
HEAT STORAGE

On the other hand when the PCM stores heat in a sensible way , the temperature of the PCM increases over time.This means that the Q_{tot} which is calculated again will not have a constant value but in fact it will change over time.Graphically, this means that the cummulative heat will be represented with a curved and not a straight line.

The graph in general shows a line which starts with a small curvature (sensible heat stored) and then in the middle of the cycle there is a slight curvature and the line is amost straight which indicates a mixed form storage (both latent and sensible heat stored as the material is melted but not fully melted) .Afterwards, there is a clear curved line which represents a form of sensible heat and in the end of the cycle the line become again straight showing a form of latent heat.

In general the heat which is stored in the PCM during the thermal cycle is 8.2 * 10^6 J/m^2 .This value is quite higher than the maximum latent heat storage measured by the manufacturer which is 7.56* 10^6 J/m^2 .This happens as the material also stores except for latent heat storage a smal part of sensible heat storage.

SAMPLE 2 : PCM 25|TEMPERATURE MEASUREMENTS



Graph 8.4:Temperature measurements of the PCM 21. Graph exported from Eltec Darca Plus.

As it is shown from the graph the initial temperature of the sample SP25 is 21 °C and the room temperature 22.5 °C.The material was 90% in solid state.For the melting process it was required the sample to be exposed to 44°C (temperature inside the box).In the first hour of the measurements,in both the surfaces of the sample there is a steep increase in the temperature till the temperature inside the box reaches and stabilizes to 44 °C.From that time, the temperature in both surfaces of the sample continues increasing in a stable rate till it is almost stabilized for a little and then it continues increasing in a stable way till both the temperatures of the sample are stabilized.The first stabilization shows that at that point of time the pcm stores heat in a latent way but later the temperature starts again increasing till it reaches a stable value (till it is fully melted).By taking into account the data taken from the graph,the melting process duration is almost 20 hours.

TIME REQUIRED FOR MELTING ACCORDING TO ΔT

The duration of the melting process is also calculated by the equation 1 ,described in the previous sample.The table below indicates the amount of time that is needed so as the PCM 25 to get fully melted.

Heat Capacity(kJ /kg)	Density(kg/m^3)	Thickness(m)	Heat transfer coef in	Heat transfer coef/ o
PCM25				
180	1450	0.03	7.8	7.8
Tpcm(°C)	Tin(°C)	Tout(°C)	Time for melting(s)	Time melting (h)
25	45	22	59049.77	16.4

Table 8.4: The data given for the sample PCM 25 and the required hours for full melting of the PCM.

The duration of the melting process based on ΔT is 16.4 hours for the sample PCM 25. Compared to the physical measurements, the hand calculations indicate less time for melting (3.5 hours less). This deviation occurs because the initial temperature in the climate box is not 45 °C .A couple of hours are also required till the box reaches this temperature.However, these results are not refered to real conditions because no solar irradiation is taken into account.

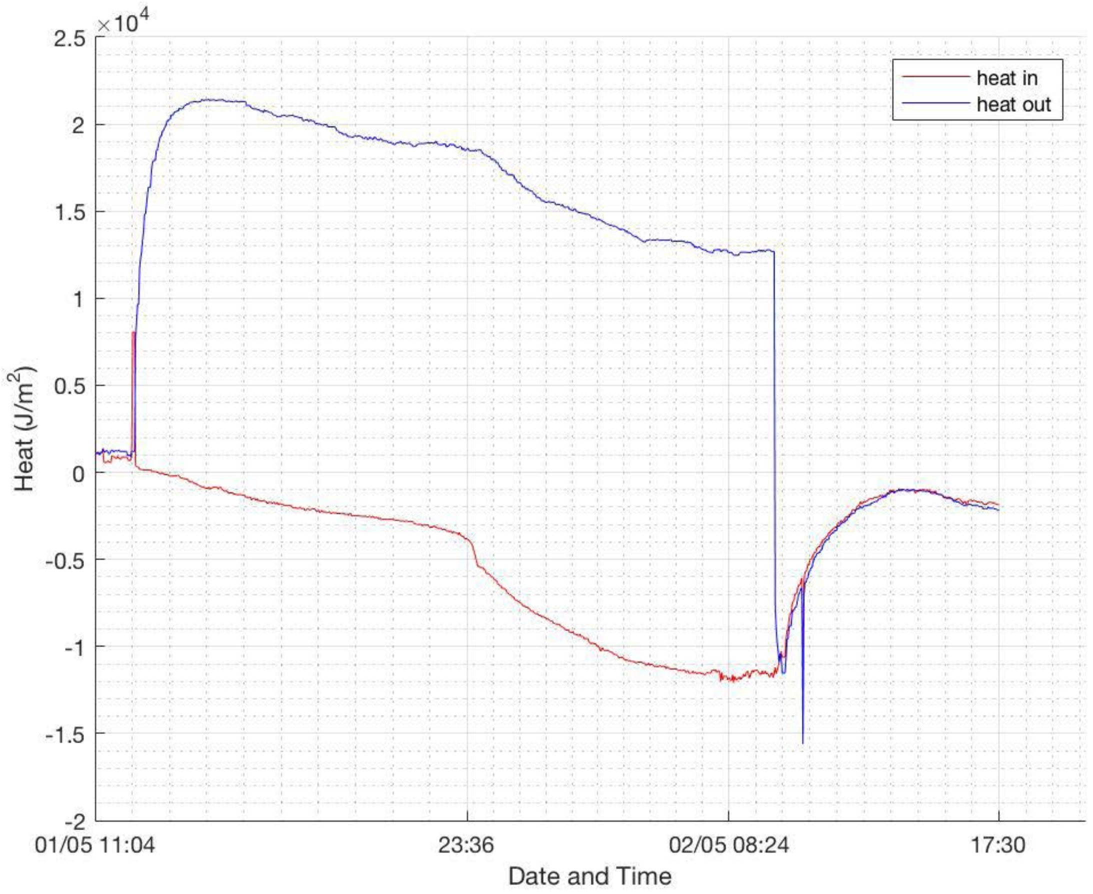
TIME REQUIRED FOR MELTING BASED ON SOLAR IRRADIATION

It is logical that with the sun's presence the melting procedure for the PCM requires much less time than it is measured in the physical test.

Heat Capacity(kJ /kg)	Density(kg/m^3)	Thickness(m)	Heat absorption coef	Solar irradiation(W/m2)	Time (h)
PCM25					
180	1450	0.03	0.8	300	9.06

Table 8.5: The required hours for full melting of the PCM.

SAMPLE 2: PCM 25| HEAT FLUX MEASUREMENTS



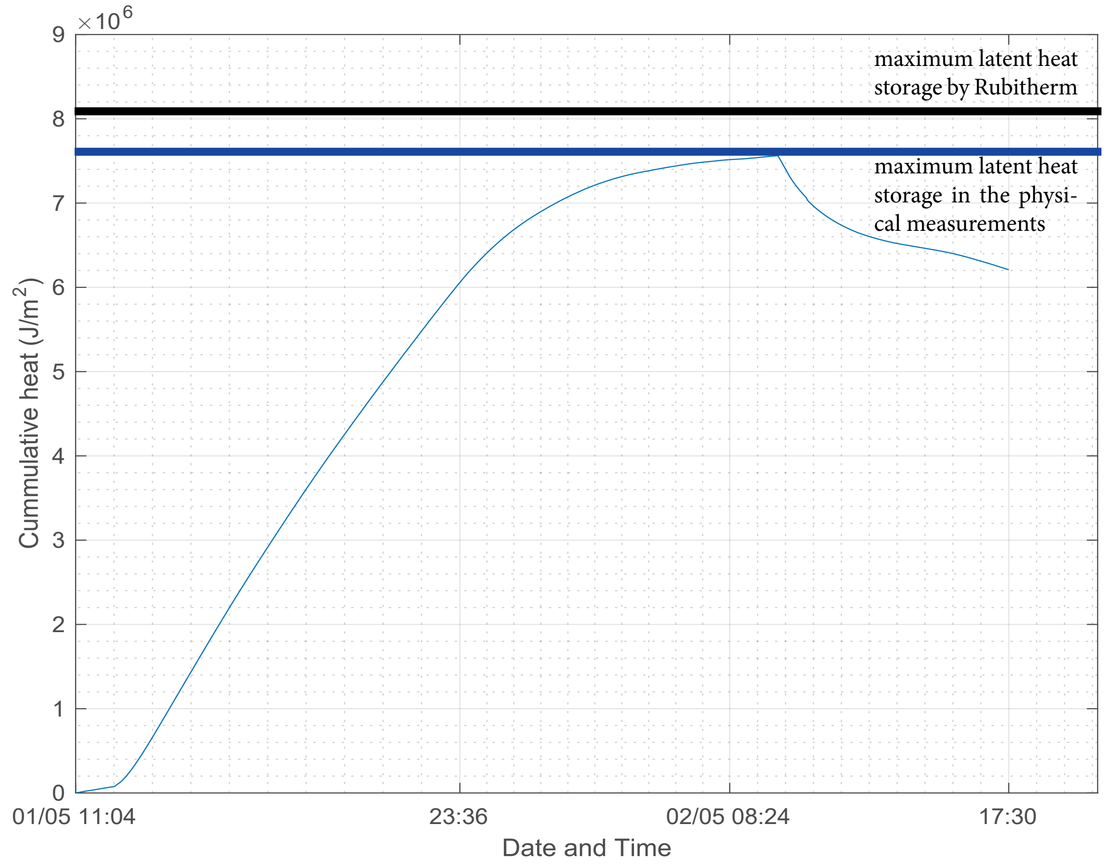
Graph 8.5:Heat transfer from the inside and the outside .Graph data exported from Eltec Darca Plus.Graph made by the author.

The heat flux measurements are helpful in order the cummulative heat to be calculated and information about the heat storage capacity of the system to be given.As it is data of the pcm 25 given by the manufacturer are shown in the table below.

SP 25 / RUBITHERM	Column1
PROPERTIES	
Melting area °C	24-26
Congealing area °C	24-23
Heat storage capacity(kJ/kg)	180
Specific heat capacity (kJ/kg *K)	2
Density solid(kg/m^3)	1.5
Density liquid(kg/m^3)	1.4
Volume expansion(%)	3
Heat conductivity (W/ m*K)	0.6
Max. operation temperature °C	45
Heat stored in 0.03 thk container (J/m2)	8100000

Table 8.6 :Properties of SP 25 . Data reviewed from : https://www.rubitherm.eu/media/products/datasheets/Techdata_-SP25E2_DE.PDF, table redrawn by the author

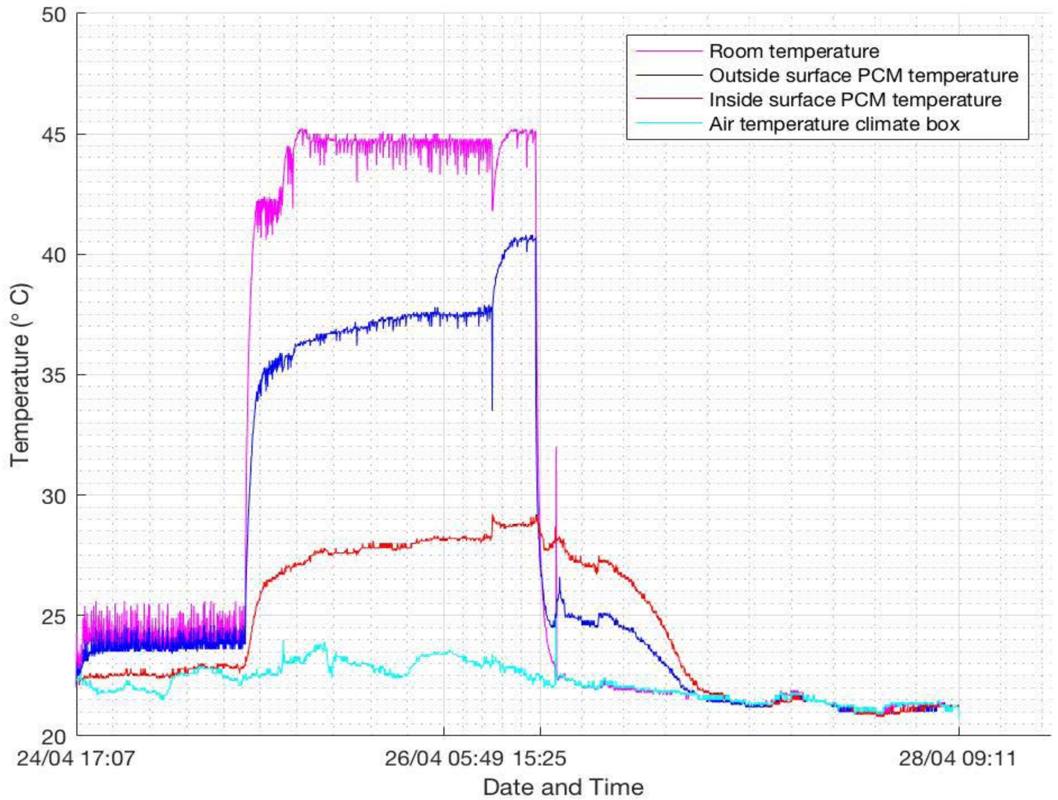
SAMPLE 1: PCM 25|CUMMULATIVE HEAT MEASUREMENTS



Graph 8.6:The heat stored over time.Graph made by the author

As it is shown from the graph , the heat which is totally stored by the pcm 25 is 7.6 MJ/m^{2}.This value is a bit lower than the heat storage capacity of the material given by the manufacturer..This happened because when the heat flux measurements took place the material was 90% in solid state and not fully in solid state.From the graph it is shown for how much time the material stores heat and when it starts releasing it (during the solidification process). As it was refered before the curved line indicates sensible heat storage and the straight line latent heat storage.In this graph it is observed that till the material is fully melted there are moments where the curvature is more obvious (clear sensible heat storage) and at some point of time the curvature starts transforming to a slightly curved line (almost straight) that indicates mixed form of heat storage.(both latent and sensible heat storage).In the last two hours before the solidification starts it is shown a straight line which shows that the material has already been melted and it stores heat in a latent way.

SAMPLE 3: PCM 31|TEMPERATURE MEASUREMENTS



Graph 8.6:Temperature measurements of the PCM 31. Graph exported from Eltec Darca Plus.

As it is shown from the graph the initial temperature of the sample SP31 is 22 ºC (the same with the room temperature).The material has already undergone one thermal cycle before this measurement and the sample is 90% melted.Moreover,the sample is not fully filled with PCM because of some difficulties presented during the construction process of the samples.For the melting process it was required the sample to be exposed to 44ºC (temperature inside the box).In the first hour of the measurements,in both the surfaces of the sample there is a steep increase in the temperature till the temperature inside the box reaches and stabilizes to 44 ºC.From that time, the temperature in both surfaces of the sample continues increasing with a slower rate till it is almost stabilized having a really slight increase till it stabilizes completely(the point where the material is fully melted.The melting process lasts for 30 hours according to the graph. On the other hand, the drop in temperature indicates the solidification of the PCM31.The material needs 20 hours to reach its solid state.

TIME REQUIRED FOR MELTING ACCORDING TO ΔT

The duration of the melting process is also calculated by the equation 1 ,described in the previous sample.The table below indicates the amount of time that is needed so as the PCM 31 to get fully melted.

Heat Capacity(kJ /kg)	Density(kg/m^3)	Thickness(m)	Heat transfer coef in	Heat transfer coef/ o
PCM31				
210	1325	0.03	7.8	7.8
Tpcm(°C)	Tin(°C)	Tout(°C)	Time for melting(s)	Time melting (h)
31	45	22	118125	32.8

Table 8.7 :The data given for the sample PCM 25 and the required hours for full melting of the PCM.

The duration of the melting process based on ΔT is 32.8 hours for the sample PCM 31. Compared to the physical measurements, the hand calculations indicate more time for melting (2.8 hours less).This deviation occurs because the container was not fully solidified(90% solidified) and also the container was not filled till the top with PCM.It is logical that the least proportion of PCM encapsulated in a container the less time it is required to get melted.

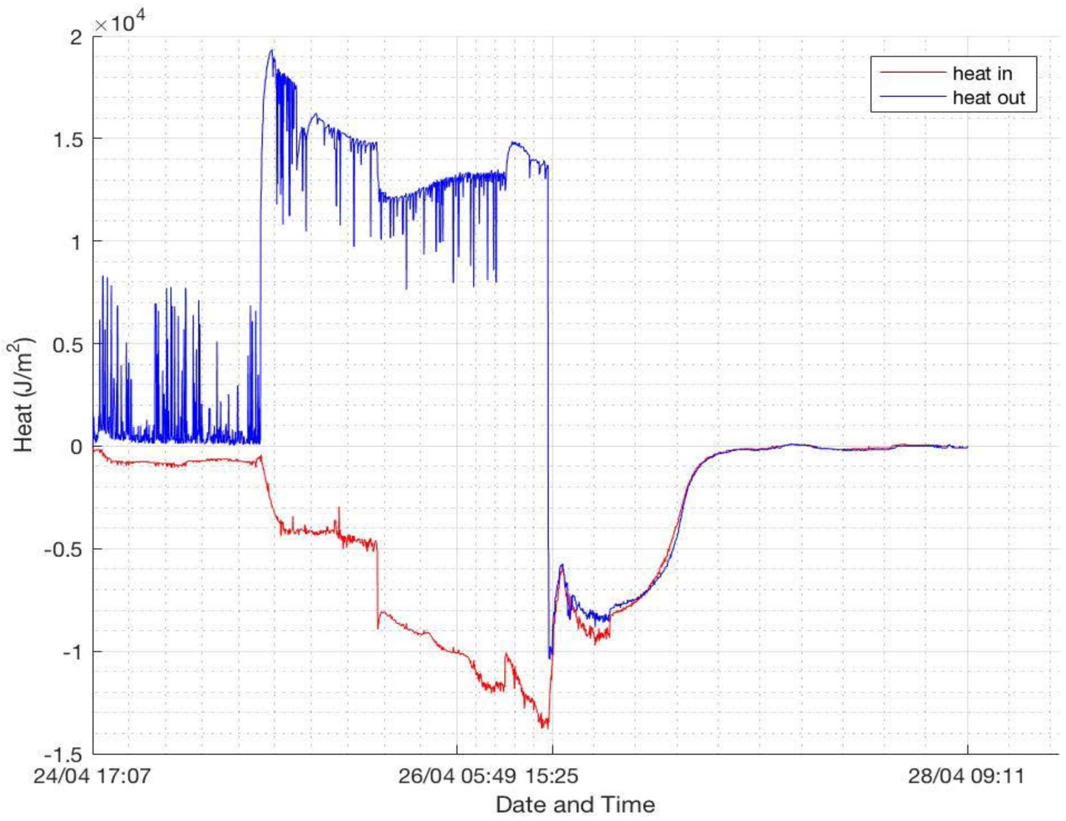
TIME REQUIRED FOR MELTING BASED ON SOLAR IRRADIATION

It is logical that with the sun's presence the melting procedure for the PCM requires much less time than it is measured in the physical test.

Heat Capacity(kJ /kg)	Density(kg/m^3)	Thickness(m)	Heat absorption coef	Solar irradiation(W/m2)	Time (h)
PCM31					
210	1350	0.03	0.8	300	9.84

Table 8.8: The required hours for full melting of the PCM.

SAMPLE 3: PCM 31 | HEAT FLUXES MEASUREMENTS



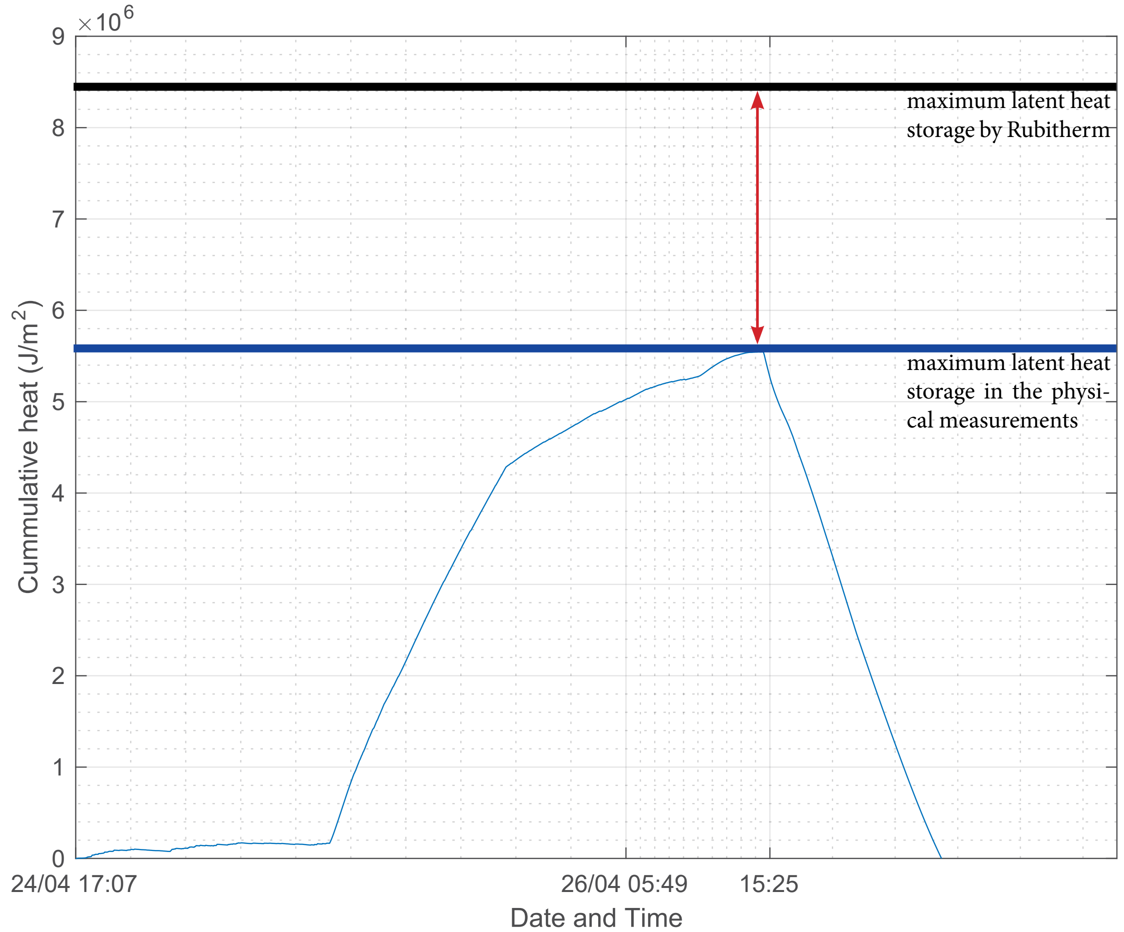
Graph 8.7:The heat stored over time.Graph made by the author

The heat flux measurements are done in order the cummulative heat to be calculated and information about the heat storage capacity of the system to be given.In the following table they are presented the properties of the PCM31 as they are given by the manufacturer.

SP 31 / RUBITHERM	Column1
PROPERTIES	
Melting area °C	31-33
Congealing area °C	28-30
Heat storage capacity(kJ/kg)	210
Specific heat capacity (kJ/kg *K)	2
Density solid(kg/m^3)	1.35
Density liquid(kg/m^3)	1.3
Volume expansion(%)	3
Heat conductivity (W/ m*K)	0.8
Max. operation temperature °C	45
Heat stored in 0.03 thk container (J/m2)	8505000

Table 8.9:Properties of SP 31 . Data reviewed from : https://www.rubitherm.eu/media/products/datasheets/Techdata_-SP31_DE_02062016.PDF, table redrawn by the author

SAMPLE 3: PCM 31 | CUMMULATIVE HEAT MEASUREMENTS



Graph 8.8:The cummulative heat stored over time.Graph made by the author

As it is shown from the graph , the heat which is totally stored by the pcm 31 does not reach the value calculated in the previous table based on the manufacturer's data about the specific phase change material.This happens because the line should be moved in an uppe layer starting from 1MJ/m^2 the line of the cummulative heat as the material was not fully solidified when the measurements are done. However, if this is taken into consideration, according to the graph the heat stored reaches the value of 7.5MJ/m^2 which is 1 MJ//m^2 less than the value measured by the manufacturer's material data sheet. This is happens as the container was not fully filled with the pcm and consequently the heat flux plate which were used were adjusted in the surface of the container which were partially covered with the SP31.As a result, they were not measured the full potentials of the PCM31 in storing heat.

THE EXPERIMENT|REFLECTION

Can we expoit the full potentials of SP21, SP25, SP31 in terms of heat storage when the PCMs are applied to containers of 3cm thickness?

The most important thing is that the physical measurements that took place in TU Delft come in agreement with the measurements provided by the manufacturer.

However, the SP31 seemed not to take advantage of its maximum latent heat capacity as the calculated stored heat reach in a lower value than the provider's (Rubitherm) datasheet .This happened due to the conditions of the set up of the heat flux plates on the two surfaces of the container. The heat flux sensors did not come in contact fully with PCM as the containers were not fully filled with PCM.

As for the SP21 it is shown to store more heat than it is supposed to store according to the manufacturer's datasheet.This happens as the material when was partially melted stored heat also in a sensible way.As a result, the measurements is a combination of latent and sensible heat which is stored in the PCM.

As far as the SP25 is concerned, this specific PCM stored almost the same amount of heat that the manufacturer provided in the datasheet of the PCM.The difference between the real measurements and the data which are provided by Rubitherm is slight and shows that the SP25 stored a little less heat than it was expected.This happened due to the fact that the PCM was not fully solidified (90% solid, 10% liquid) when the melting process started.

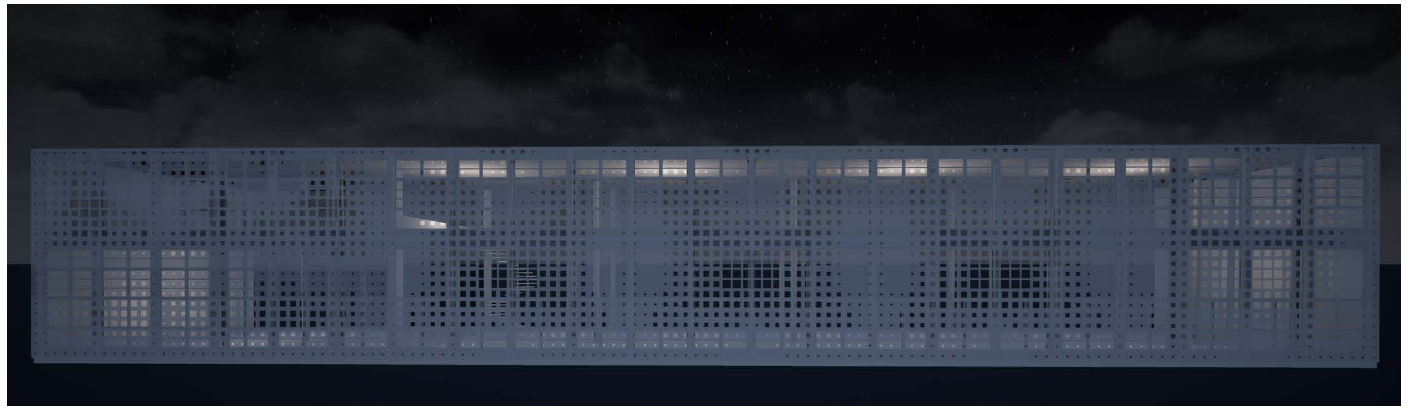
However, it can be concluded that during the physical measurements, the research should focus his attention in an accurate set up being very careful on the way he/she makes the containers (fully sealed preventing from leakage during the melting process) and also on the way he/she locates and connects the sensor system to the testing sample.

Moreover, another point that should be highlighted is the fact that the PCM in the summer will undergo very high temperatures as it is fully in contact with exterior weather conditions.This means that when it will be fully melted, then it will start rising its temperature (sensible heat).However,-this temperature increase should not reach a point that is the maximum temperature point that the PCM undergo.This can be avoided if the thickness of the containers is larger (more PCM quantity) so as to be spent more time in the melting process of if the PCM is protected with a shading system.

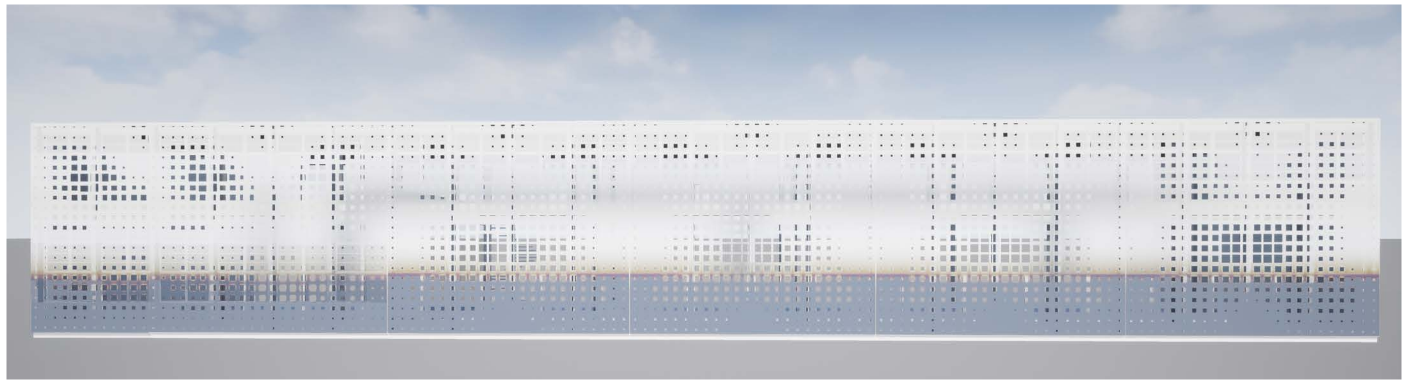
How the facade looks like during the day if we take into account the thermal cycle of the PCMs?

SUMMER DAY

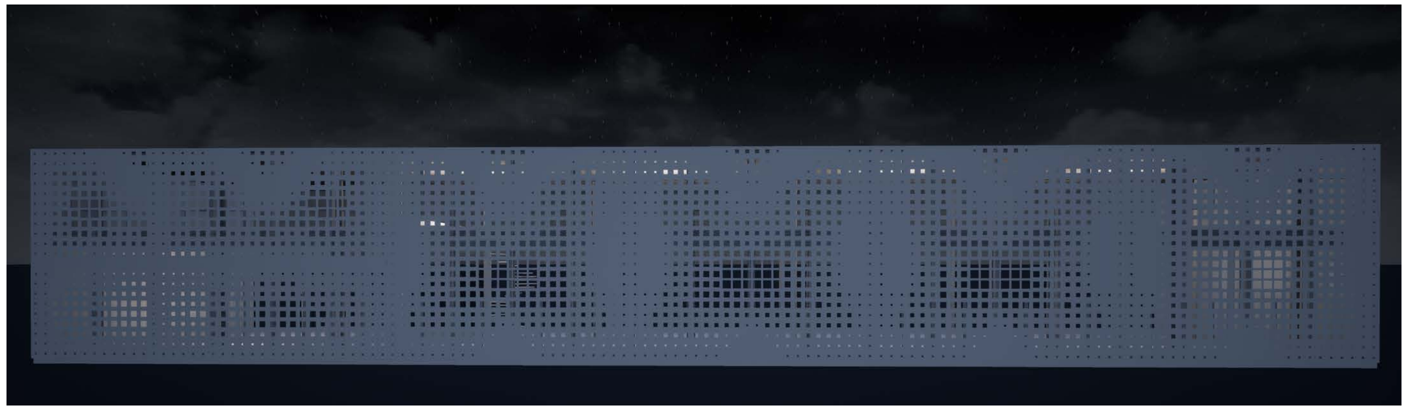
SUMMER NIGHT



WINTER DAY



WINTER NIGHT



9

the facade system

WINTER|DAY

During the day , both layers are close so as to protect the inside space from heat losses.All the PCMs placed in the panels start melting by the solar heat and they store the heat during the melting process.As different melting temperatures are used (SP21, SP25, SP29 or SP11, SP21, SP25), the panels that will melt earlier are the A type (lower melting temperature) and then the B and C type respectively.All the types of panels will store the solar heat during the day in different levels (higher heat stored by the A panels and lower heat stored by the C panels).This will happen because the type with the lower melting temperature will manage to melt completely, exploiting the maximum heat storage capacity of the materials, whereas the other two types will melt partial, storing an amount of heat and not in a maximum level.

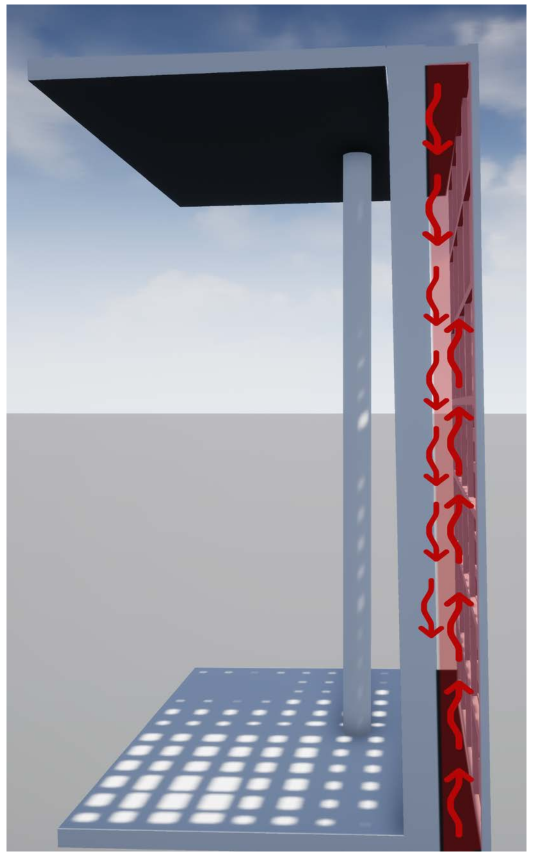


Figure 9.1: The performance of the system in the winter (day mode)

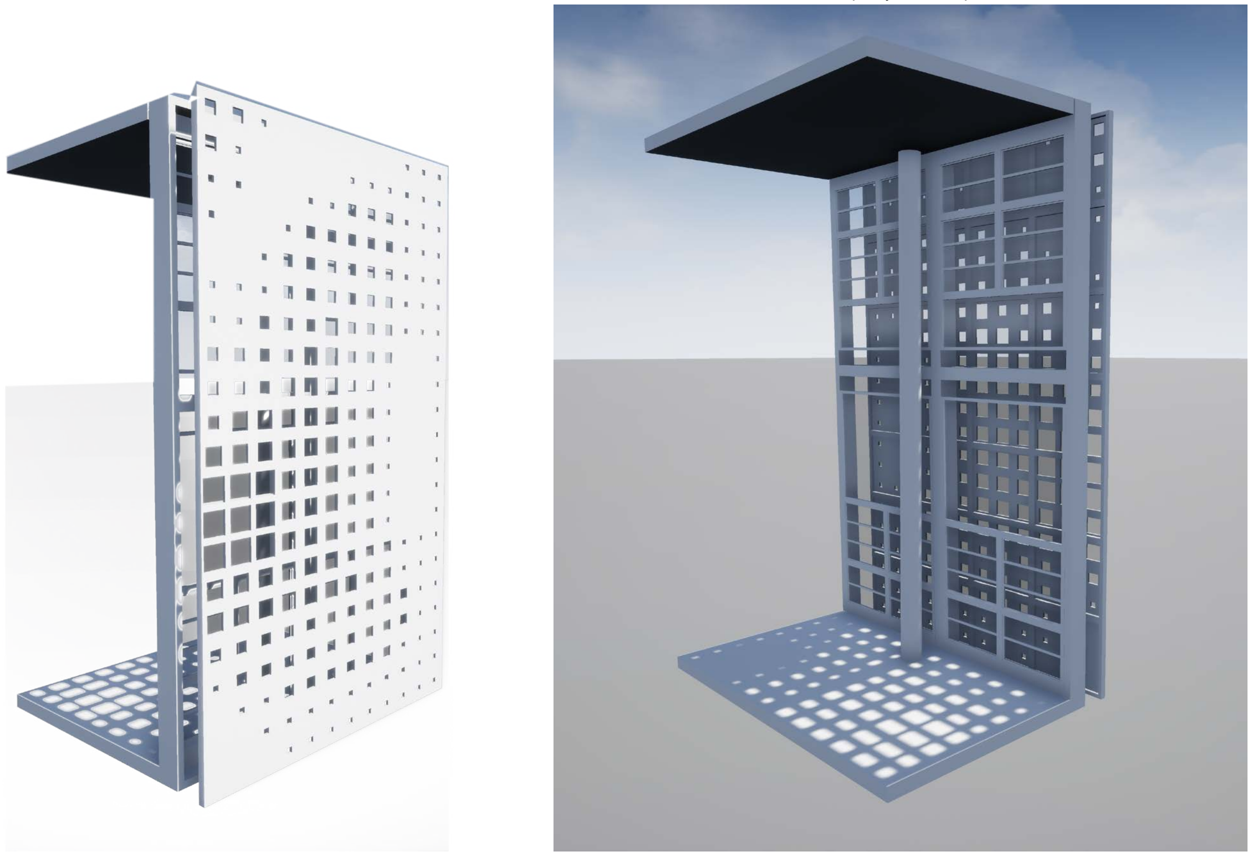


Figure 9.2:Perspective views of the system

WINTER|NIGHT

During the night, the PCMs release the heat that they stored in the day.Because the lower melting temperature in Netherlands is 11 ^{0}C, this means that the hot air that they will release at night will be in reality cooler than the air temperature of the room.On the other hand, the other PCMs will release hotter air than the air room temperature.For this reason and because it is needed the heat to be released from the PCMs to the inside space, the inner skin of the facade is partially open.In order to promote the stack effect logic, the hot air should be directed from the top part of the inner facade layer. Consequently, the windows are operated only in the upper part of the facade.

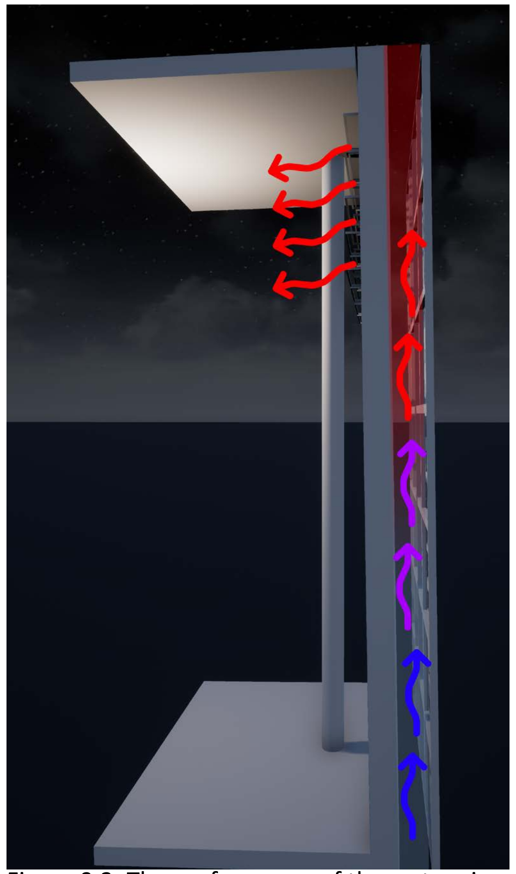


Figure 9.3: The performance of the system in the winter (night mode)

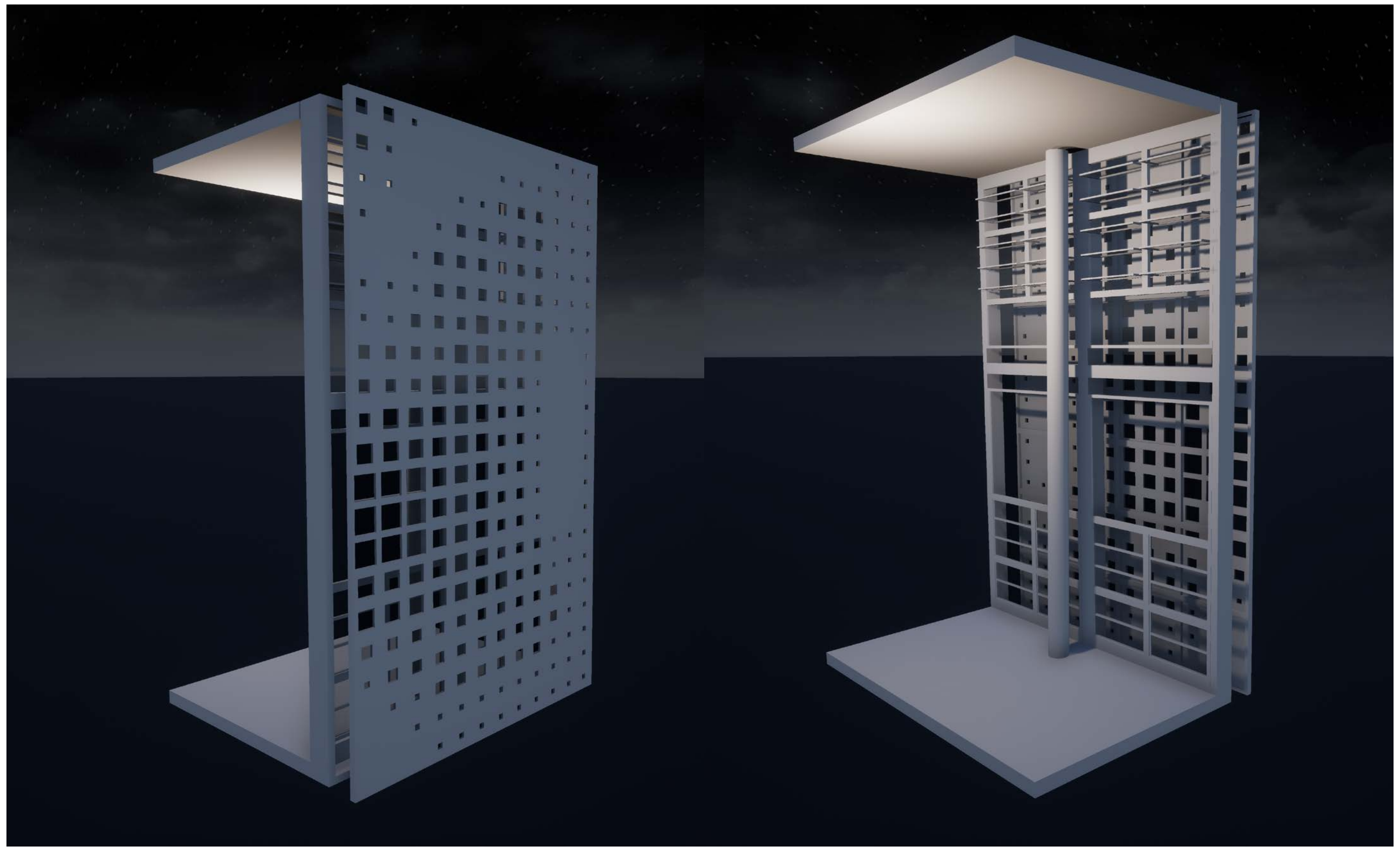


Figure 9.4:Perspective views of the system

SUMMER|DAY

During the day , the inner layer is closed so as to decrease the solar heat gains and the outer skin is partially open in the bottom and the top part to promote the natural ventilation inside the cavity through the stack effect logic.With this way, overheating problems can be avoided .As for the PCMs, the PCM panels with the lower melting temperature they are inactive because they are in a sable liquid phase.This happens because the exterior air temperature is much higher than the melting temperature of the pcm.Under this conditions, it can be ensured that the fresh air entering the cavity from the bottom inactive panels will be always cooler than the air circulating in the medium or the top level of the facade.Both the other two types will start melting with the help of the solar irradiation storing the solar heat.

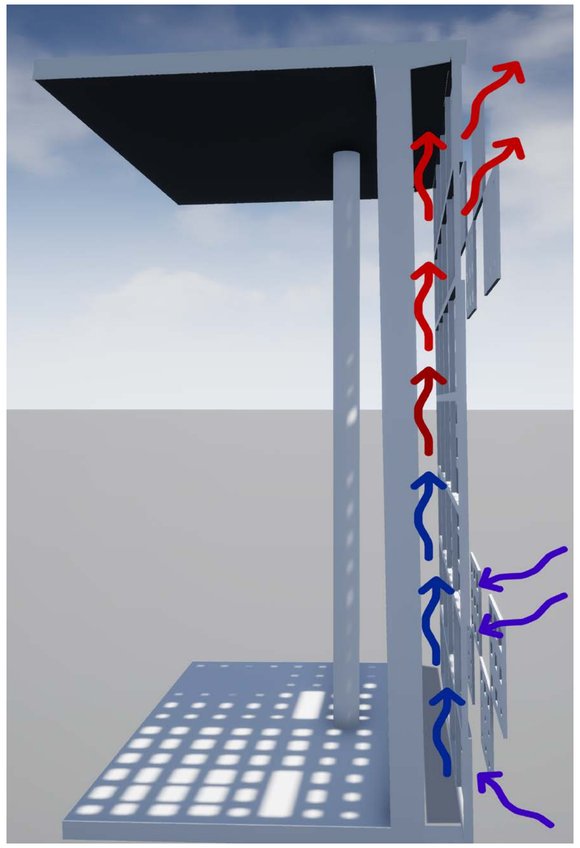


Figure 9.5: The performance of the system in the summer(day mode)

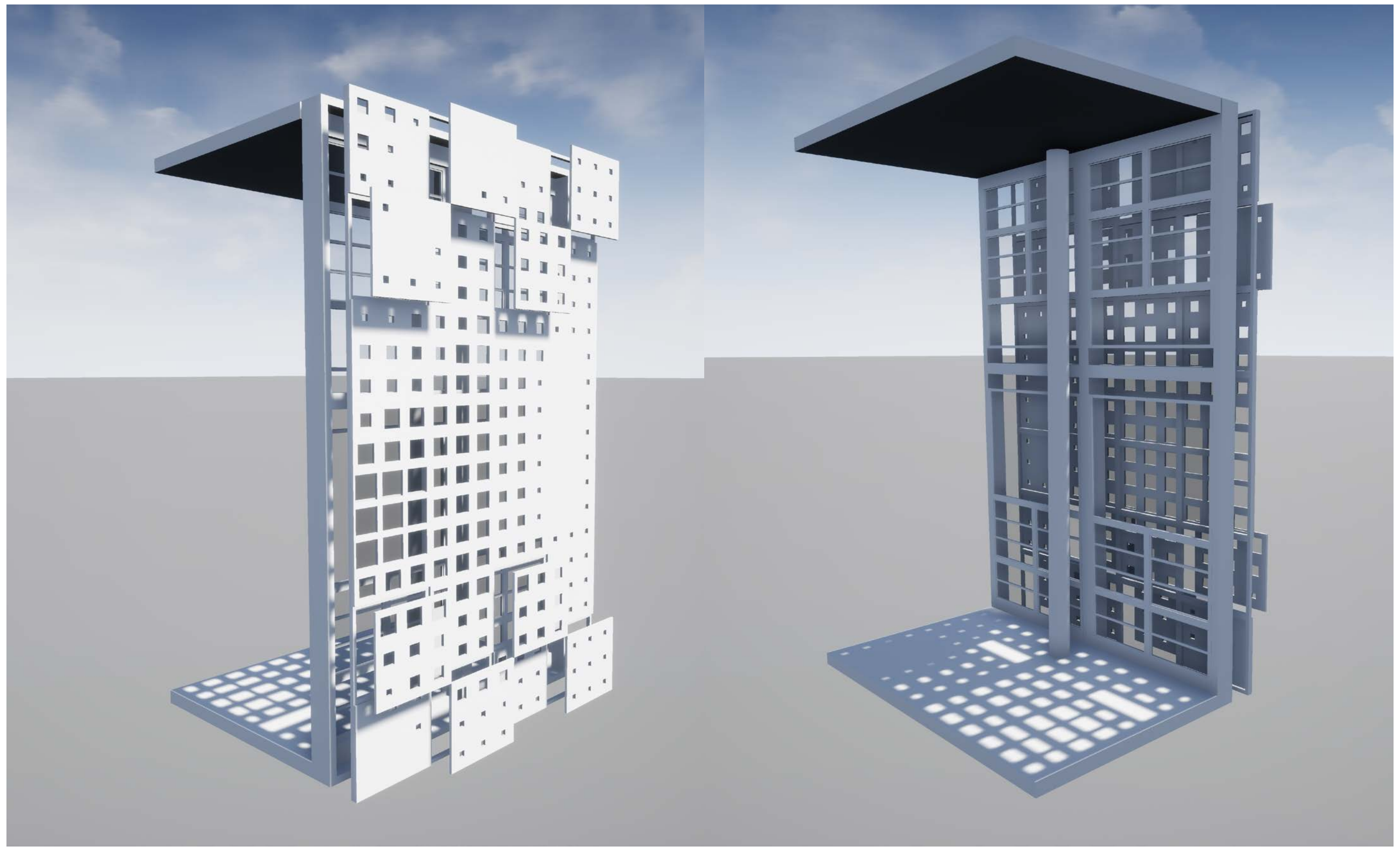


Figure 9.6:Perspective views of the system

SUMMER|NIGHT

At night, it is needed the heat coming from the PCMs to be released to the outside and not to the inside so as to prevent the facade from creating extra cooling loads for the inddor space.However, it should be taken into account that natural ventilation and especially night cooling is needed so as to release the excessive heat from the inside to the outside and reach thermal comfort levels.Again, the A type panels are inactive and this means that they do not release heat neither to inside nor to outside.For this reason the inlet of fresh air is achieved by opening partially both skins in the lower and the bottom part to ensure that the stack effect will take place and the hot stale air will be released from the upper operable facade panels.

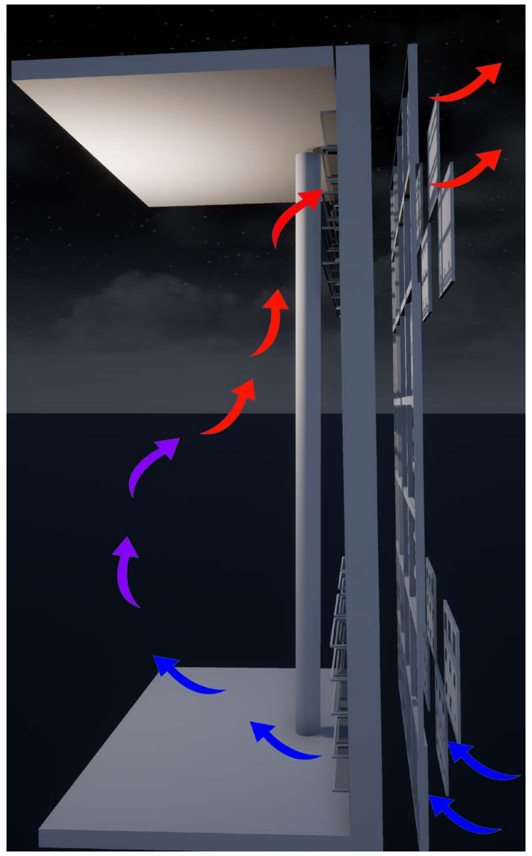


Figure 9.7:he performance of the system in the summer(night mode)

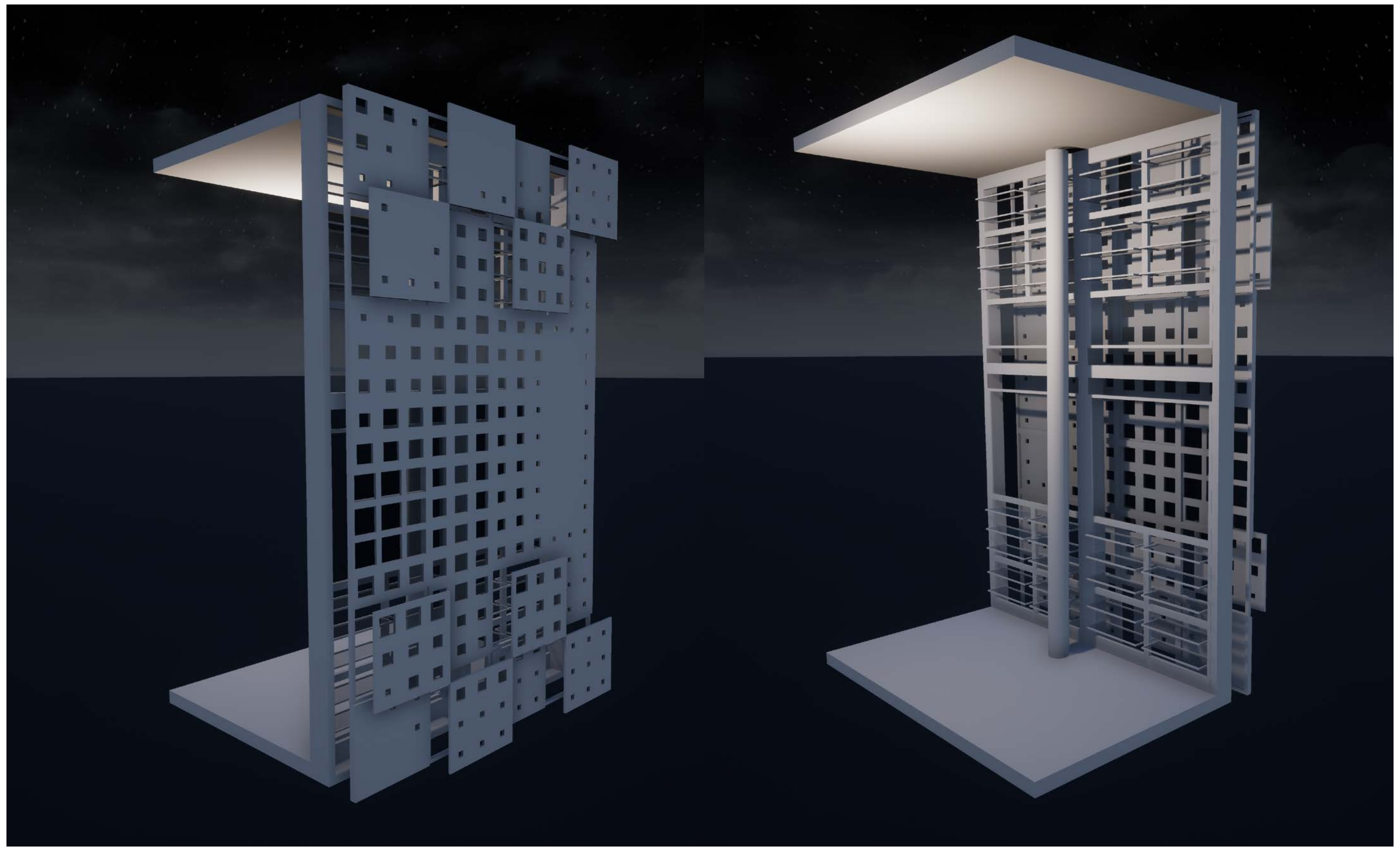


Figure 9.8:Perspective views of the system

THE FACADE SYSTEM | FACADE COMPONENTS

The facade system is a unitized double skin facade with PCM based panels.Folowing the design strategies that are defined in previous chapters, the exterior skin is composed by the PCM based panels and the interior skin includes the lamella windows and fixed windows and a layer of thermal insulation in front of the slabs.
In more detail, the exterior facade layer contains panels which include PCMs with different melting temperatures(A, B, C type).Their placement is done according to their melting temperature and more specifically the A panels(lower melting temperature are placed in the bottom part of the facade), the B panels(medium melting temperarure) in the intermediate facade level and the C panels(higher melting temperature) in the upper part of the facade.The operable parts of the skin are the ones that belong to the A and C type so as to achieve natural ventilation based on the stack effect.
As far as the internal skin is concerned,the operable windows are placed relatively in the top and the bottom part and they are lamella windows. This choice is derived from the fact that with this window type almost 100% of the window is open and heat tranfer from the PCM to the interior space can be done in a quicker and more efficient way.
Another apect that should be taken into account is the depth of the cavity which is quite small for a double skin facade (0.30 m) in order not to waste useful area in a plan view.

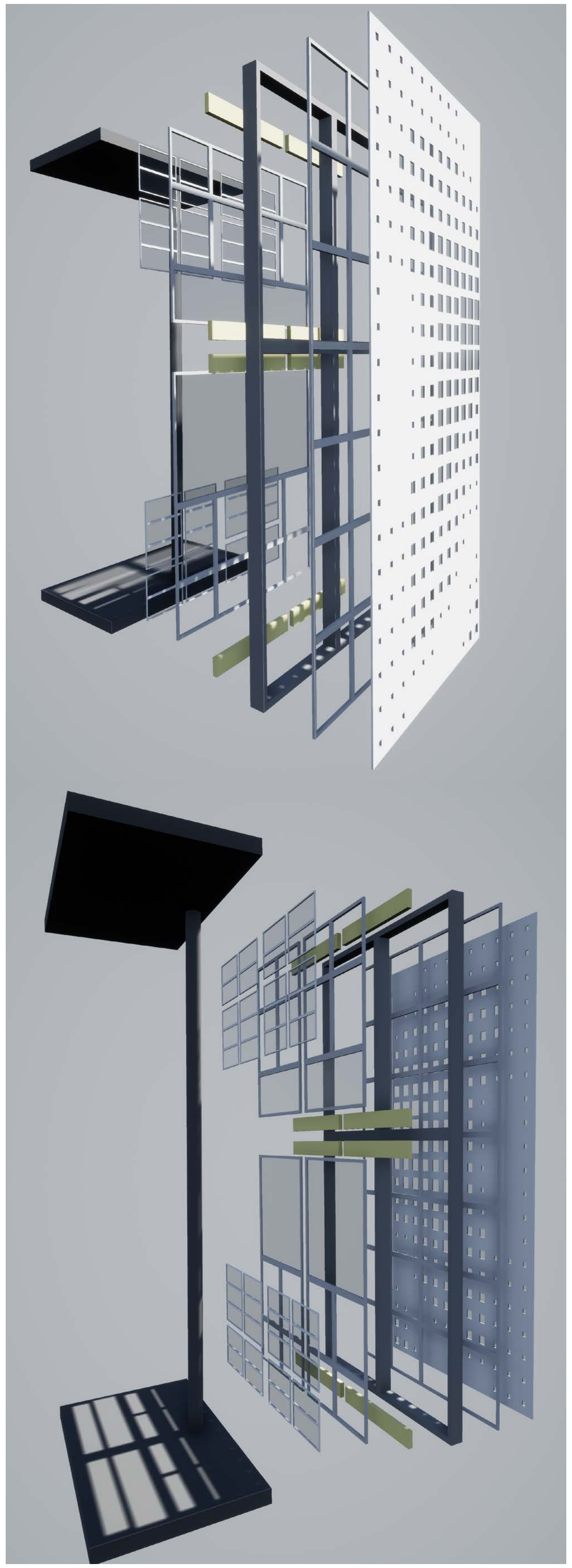
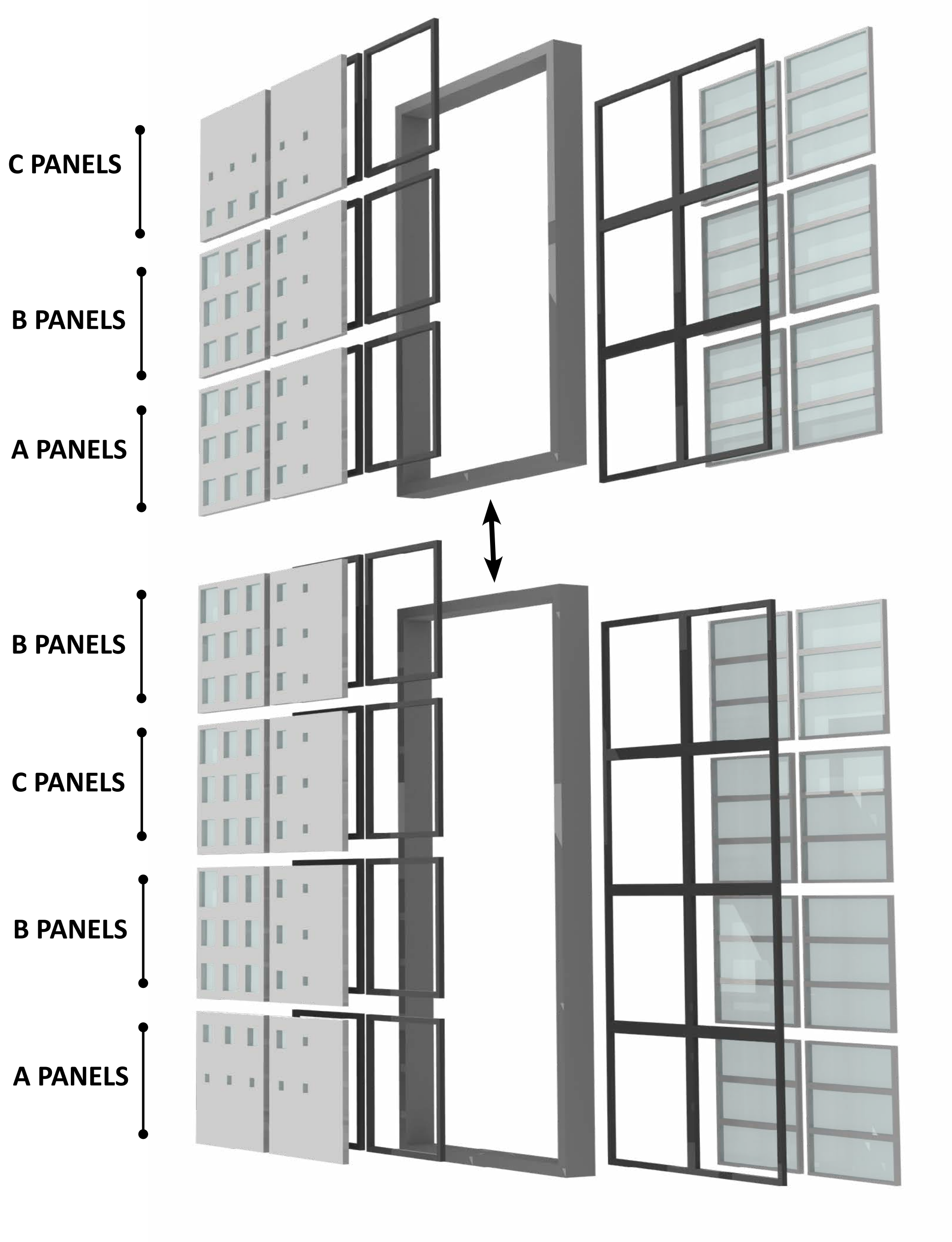


Figure 9.9:The facade components



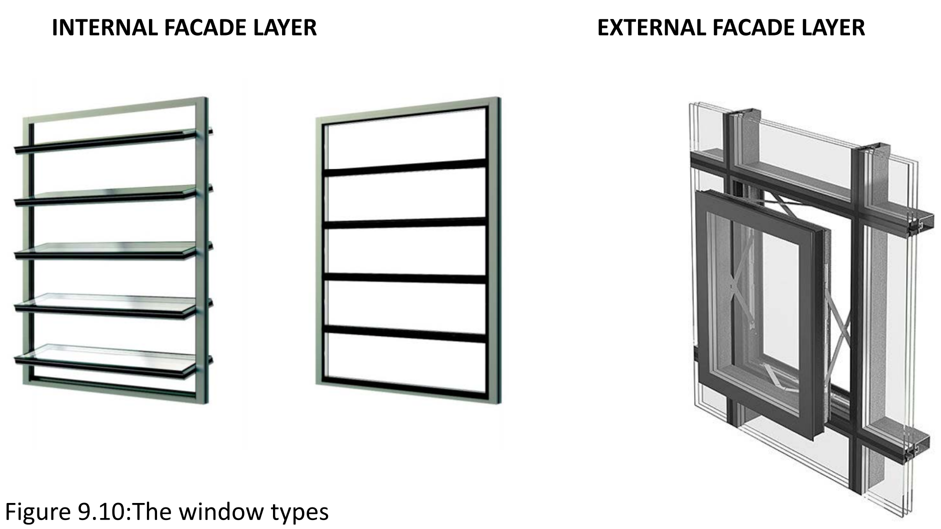
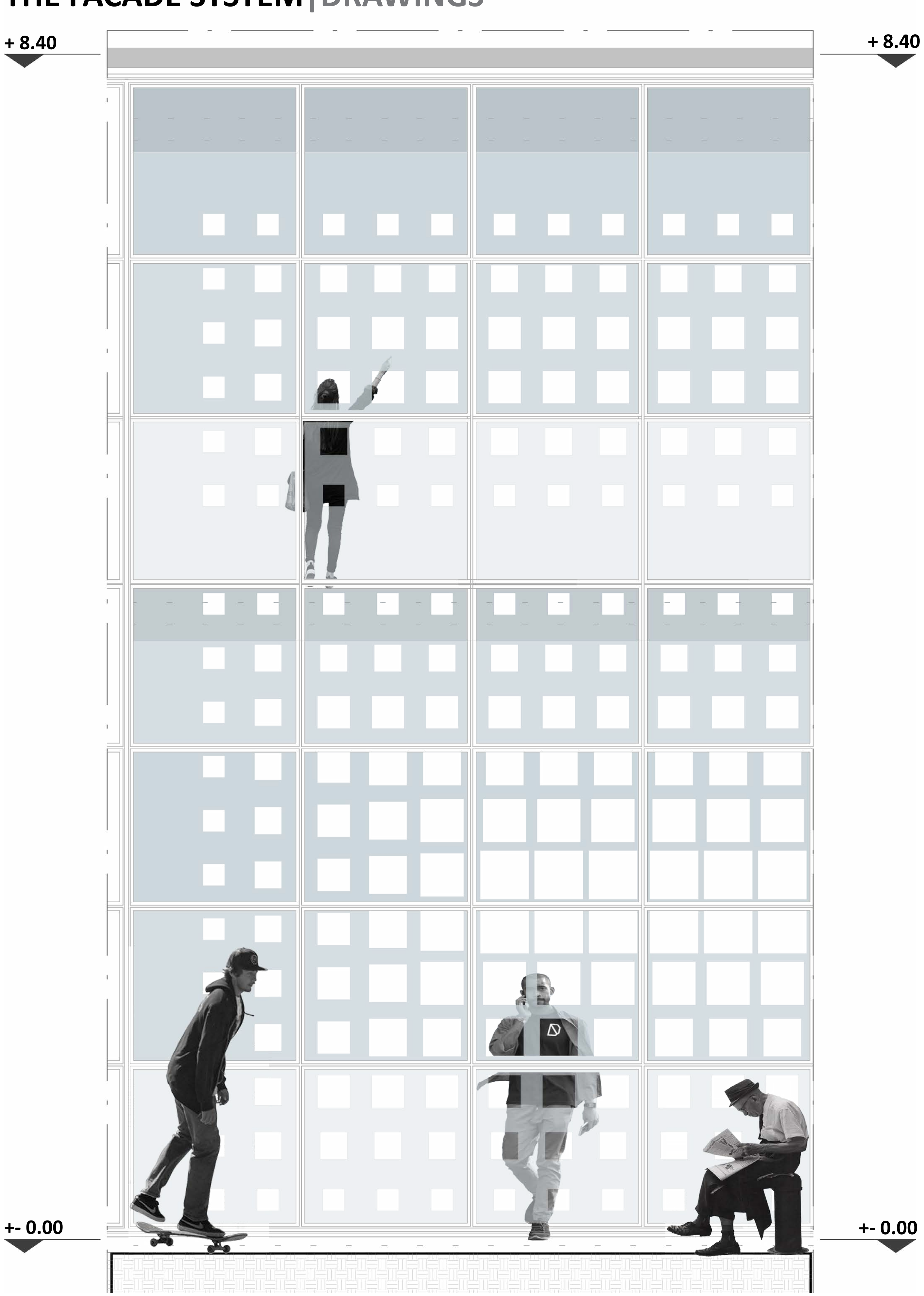


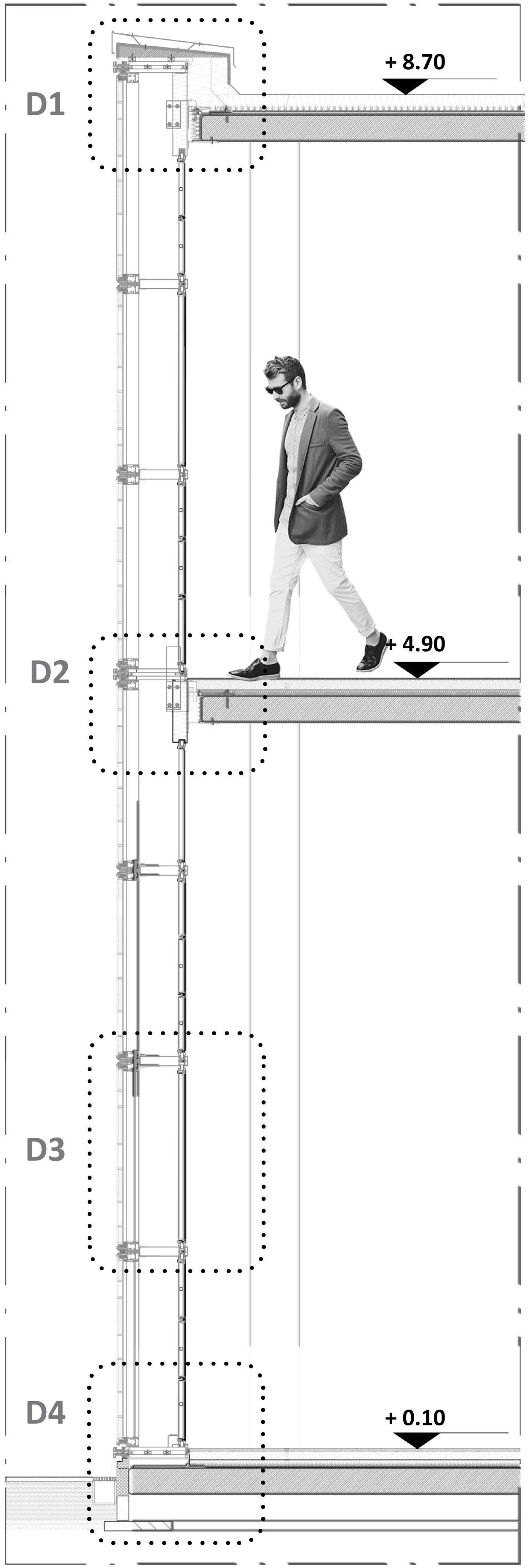
Figure 9.10:The window types



ELEVATION| SCALE: 1:50

INNER ELEVATION| SCALE: 1:50

SECTION A-A| SCALE: 1:50

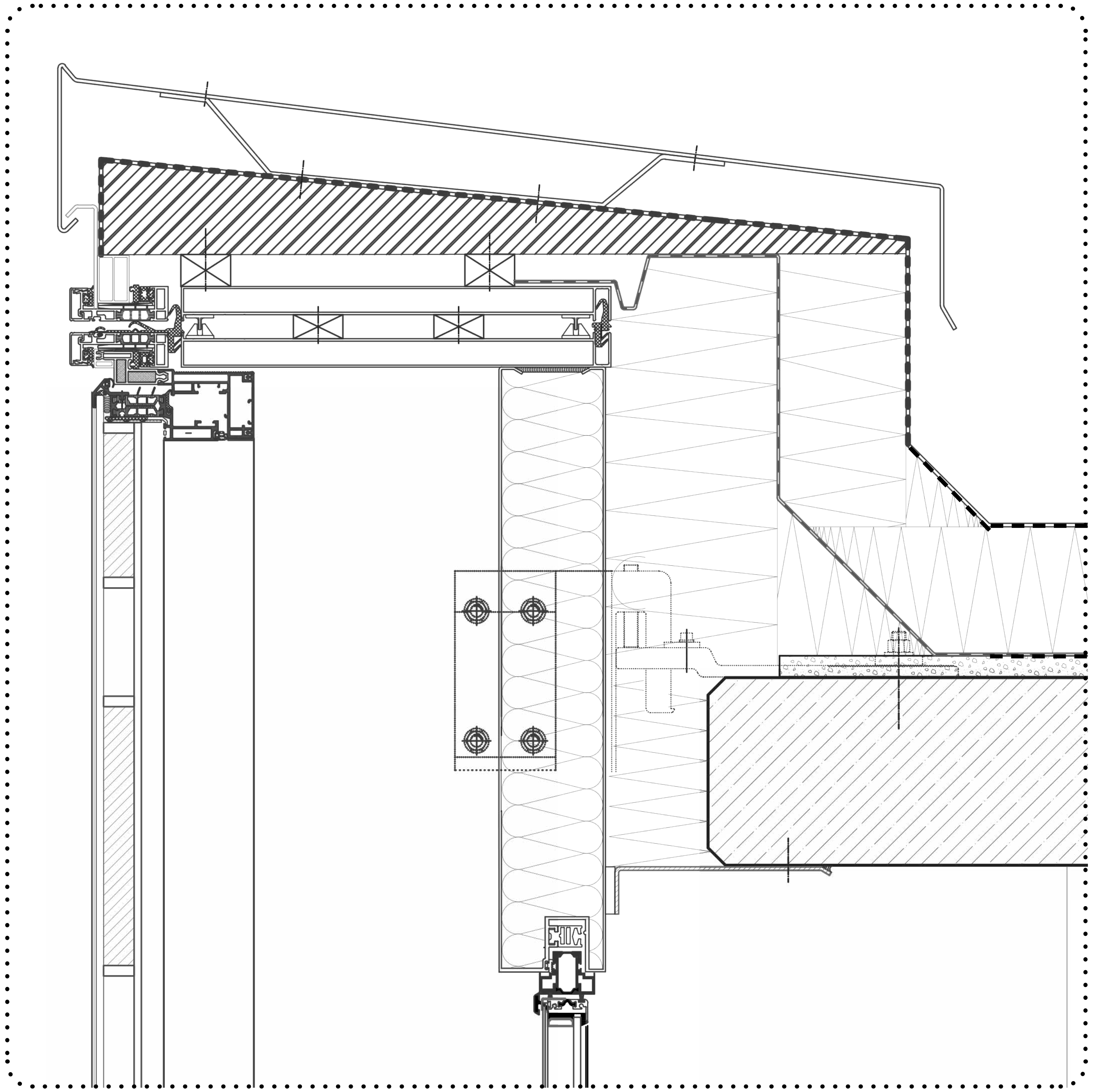


CONSTRUCTIONAL DETAILS

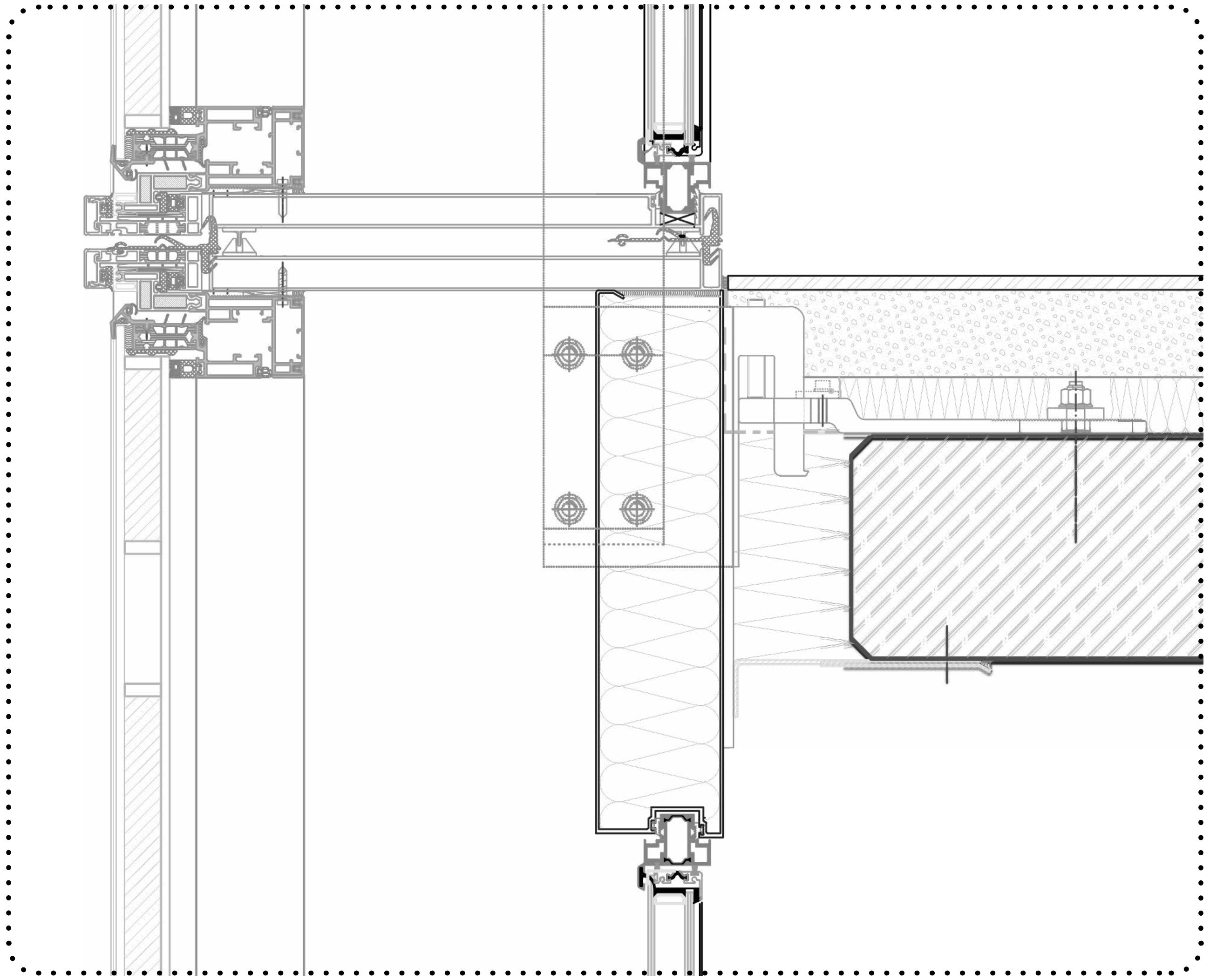
- **D1:** ROOF DETAIL
- **D2:** FACADE FIXING BRACKET
- **D3:** MODULAR PANEL
- **D4:** BOTTOM DETAIL

CONSTRUCTIONAL DETAILS

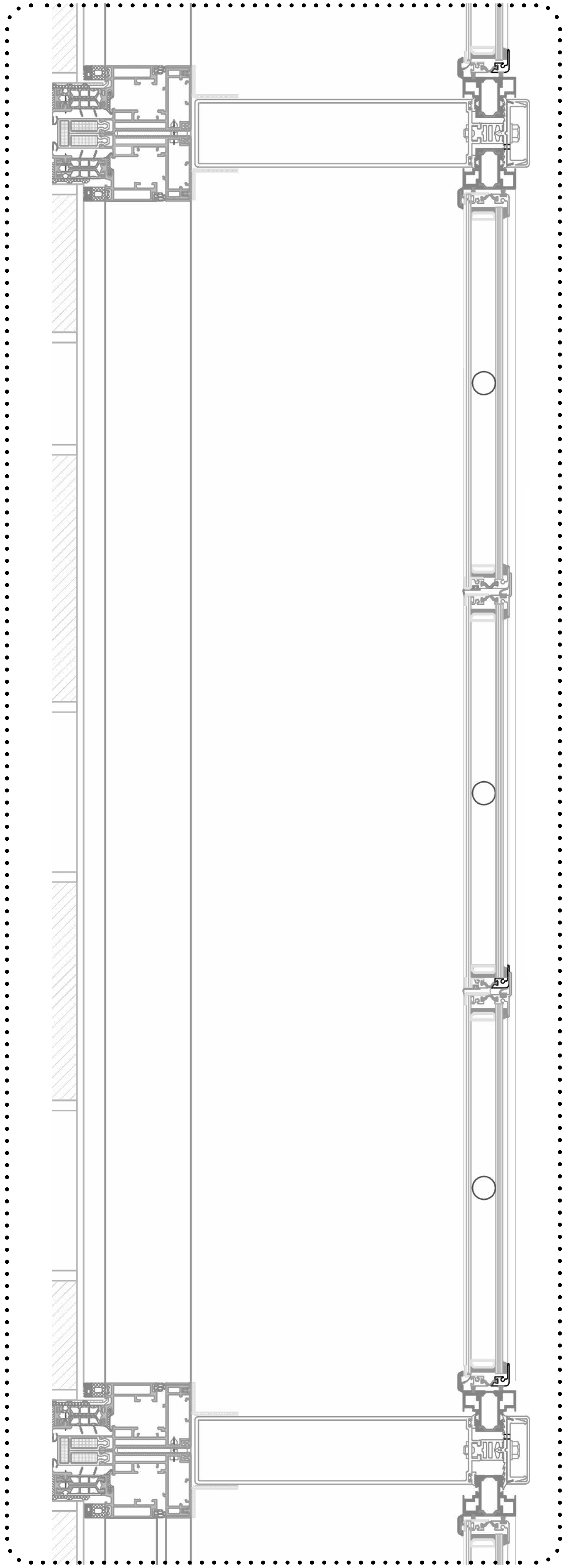
D1|ROOF DETAIL_SCALE: 1:5



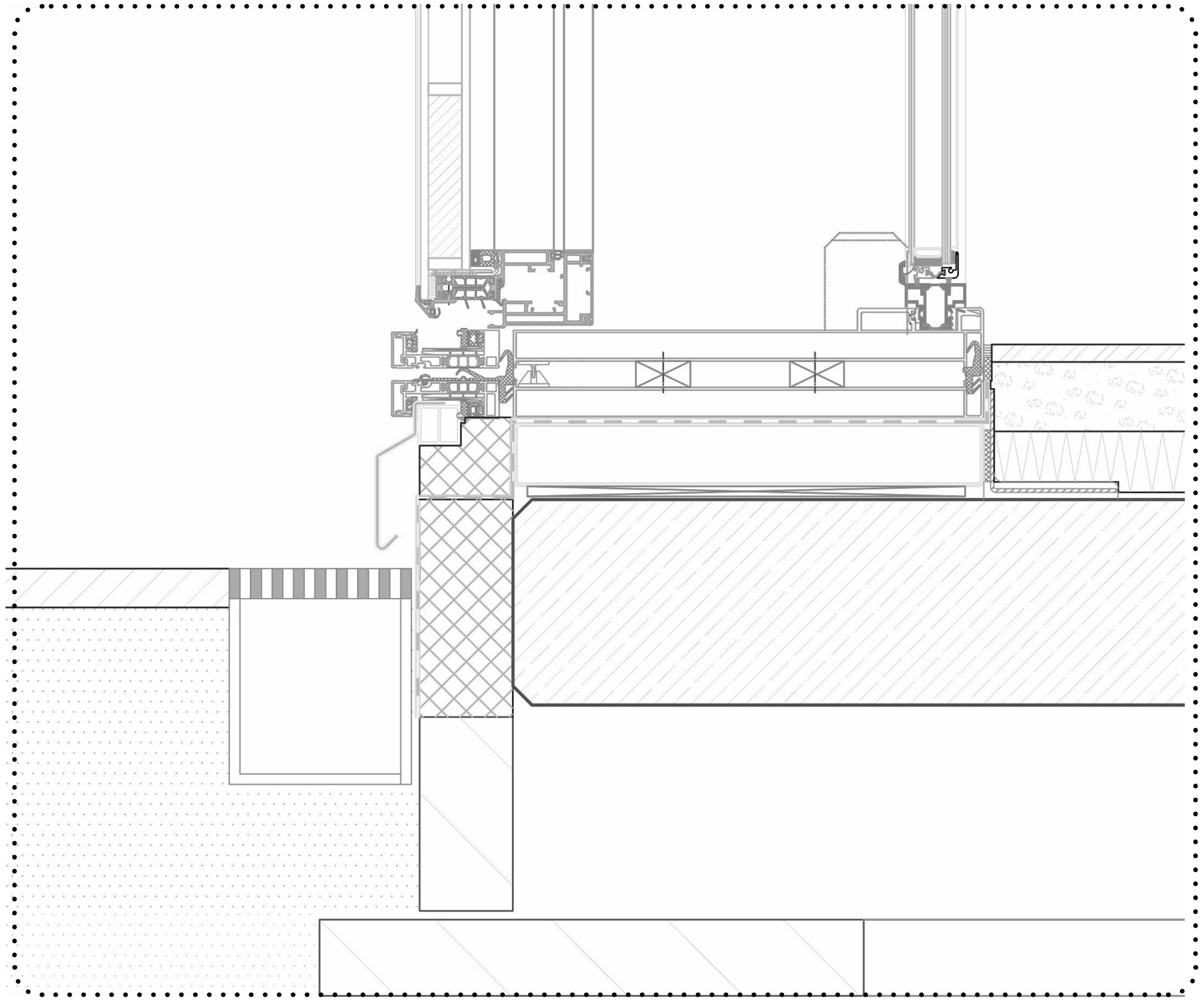
D2|FACADE FIXING BRACKET_SCALE: 1:5



D3| MODULAR PANEL_SCALE: 1:5



D4| BOTTOM DETAIL_SCALE 1:5



A unitised façade offers endless possibilities in design freedom whilst ensuring a high quality finished product due to pre-fabricated PCM based panels. Element façades constitute a collection of individual pre-fabricated elements. The installation is both speedy and economic, as it doesn't demand much manpower and tooling compared to traditional curtain walls.

Before being sent to the construction site, unitised systems, which are made out of large glass units are created and glazed at factory level. Once on site, the units can then be hoisted onto anchors connected to the building. The fabrication involves tight tolerances in a climate-controlled environment; this means that high quality is one of the many hallmarks of such a system. The speed of installation is rapid as there is no on-site glazing. It can be installed within a third of the time of a stick-built system. This system is well suited when a large number of such panels are required since it doesn't require much labour costs (thereby making it cost effective). It is also useful for tall structures and when a higher performance is a necessity (for wind loads, air/moisture protection, seismic/blast performance).

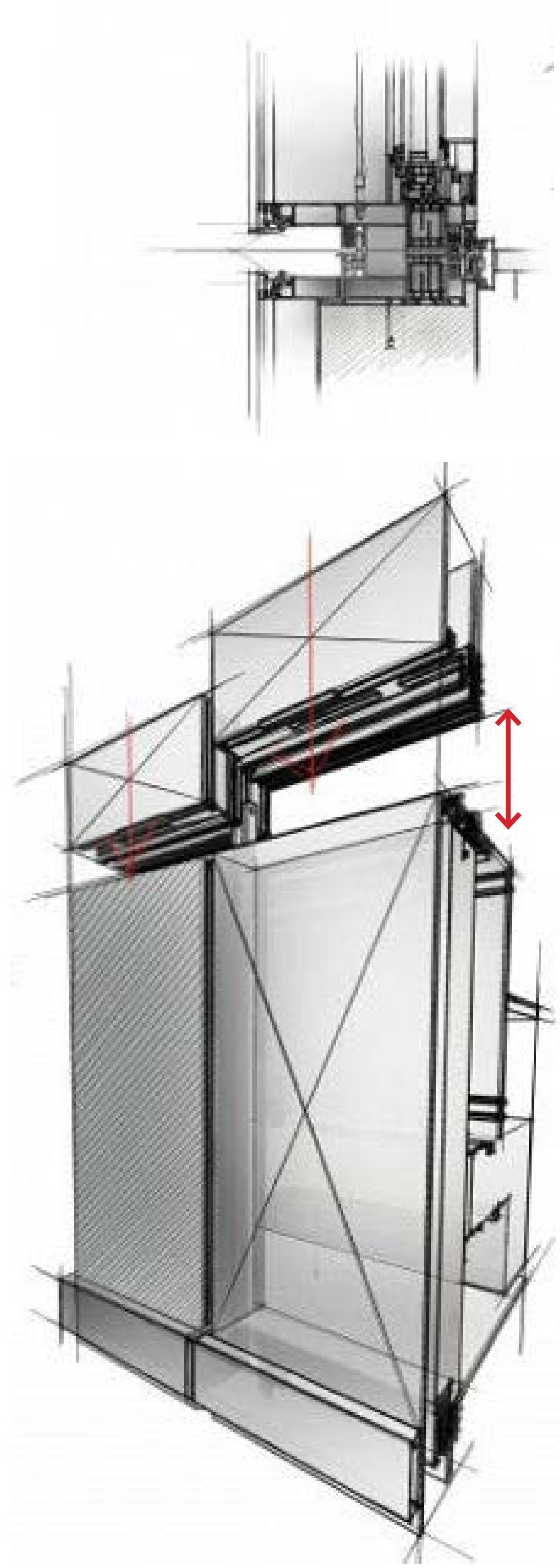


Figure 9.11 The Unitized double skin facade system,Reviewed from https://www.reynaers.de/sites/default/files/public/media/element_facades_lr.pdf

In order to assess the facade system, several aspects should be taken into account.First of all, the cost is a very important point.In this case, the cost is quite high because of the construction expenses,the large amount of materials applied and the motorized lamella windows and all the equipment needed for its control.Moreover, phase change materials are used inside the double glazing's cavity and this makes the construction more complex and demanding in order to achieve no leakages and high protection of the PCMs from the exterior weather conditions.
The recyclability of the system is a controversial issue as some of the materials can be reused (the metal frame and the glazing) but others like the PCMs cannot be recycled.The system control of the facade is quite compicated, making the automatic control its basic characteristic.However, the properties of the PCMs are changing according to the season and the weather conditions,but still their performance can be partially controlled if adequate ventilation, sun protection and expoitation of the stored heat take place.
The maintenance is again an ambivalent in terms of the facade design because in general damaged facade elements can be replaced in an easier way when stick and not unitized curtain wall system is applied.In addition, the phase change materials can undergo 10.000 thermal cycles and this means that after a couple of years they will need replacement.A negative point is that the PCM facade panel cannot be refilled on site in the existing facade panel and consequently the whole facade panel should be replaced.
This facade system is flexible and responds in a different way to different climates and weather conditions.This climate responsiveness can lead to energy efficiency and less energy demands for heating and cooling.
The transparency levels of the facade are adaptive according to the air temperature and the phase that the PCM undergo.This gives to the facade an interesting optical effect with satisfying levels of transparency during the day and less transparency at night.
Finally, as it was discussed before the unitized system which is proposed can be time efficiency in terms of assembly and construction as less work is done on site (prefabricated elements)

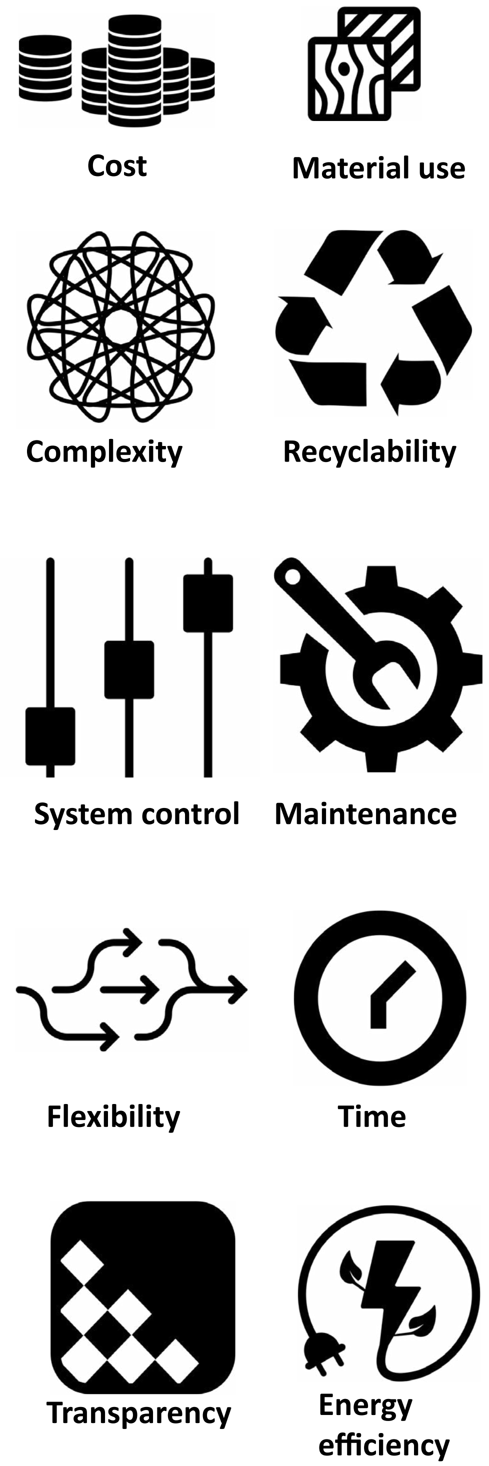


Figure 9.12:The key aspects for the assessment of the facade system

10

cfd analysis

CFD ANALYSIS

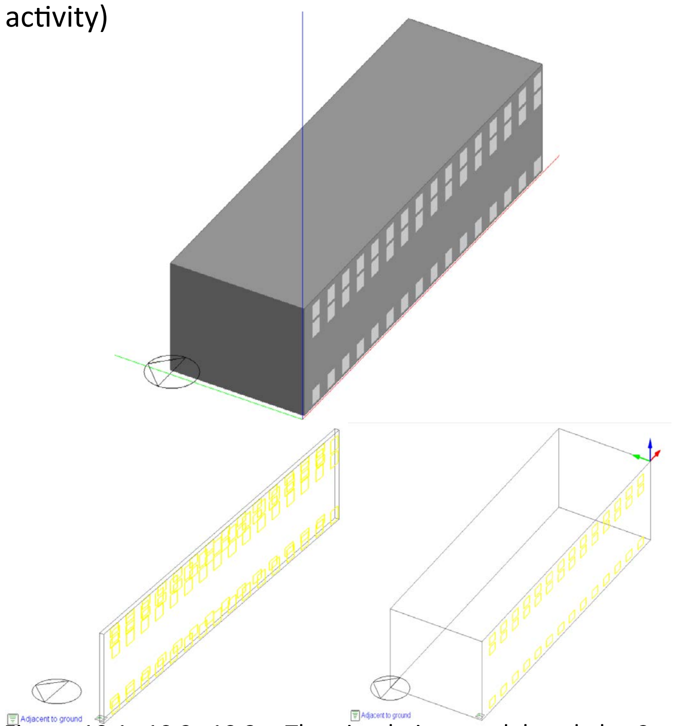
TEMPERATURE

In this CFD analysis measurements of the facade performance are taken in different states for both Netherlands and Greece.

In order the CFD calculations to be done energy simulations of the model should be done for the day mode (winter and summer) and the night mode (winter and summer).According to the season, the facade operation (window openings) is different.

Specifically, for the cfd analysis,they are done measurements selected a specific date and time for the winter and the summer.For the winter it was selected the 1 st of January at 12:00 and 20:00 for the day and the night mode relatively. On the other hand, for the summer it was selected the 1st of July at exactly the same daytime periods with the winter.

The PCM 21 (melting temperature:21)
: is applied in the south facade of the building and a series of windows have been created in the bottom and the top part of the facade.The part of the building that was selected for the simulations was the area when the silent room has double height. (37.75*12.5*8.4 m).The model is separated into two thermal zones (the double skin facade :cavity function and the interior space : standard library activity)



Figures10.1 ,10.2, 10.3 : The simulation model and the 2 zones,picture made by the author in Design Builder.

MEASUREMENTS

Through the CFD measurements it is given useful information for the thermal performance of the system and the air flow moving through the facade and to the indoor space.
More specifically,in first place it is analysed the air temperature that is developed in the indoor space taking into account different modes of natural ventilation according to the season and the time of the day.This along with the velocity vectors show how the air enters the facade and how it is moving and distributed in the indoor space.
As for the comfort levels , it is done Mean radiative temperature analysis where the human factor is taken also into consideration.The radiative temperature contours distributed in the space gives an insight on how the heat is radiated from the facade to the indoor space.

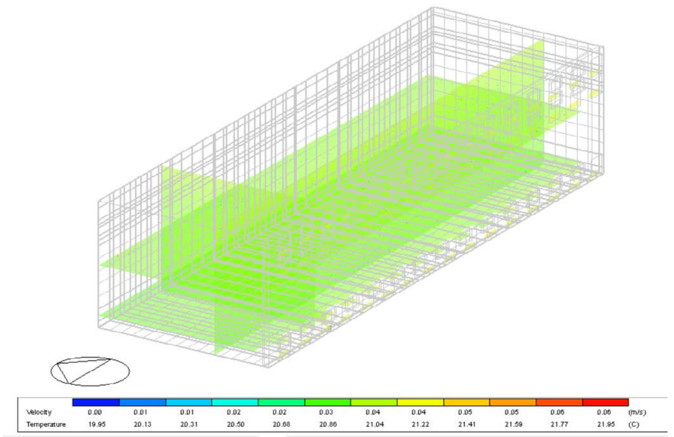


Figure 10.4: The air temperature and the velocity vectors,picture made in Design Builder by the author.

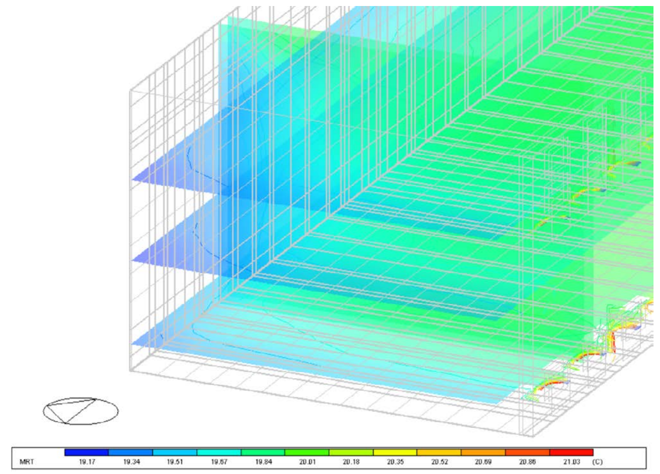


Figure 10.5: MRT calculations,picture made in Design Builder by

CASE 1:NETHERLANDS|PERFORMANCE_BOUNDARY CONDITIONS

A.SUMMER| DAY MODE

In this case, it is analysed the performance of the façade during the summer period in The Netherlands. The ventilation of the cavity forms the basis of the operation of the façade. This is achieved by locating openings in the bottom and top parts of the external skin. The internal skin is completely closed in order to prevent hot air from entering the building. The apertures of the exterior skin are placed at the right side and 20% of glazing allows the entry and release of fresh air into and out of the cavity.

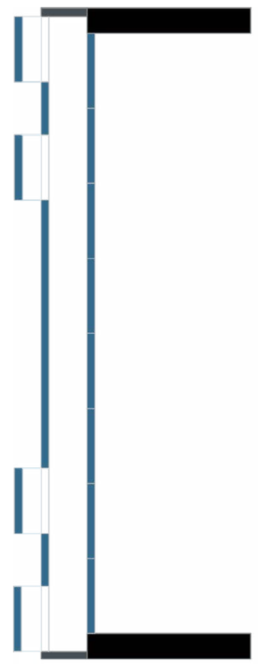


Figure 10.6:Facade operation summer day

B.SUMMER| NIGHT MODE

During the night, the operation of the façade system should allow night ventilation. This is done by opening the windows in the bottom and top parts of both skins. More specifically, the lower and upper parts of the façade allowsthe air circulation whereas the middle part consists of a closed cavity which restricts air entry. This enhances again, the stack effect logic. The windows of the exterior and interior skin open 20% and 100% respectively.

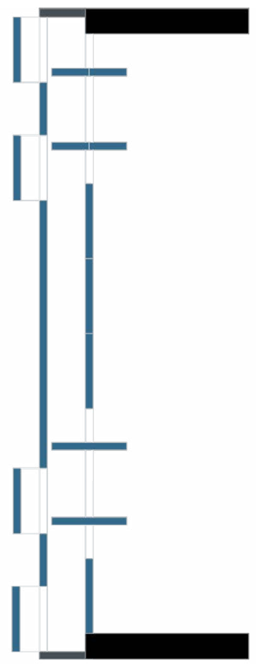


Figure 10.7:Facade operation summer day

SUMMER MODE			
FAÇADE SKIN	**WINDOW TYPE**	**STATE**	**CONSEQUENCE**
DAY OPERATION			
External skin	windows with opening at the right side	open modular units 20%	cavity ventilation
Internal skin	lamella windows	closed modular units	no overheating
NIGHT OPERATION			
External skin	windows with opening at the right side	open modular units 20%	fresh income and stale air release
Internal skin	lamella windows	semi- open modular units	night cooling

Table 10.1: The operation of the facade system during the summer, made by the author

C.WINTER| DAY MODE

During the winter day, both skins of the façade remain closed to prevent cold air from entering the cavity and the interior space. The PCM which is placed in the exterior layer, starts melting from the solar radiation and stores solar heat, The internal scheme is also closed to create a closed cavity that will act as a buffer zone. The apertures in both skins are set to 0% open.

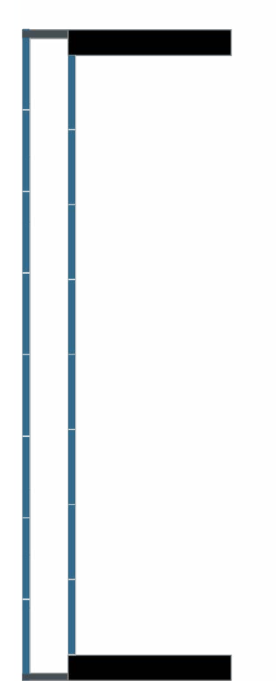


Figure 10.8:Facade operation winter day

D.WINTER| NIGHT MODE

At night, the external skin remains closed in order to restrict the entry of cool air into the cavity and the studying area. On the other hand, the inner façade layer is semi-open. The bottom part of the skin is closed whereas the openings in the upper parts are 100% open. The PCM that is located on the external skin, releases the stored heat through the openings on the top of the internal skin.

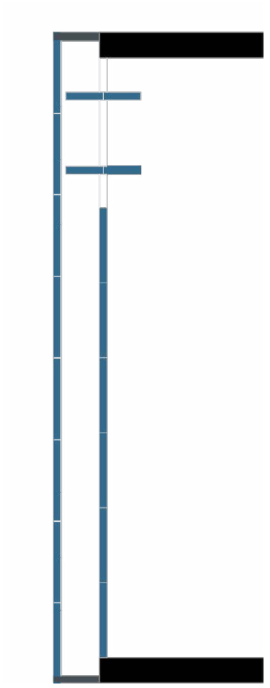


Figure 10.9:Facade operation winter night

WINTER MODE			
FAÇADE SKIN	WINDOW TYPE	STATE	CONSEQUENCE
DAY OPERATION			
External skin	windows with opening at the right side	closed modular units	no cool air circulation in the cavity
Internal skin	lamella windows	closed modular units	buffer zone
NIGHT OPERATION			
External skin	windows with opening at the right side	closed modular units	PCM releases heat
Internal skin	lamella windows	semi-open modular units	passive heating

Table 2: The operation of the facade system during the night, made by the author

CASE 1:NETHERLANDS| RESULTS

A.SUMMER| DAY MODE

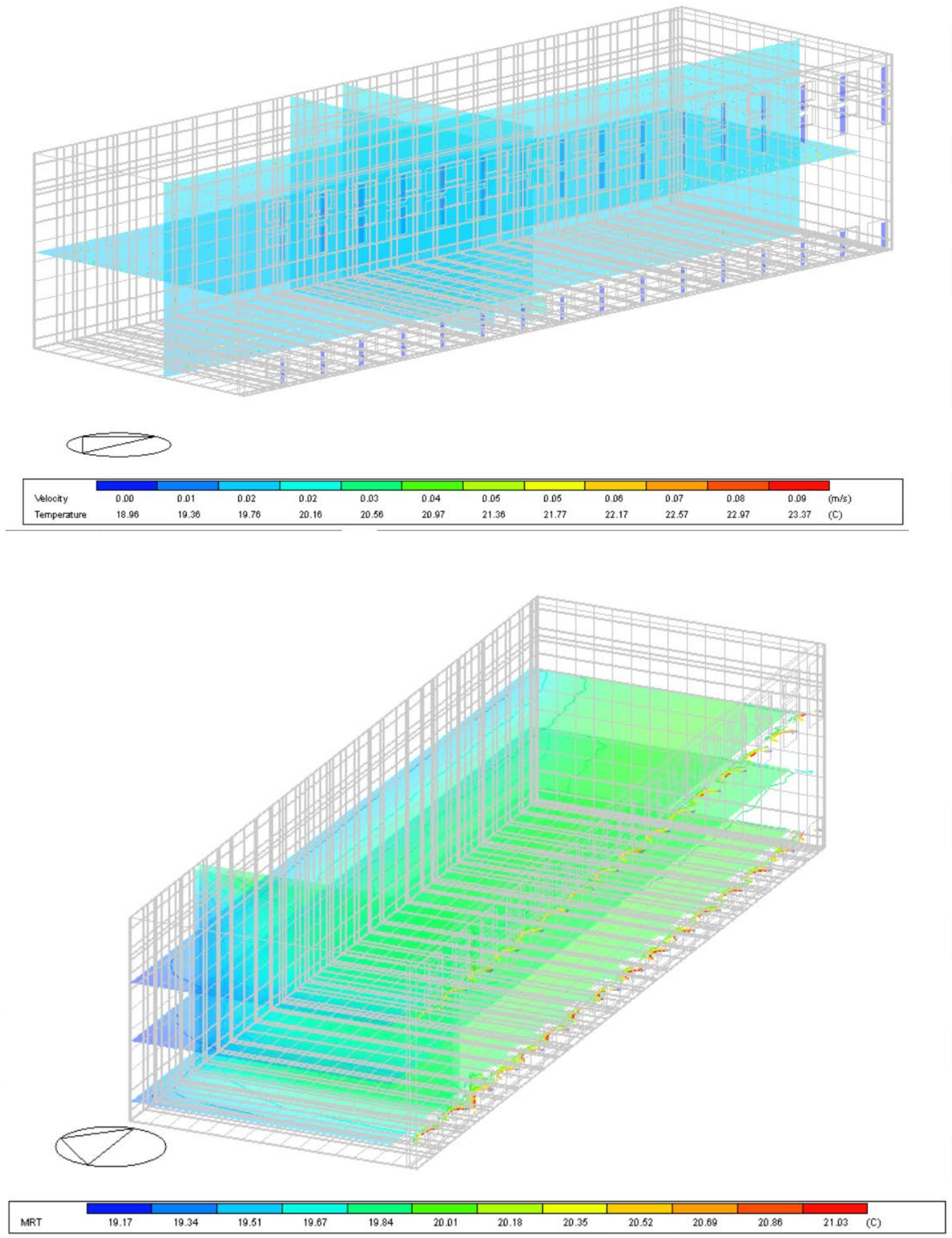
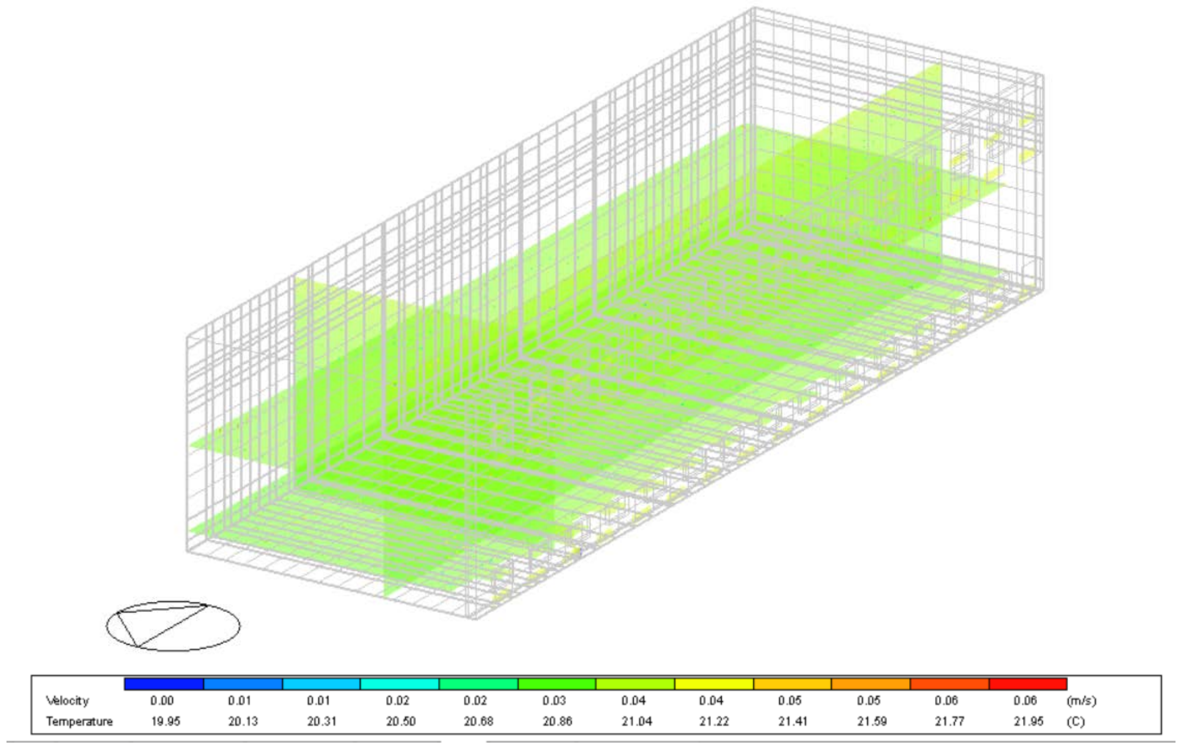


Figure 10.10 : CFD results for summer day

In the graph, it is shown that the average air temperature is about 20 degree C. The highest air temperature appearing 0 to 2 metres from the façade is 20.5 degree C. In general, the average air temperature is quite low because the inner layer of the façade is completely closed and doesn't allow hot air to enter the building. As far as the radiative temperature is concerned, the front of the windows are measured to be 20.8 – 21 degree C whereas the front of the façade portion (which is composed of PCM) is about 1 degree less. This happens due to the higher thermal mass of PCM relative to glass in addition to its ability to store thermal heat. It is also a better thermal insulator compared to glass.

B.SUMMER| NIGHT MODE



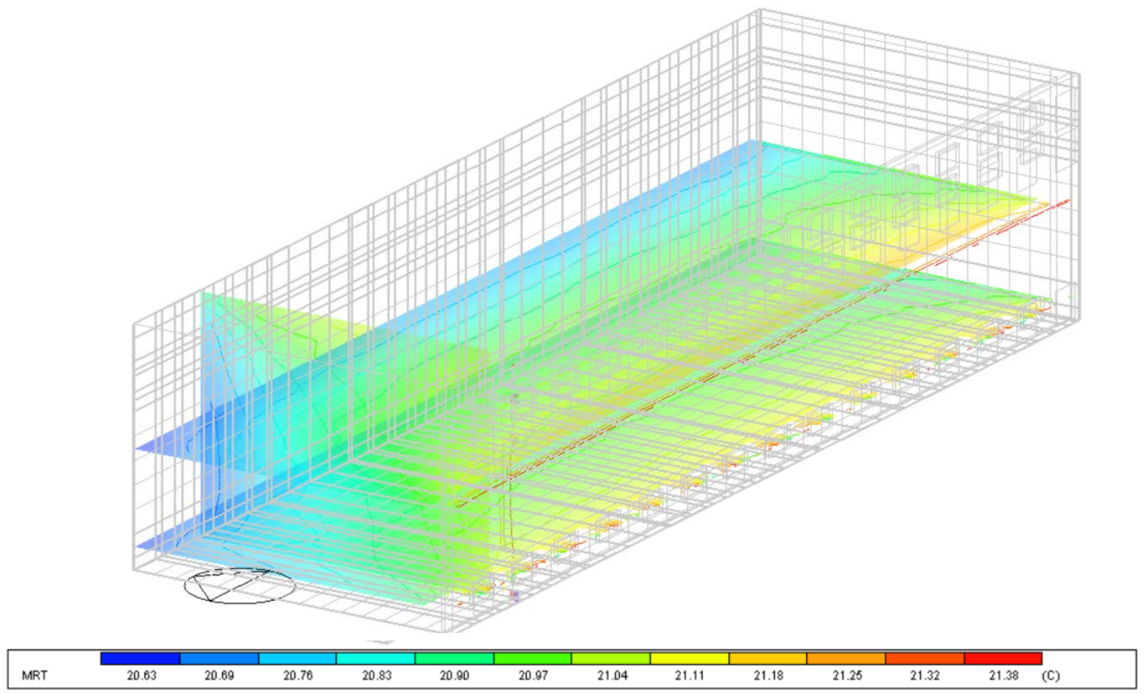
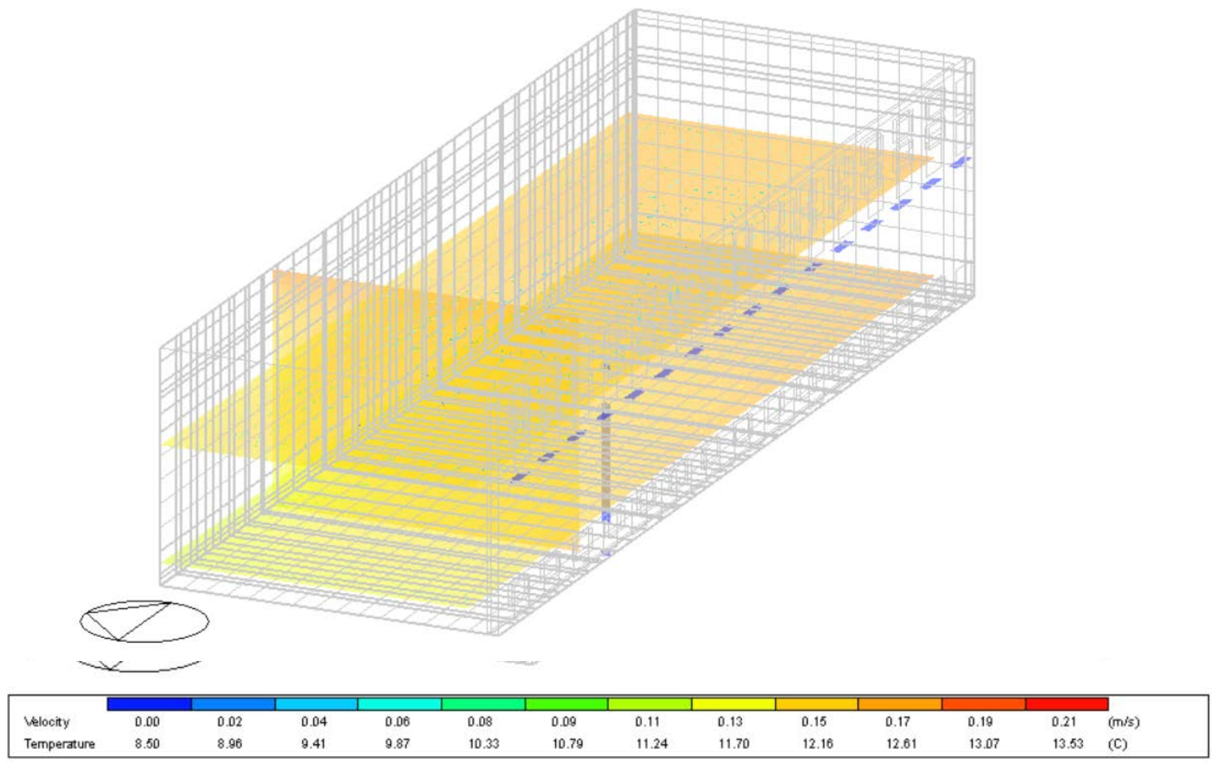


Figure 10.11 : CFD results for summer night

The average air temperature during the night is relatively higher than during the day. In the zone, 0 to 2 metres in the façade, the air temperature 21.04 degree C. The temperature is slightly higher during the night because the PCM has the ability to release the heat at night, which was stored during the day. However, the difference is very slight due to the night ventilation in the building because a large part of this heat is released outside. As far as the radiative temperature is concerned, it is 21.38 ^{0}C and 20.90^{0}C in front of the windows and PCM façade panels respectively.

C.WINTER|DAY MODE



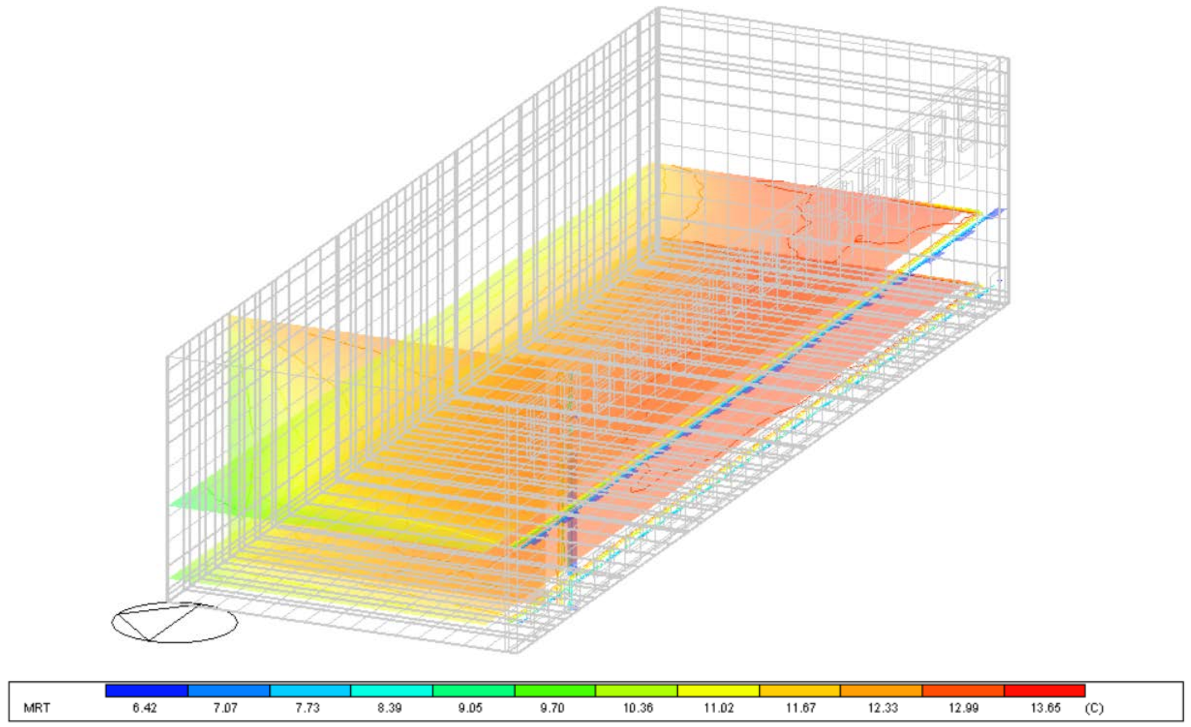
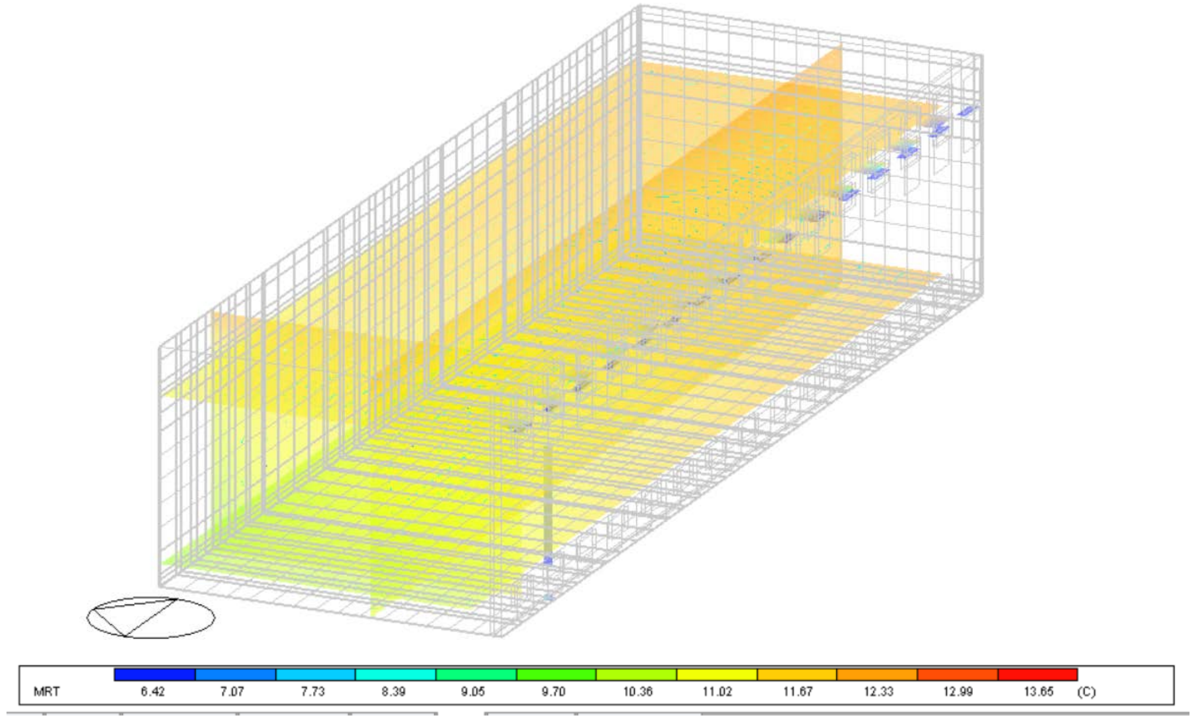


Figure 10.12 : CFD results for winter day

The air temperature without the use of mechanical heating systems is 12^{0}C to in front of the windows and 12.5 ^{0}C in front of the PCM panels. On the other hand, the average radiative temperature appears to be nearly 13 ^{0}C.In the graph they are shown two slices including radiative temperature contours.The first one “cuts” the facade where the PCM are placed and the other where the window(fully glazed unit) is located. In the first slice the radiative temperature seems to have a bit higher values compared to the other slice because of the use of the PCMs in the facade.

D.WINTER| NIGHT MODE



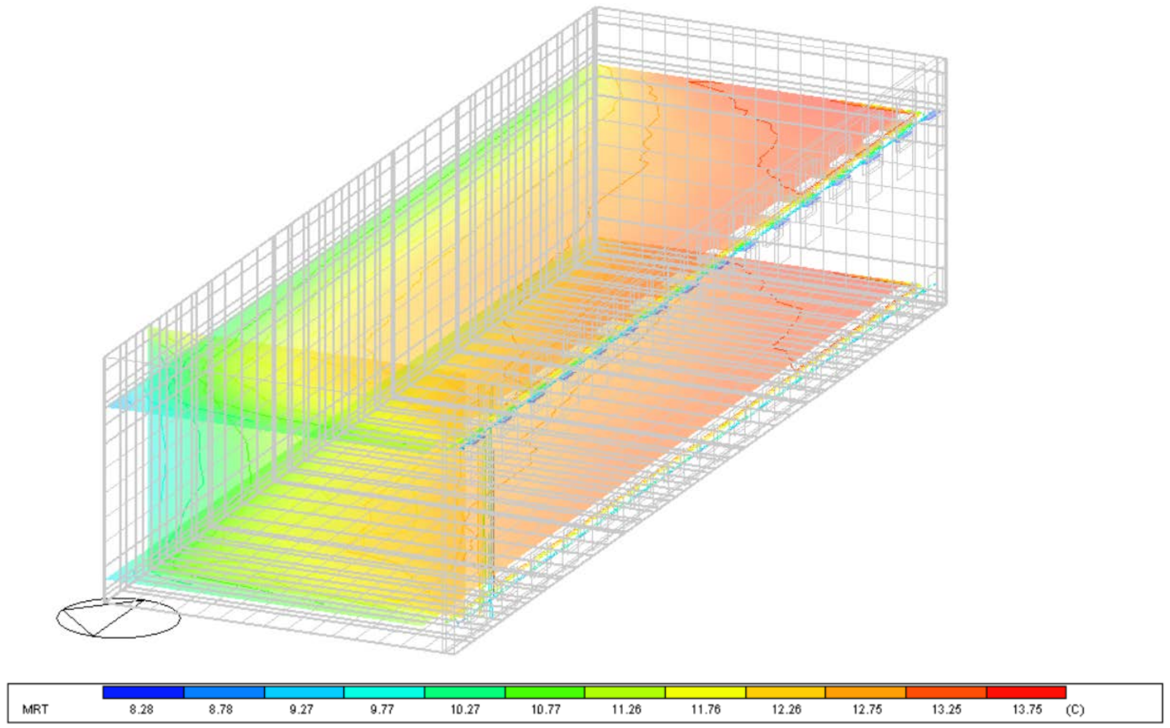


Figure 10.13 : CFD results for winter night

During the night, the average air temperature is 20 ^{0}C. which is close to the air temperature attained during daytime. However, the radiative temperature ranges from 12.9 to 13.25 ^{0}C which is higher than the value appearing during the day because the PCM applied in the façade releases the stored heat to the interior thereby, providing passive heating.

CFD ANALYSIS|DISCUSSION

As it is shown from the previous images made out of the cfd analysis the air temperature of the indoor space compared to the radiative temperature are not the same as in the second the metabolic rate, the human factor and the heat which is released from the PCMs is integrated.Under this conditions the radiative temperature is quite higher in the night mode for both seasons than in the day mode.This happens because the PCM based facade system has high thermal mass because of the PCMs. Consequently, the phase change materials in the morning, in the melting process the store the solar heat preventing the excessive heat entering the building and at night they release the heat to the indoor space rising the radiative temperature.

As far as the software(Design Builder) is concerned, the calculations that were made are refered to results for a specific day and time. This can give the user a general insight about the thermal behaviour of the PCM and the air flow movement from the exterior to the interior space but it focuses only on a specific date, something that make the simulations a bit inaccurate.

In further studies, another software like Comsol can be used for more detail CFD analysis, taking into account the dynamic character of the facade and a larger range of time (thermal simulations for the whole day and not only at a specific time.)

11

conclusions

LIMITATIONS

The transition from the literature research to the experimental phase of the thesis was marked with several restrictions.
From the initial energy calculations,a general insight was formulated about the optimal glazing to PCM ratio in the facade.The glazing percentages reached 20% for Athens and 30-40% for Netherlands.However,the range was limited, many design patterns could be created through the grasshopper definition optimization in Design Builder by changing the parameters.The choice of the author was to end up to 4 different patterns for Greece and Athens (respectively) ,following the rules of visual comfort and the general structural format of the library room (placement of columns and slabs).
This research is focused only in library buildings because their operating schedule differs from the office buildings as it includes HVAC use for both night and day.This was really important in terms of PCMs because they are materials which are supposed to change their phase at night and release the heat to the interior space providing passive heating.Of course, in practical level the facade stsem can be also applied in office buildings.
In terms of the computational design, it was used the attractor curve logic in order to create the facade patterns because it was a requirement of the author to place panels with less glazing infront of the slabs and the columns and a higher value of glazing percentage in the working area zone and the daylight zone.With the attractor logic this is possible creating attractor lines in front of the areas of interest (slabs and columns) creating an interesting gradient optical effect on the facade.However, there are also other commands and grasshopper tools that can be integrated in further research in order to make facade patterns for PCM based designs.
Moreover, in the building level, the Silent Room of the TU Delft library was selected as a study case.For simplification a less complex rectangular volume was designed in the simulation model for the computational design, the facade design and the exploration of the Building Physics aspects.

As far as the energy simulations are concerned, in order to create the simulation model, the input data coming from Grasshopper (window to wall ratio/glazing percentages per panel group),interpreted the actual facade patterns with simple windows that had exactly the same percentage with the computational design.A limitation of the Design Builder software is the fact that it could not import the actual computational model (real pattern) of the facade in order to have the exact glazing configuration in the facade.However, this would not make much difference in the calculations that had to do with the energy use (heating and cooling loads). It would make a difference in case a daylight optimization was made because then the light diffusion would be different.
As for the experiment,the samples that were made had dimensions 14.5cm * 14.5cm * 3cm because of the set up restrictions(climate box). If the actual panels were measured (40cm * 40cm * 3cm), most probably the results would be more accurate.Another significant point is that the installation of the climate box was placed inside a room not taking into account the solar irradiation factor. If the samples were located infront of a window and the temperature could be regulated by a specific installation then the results refered to the melting and solidification process would be more realistic.In this specific room, it has already created this window installation.For a further research, measurements can be done infront of the window using also pyranometer in order to be able to calculate the solar irradiotion levels and how they affect the PCM panels.

GENERAL ASPECTS

The review on the thermal and optical properties of the PCMs, the climate responsive aspects of the facade design and relevant researches done in the field of the PCMs contributed to define facade strategies taking into account the limitations of the PCMs and both their negative and positive aspects.

This research focuses more on how specific facade strategies can affect the thermal performance of the PCMs and also the energy demands of the building in which they are integrated.The facade guidelines that are formulated in this research have to do with the choice of the PCMs, the melting temperatures that can be used according to the climate of the area, the glazing-PCM ratio integrated in the facade, the combinations of the PCMs that can be used and the natural ventilation startegies that can be followed by the facade designers.

The review on previous studies that were referd to PCM Iintegrated research projects served as a reference for the formulation of my own methodology which includes parametric design,experimentation with physical measurements, energy simulations and construction detailing of the facade design.

The facade guidelines that are presented in the final chapter are derived from all the research methodology tools that are decribed in previous chapters in order to give to facade desgners an overall insight on how to integrate PCMs in a facade design.

Nevertheless, due to simplifications made in order to reduce the energy simulation time and the grasshopper process more time and computing power would be needed in order to achieve more accurate results for this kind of facade design integrating the kinetic character of the facade according to the seasons and the day or night mode.

The methodology implemented in this Thesis, that allows for experimentation of different facade patterns so as to achieve different glazing to PCM ratio showed that the PCM percentage in the facade affects positively or negatively the energy performance according to the climate.In a mediterranean climate like in Athens, the less glazing and more PCM percentage the more energy efficient is the facade as the cooling loads rare in general much higher than the heating loads.Consequently, this facade system would be more beneficial if used in the libraries instead of a fully glazed facade. On the other hand,in a temperate climate like in Netherlands the heating loads are much higher than the cooling loads leading to the conclusion that a fully glazed double skin facade would react better in termas of energy performance than a double skin PCM based facade.This would happen because with a double skin fully glazed facade can be taken advantage the solar irradiation and the solar heat gains will be increased leading to less energy consumption for heating during the winter.

However, the results of this research do not have accuracy in all levels because as it was discussed before it was not taken into consideration the adaptive strategy of the facade designer in different aspects (natural ventilation in night and day mode and changing optical properties of the PCMs.

To sum up, this research can provide guidelines to the facade designers who want to implement a facade system based on the use of the PCMs, presenting all the key properties of the PCMs that should be taken into account in order to establish facade strategies which will lead to a better energy performance and thermal comfort in the indoor space of the libraries.

RESEARCH QUESTION

What should be the design of adaptive façade system based on the use of phase change materials and how should respond to different climates conditions in order provide in the indoor spaces of libraries and minimize the energy use for heating and cooling?

In order to design a facade system based on the use of PCMs several factors should be taken into account.
First of all, when PCMs are applied in a double skin facade system, the facade should be able to respond to different weather conditions (summer and winter) and have an adaptive character according to the climate which is applied.

More specifically, in a mediterranean climate, like in Athens the increased heat gains should be avoided so as to avoid overheating during the summer.The integration of PCMs in the double skin facade can contribute to a stabilized temperature in the summer day while the PCM has the ability to store the solar heat.On the other hand,at night the PCM solidifies and the material releases the stored heat.In order to prevent the heat from affecting the thermal comfort in the libraries, natural ventilation should take place.As for the winter, PCMs are a really beneficial alternative way of passive heating reducing the heat loads when the PCM solidifies and releases heat to the inside space of the libraries.

On the other hand, in a temperate cimate, the performance of the system can be quite the same but most probably the types of the PCMs, the thickness of the PCM, the PCM to glazing ratio will be different than in Greece.With this we can conclude that the performance of the facade system can be the same for both climates if another parameters change according to the requirements and the general characeristics of this climate.

This parameters can be astablished as guidelines for the designers and contribute to create an energy efficient facade system which will provide thermal comfort in the indoor space of the libraries.(show in the designer’s manual).

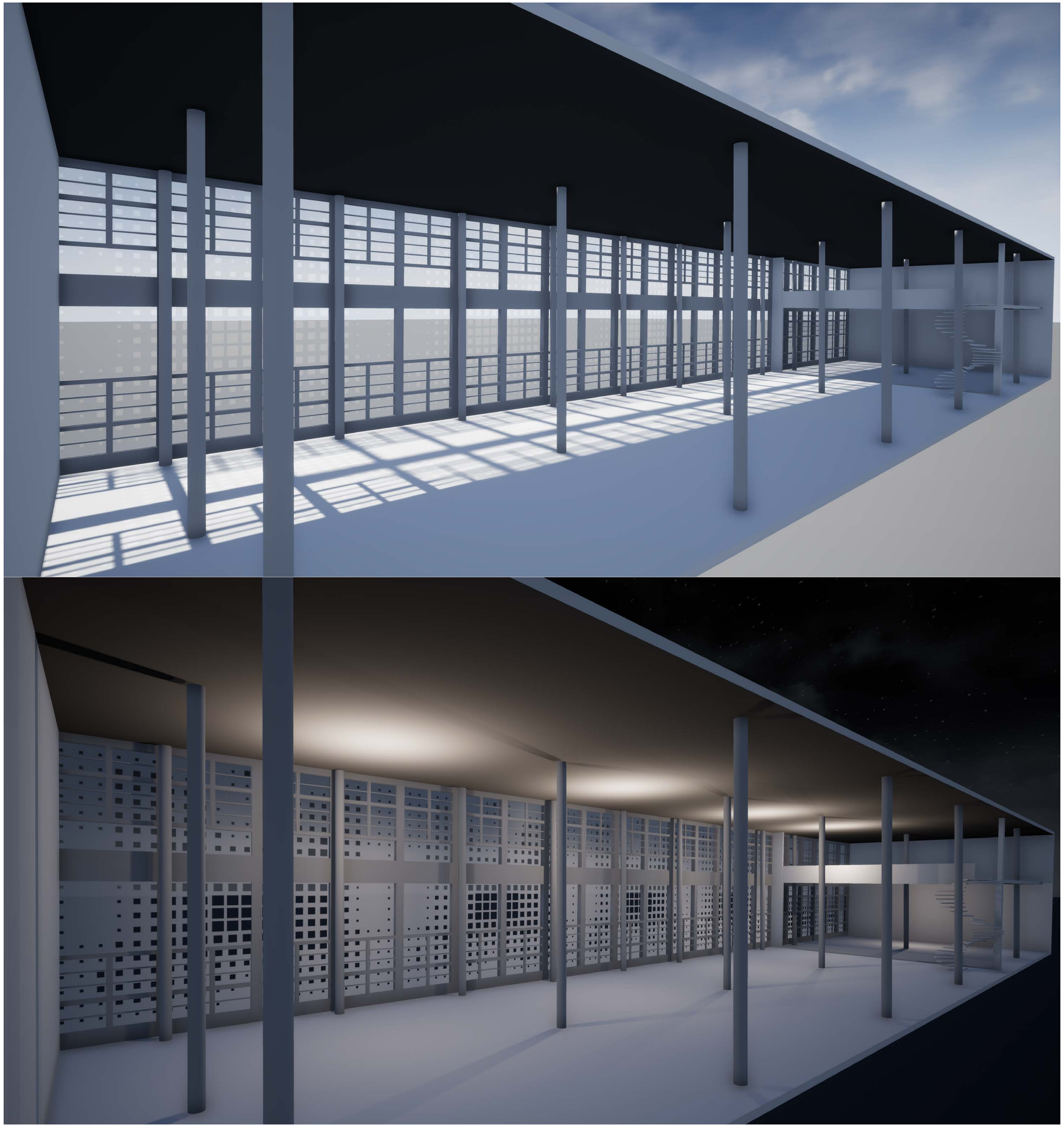


Figure 11.1:Perspective view of the indoor space

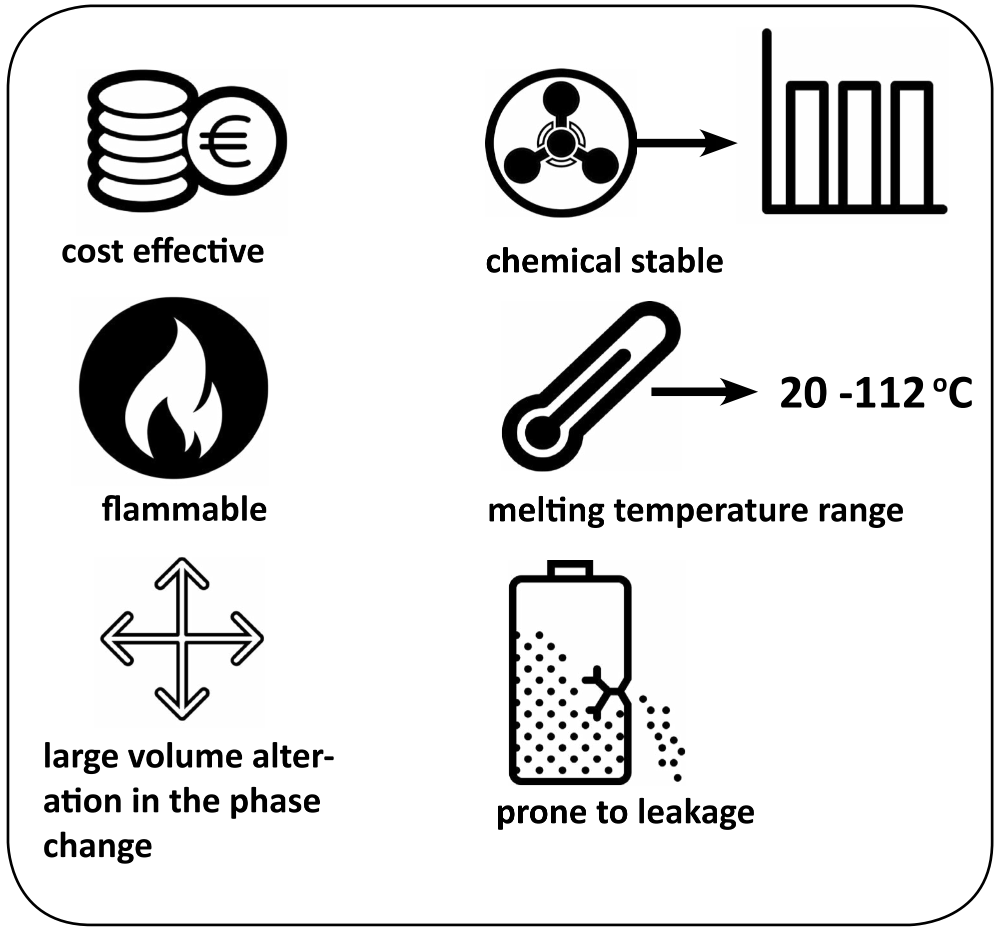
12

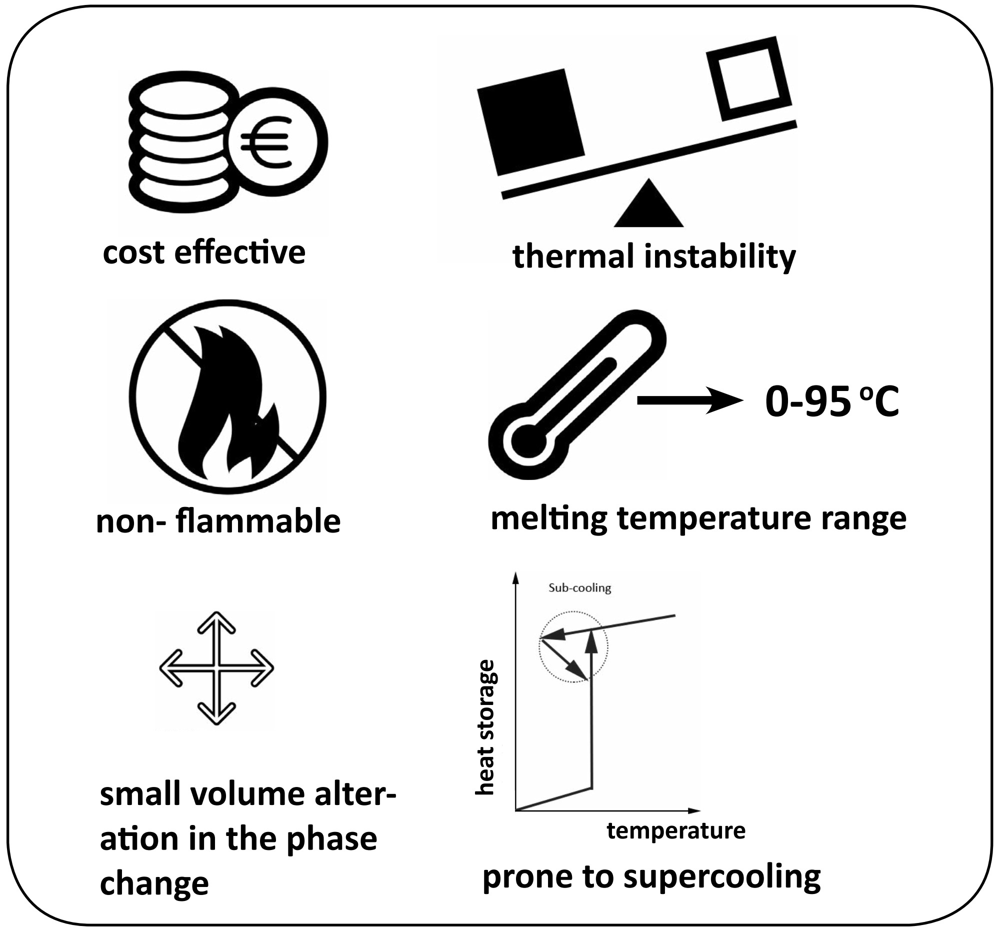
designer’s manual

STEP 1

THE CHOICE OF PCM TYPE | FACADE LEVEL

PARAFFINS OR SALT HYDRATES ?

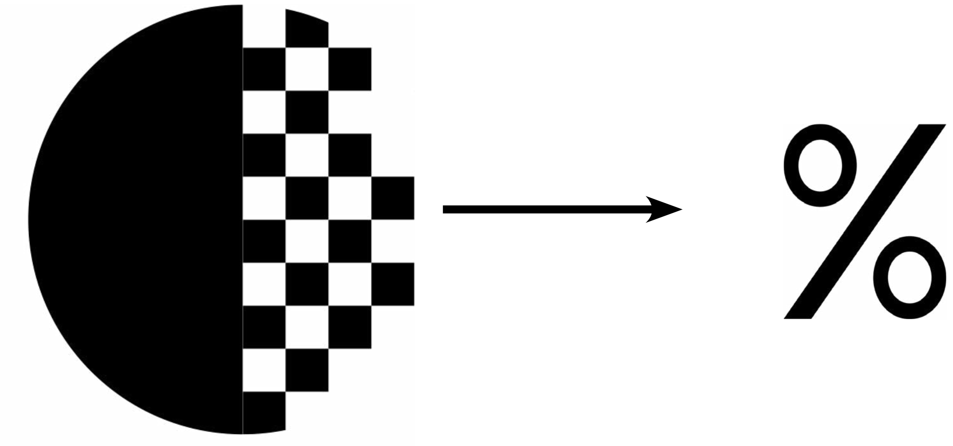




ANSWER → SALT HYDRATES

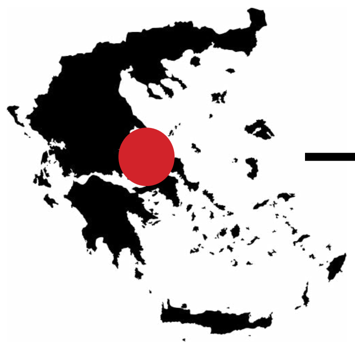
STEP 2

PCM TO GLAZING RATIO



GLAZING
PCM

A) ATHENS | MEDITERRANEAN CLIMATE



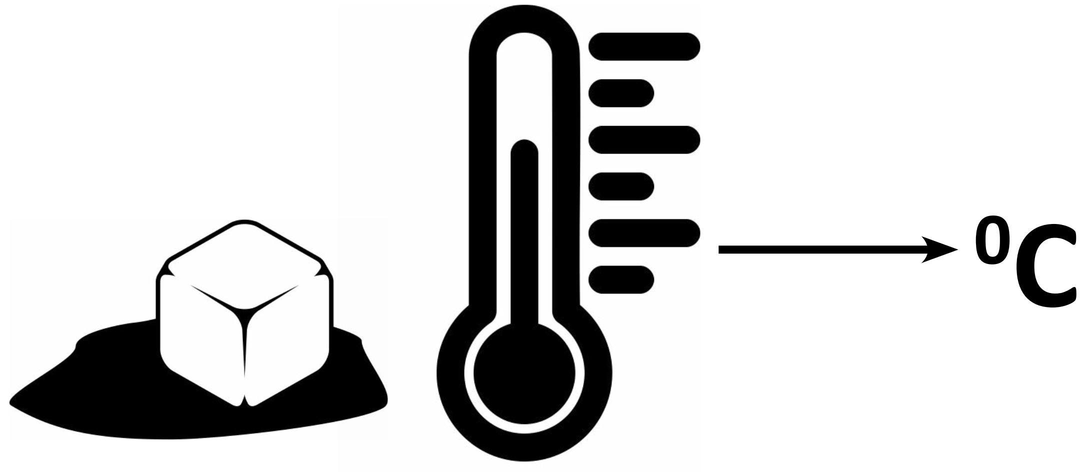
20% GLAZING
80% PCM

B) AMSTERDAM | TEMPERATE CLIMATE

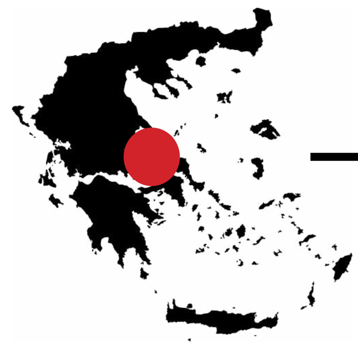
30-40% GLAZING
70-60% PCM

STEP 3

MELTING TEMPERATURE



A) ATHENS | MEDITERRANEAN CLIMATE



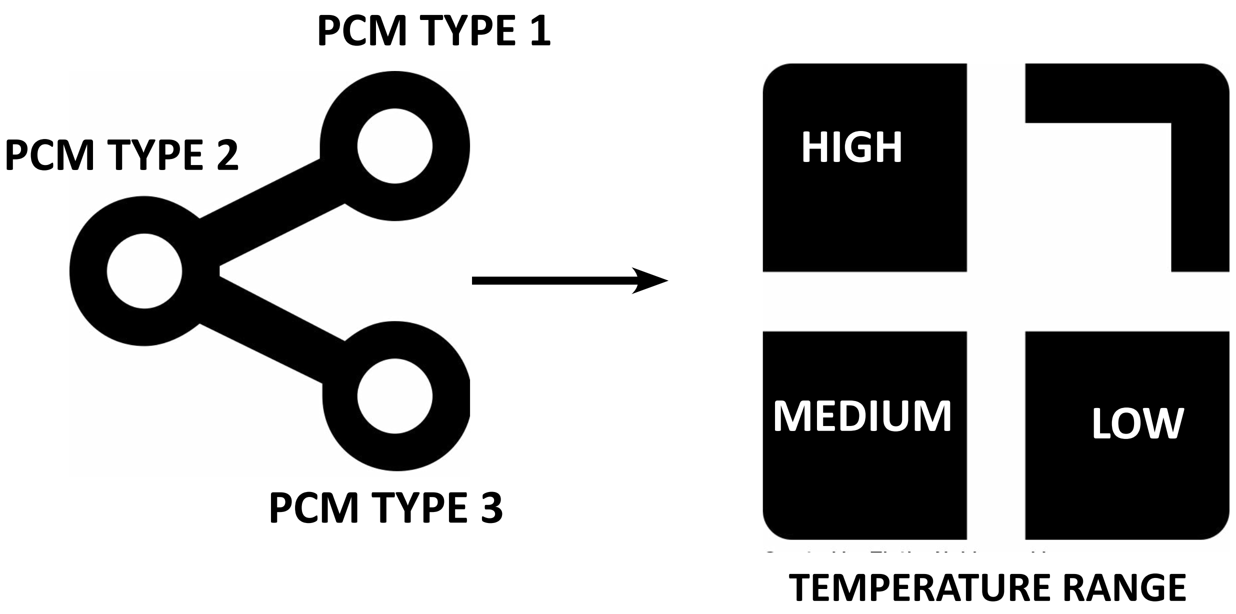
SP21 (21^{0}C)
SP25 (25^{0}C)

B) AMSTERDAM | TEMPERATE CLIMATE

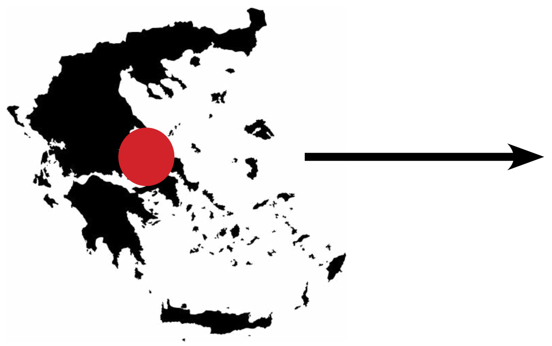
SP21 (21^{0}C)

STEP 4

PCM COMBINATIONS



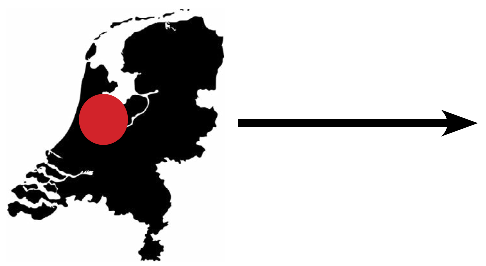
A) ATHENS | MEDITERRANEAN CLIMATE



SP21 - SP25 - SP29

SP21 - SP25 - SP31

B) AMSTERDAM | TEMPERATE CLIMATE

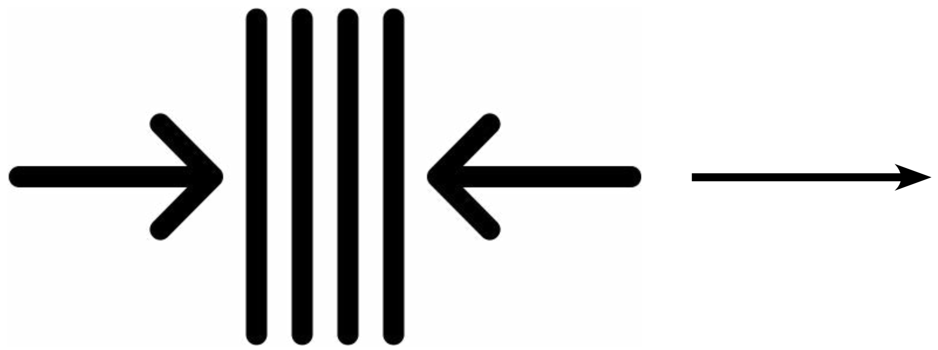


SP11 - SP21 - SP25

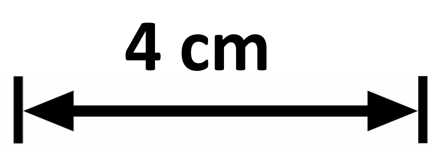
SP11 - SP21 - SP29

STEP 5

PCM THICKNESS



A) ATHENS | MEDITERRANEAN CLIMATE



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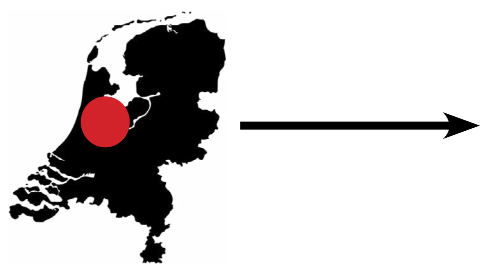
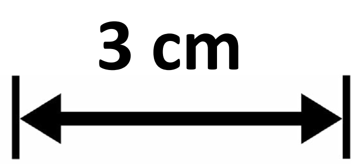
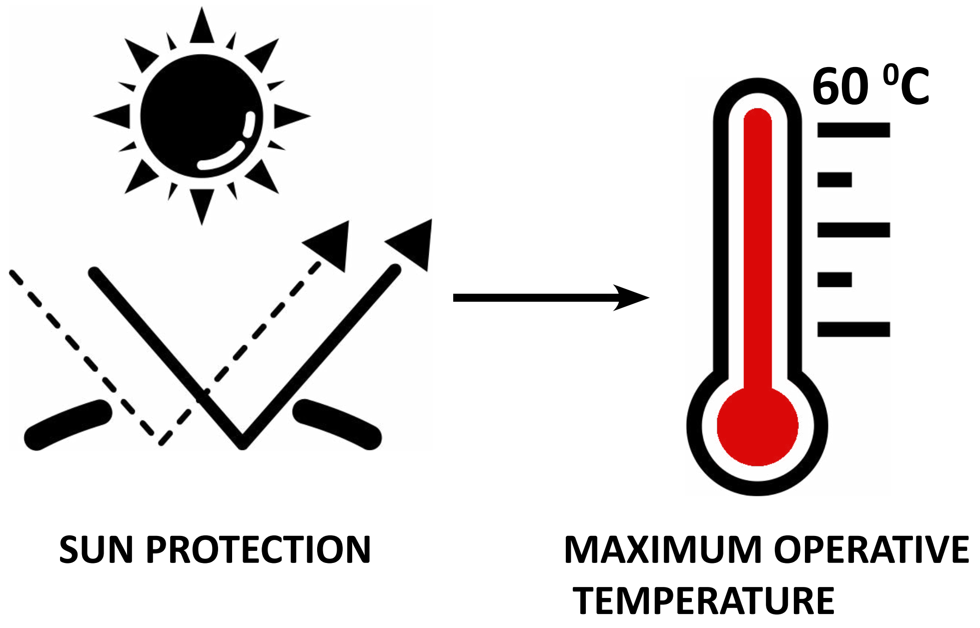


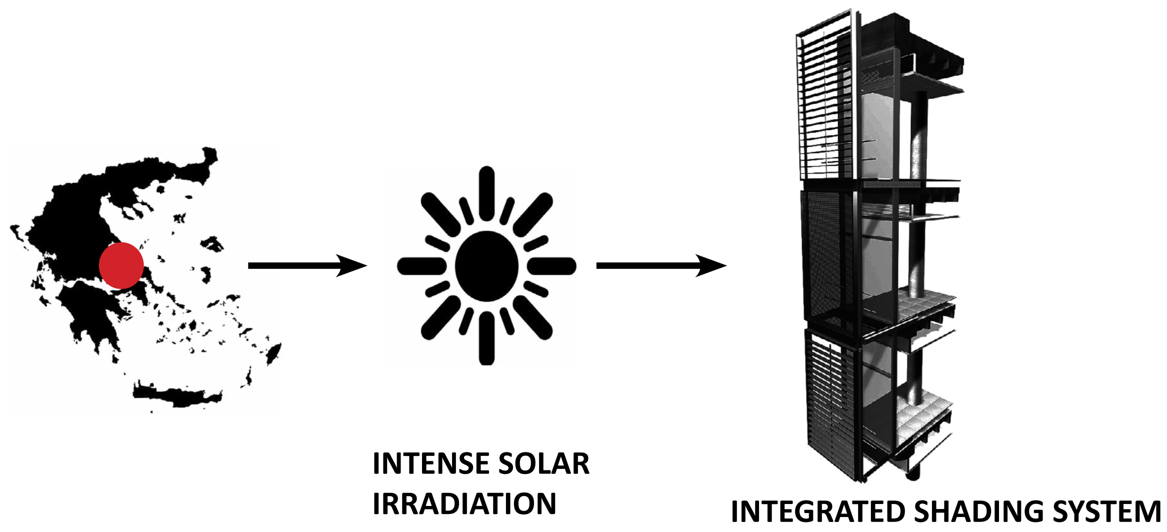


STEP 6

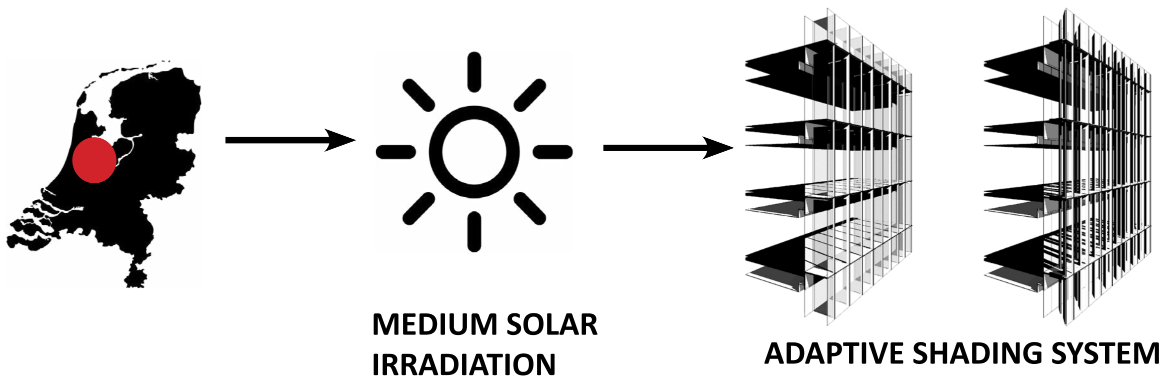
PCM PROTECTION



A) ATHENS | MEDITERRANEAN CLIMATE

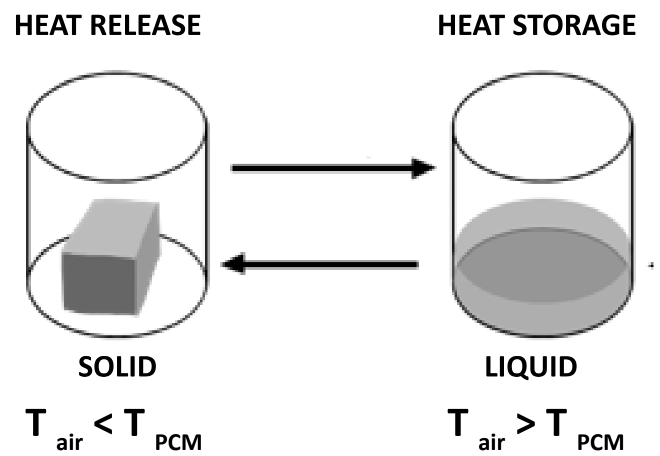


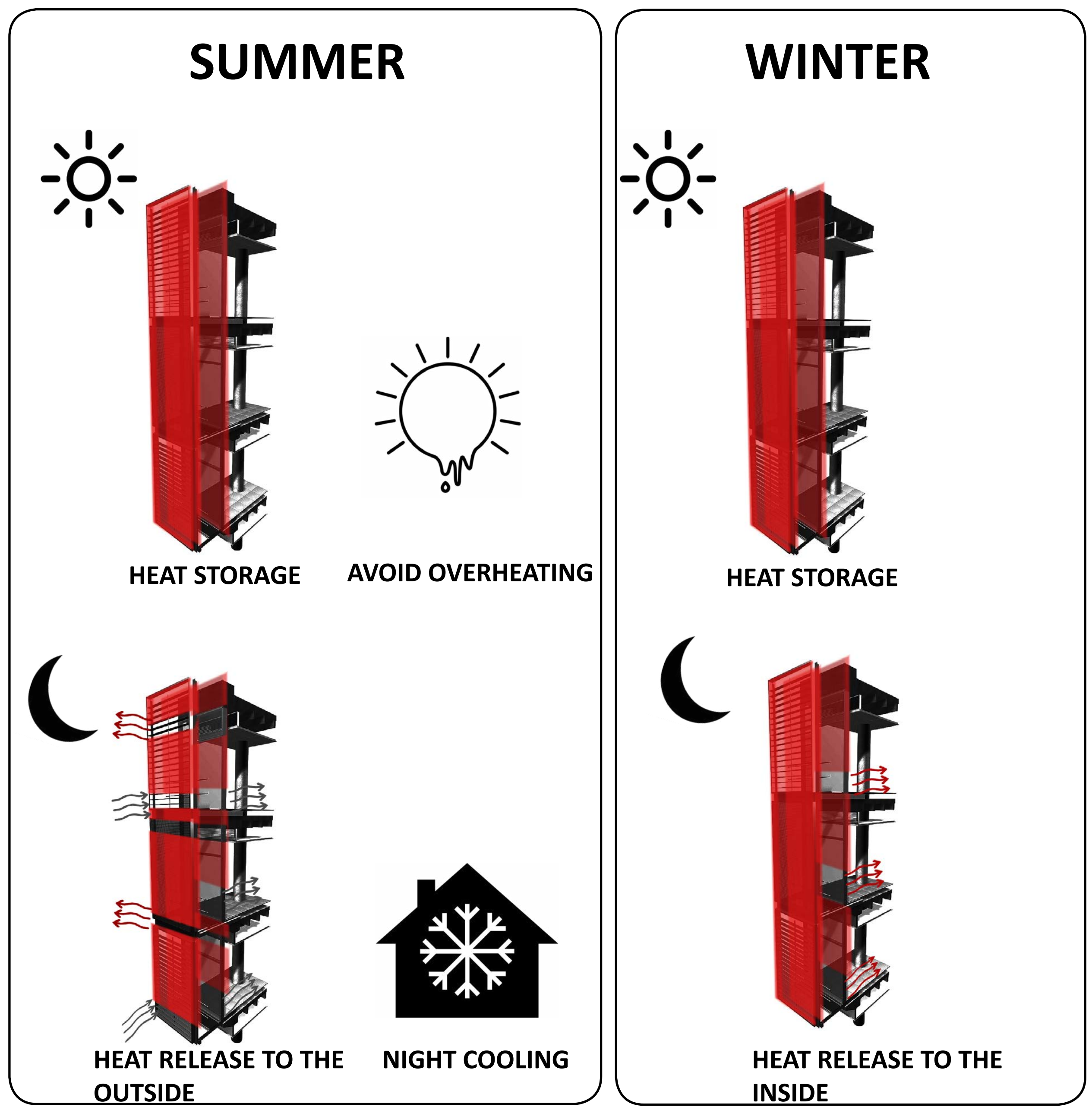
B) AMSTERDAM | TEMPERATE CLIMATE



STEP 7

RESPONSIVENESS

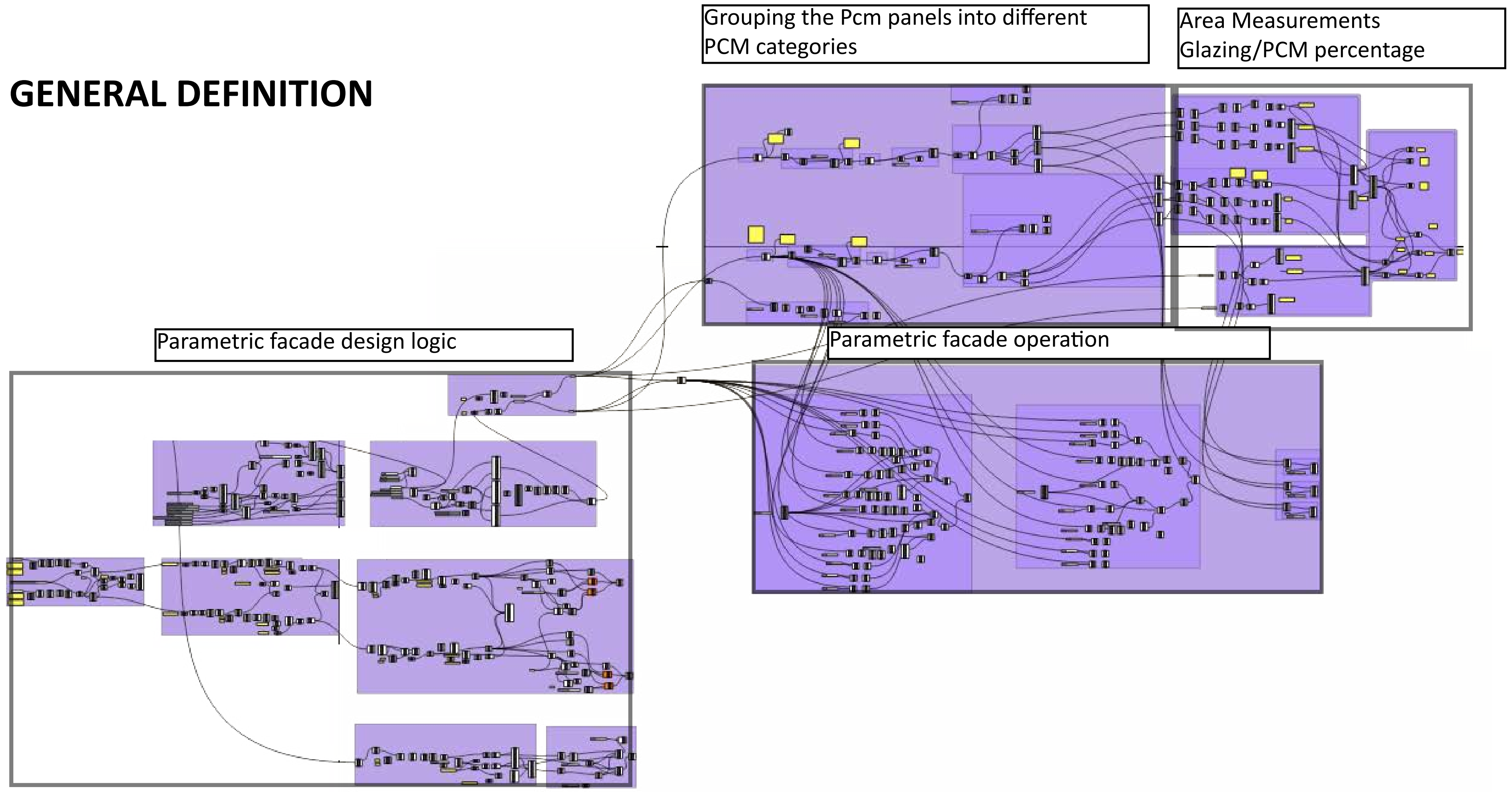


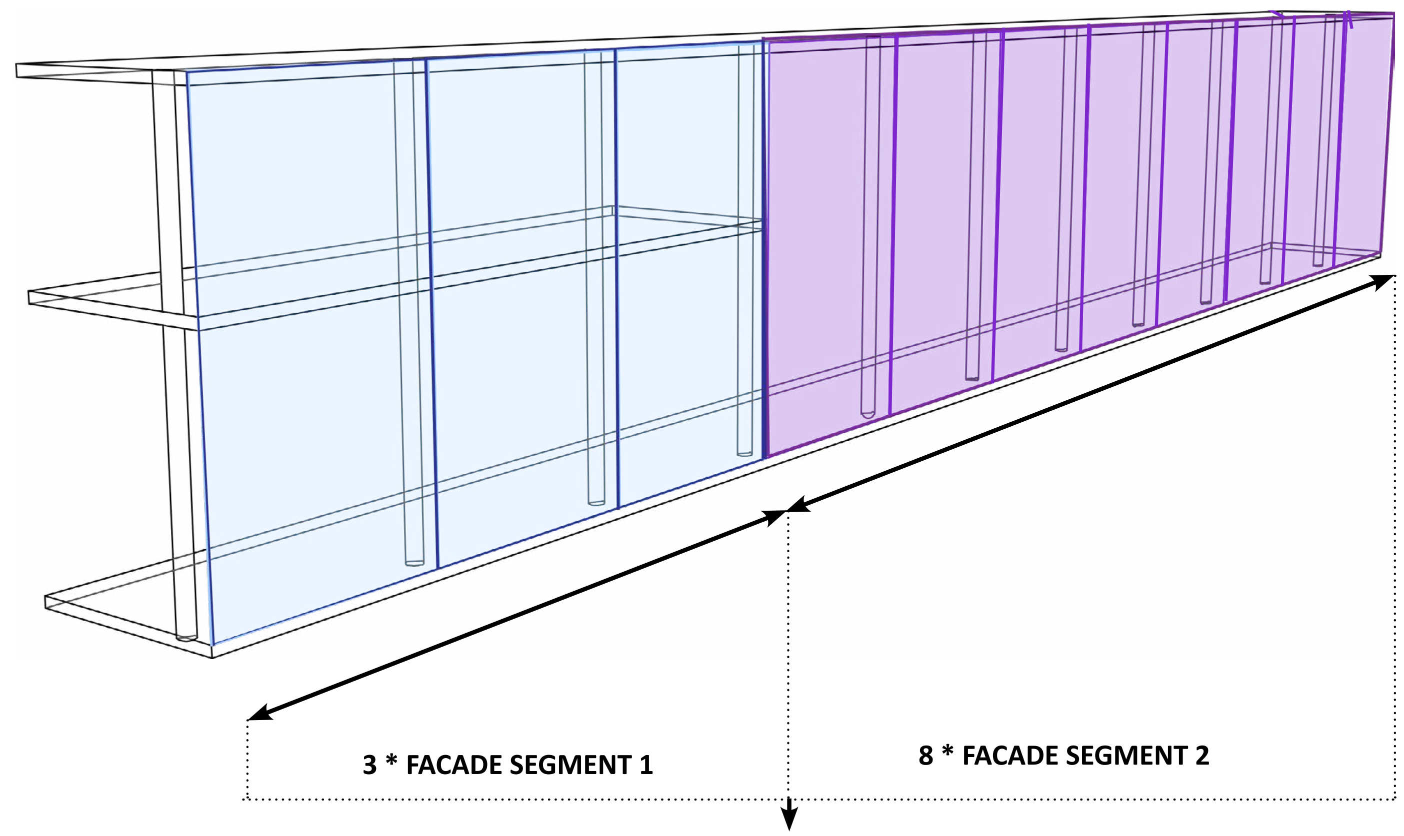


appendix

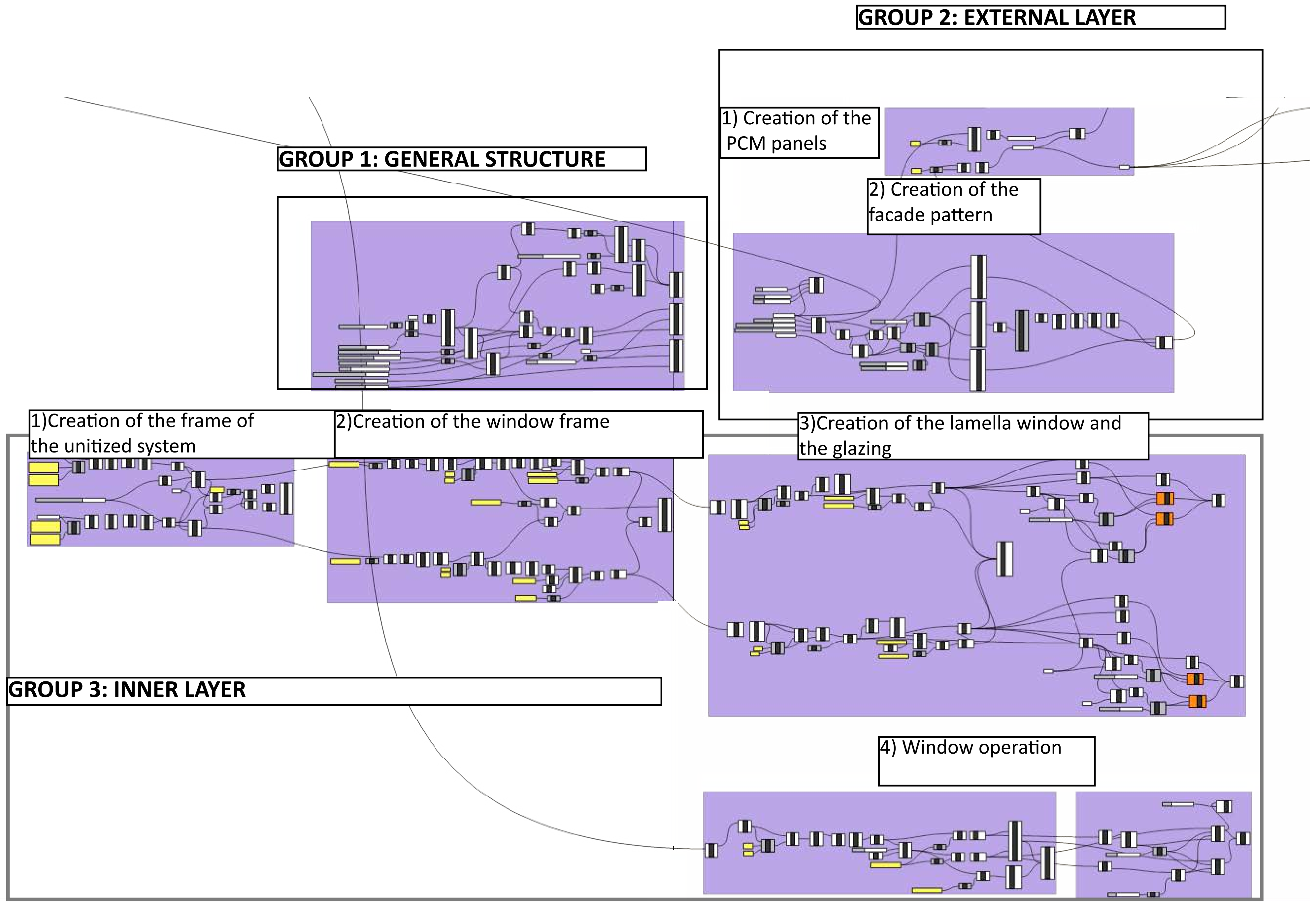
PART 1| COMPUTATIONAL DESIGN

GENERAL DEFINITION

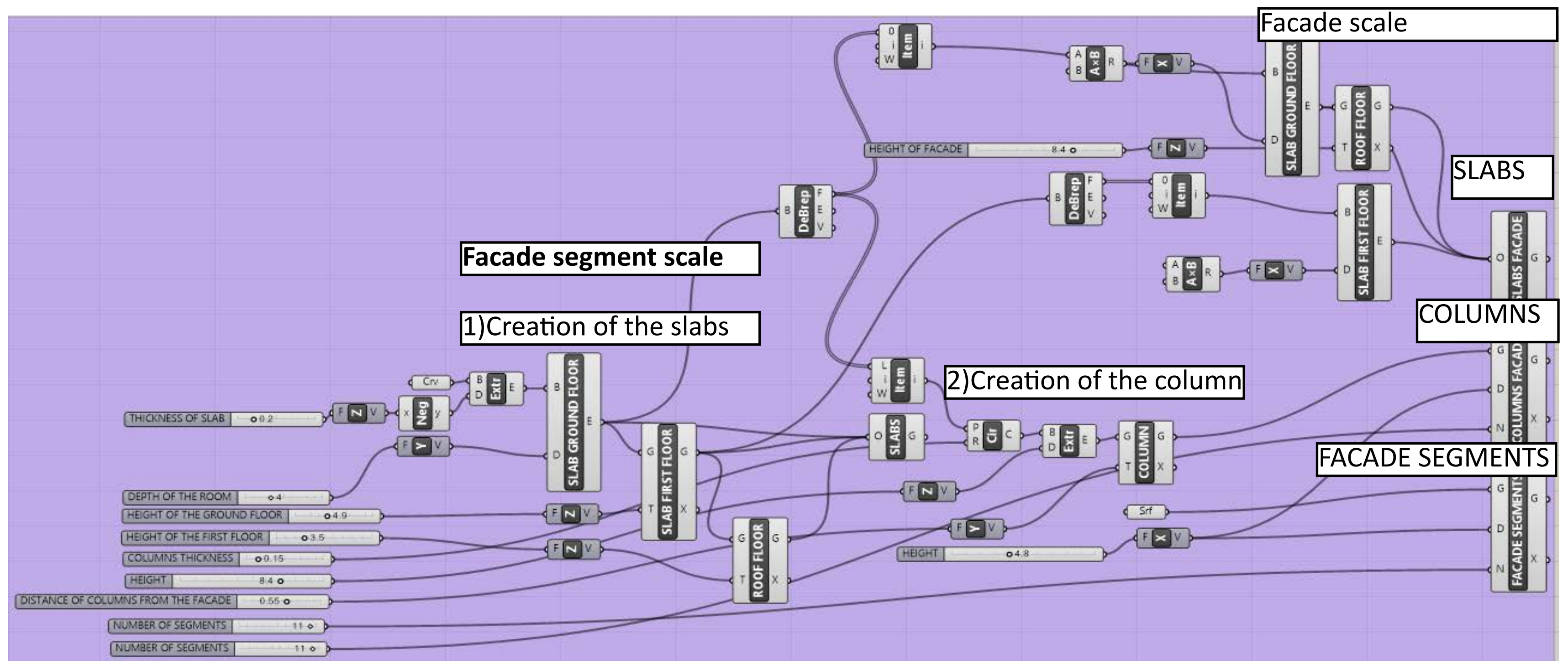




FACADE COMPONENTS



THE STRUCTURE



PARAMETERS

Thickness of the slab

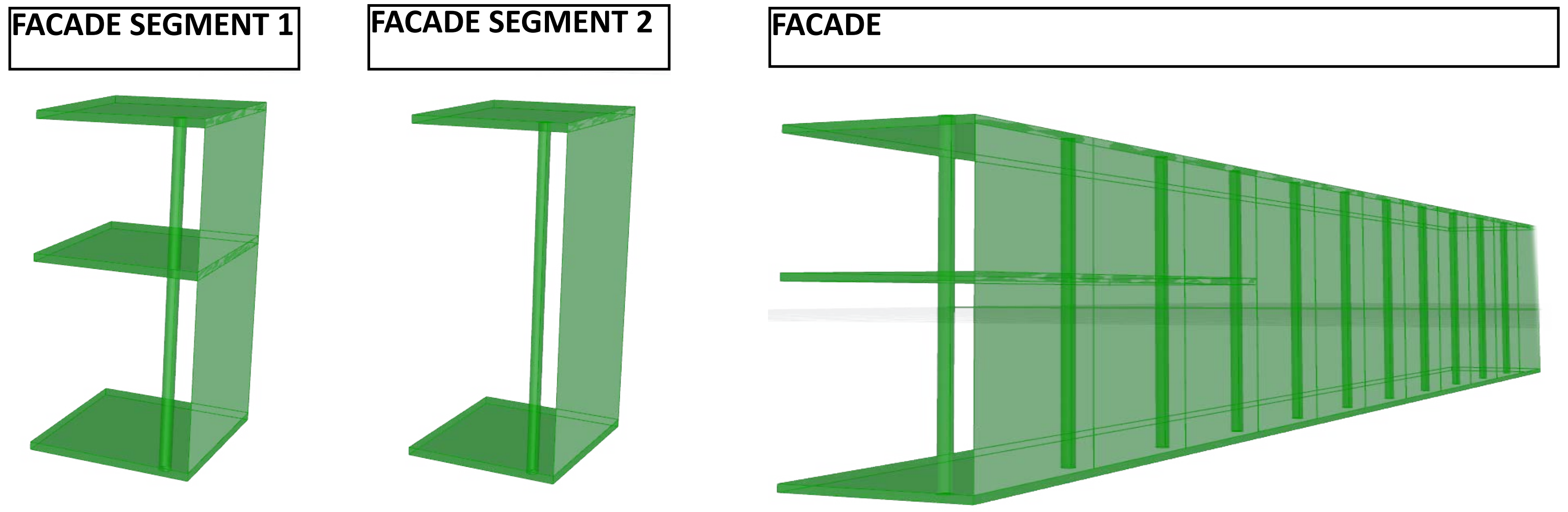
Length and height of the facade segment

Size of the columns

Column diameter

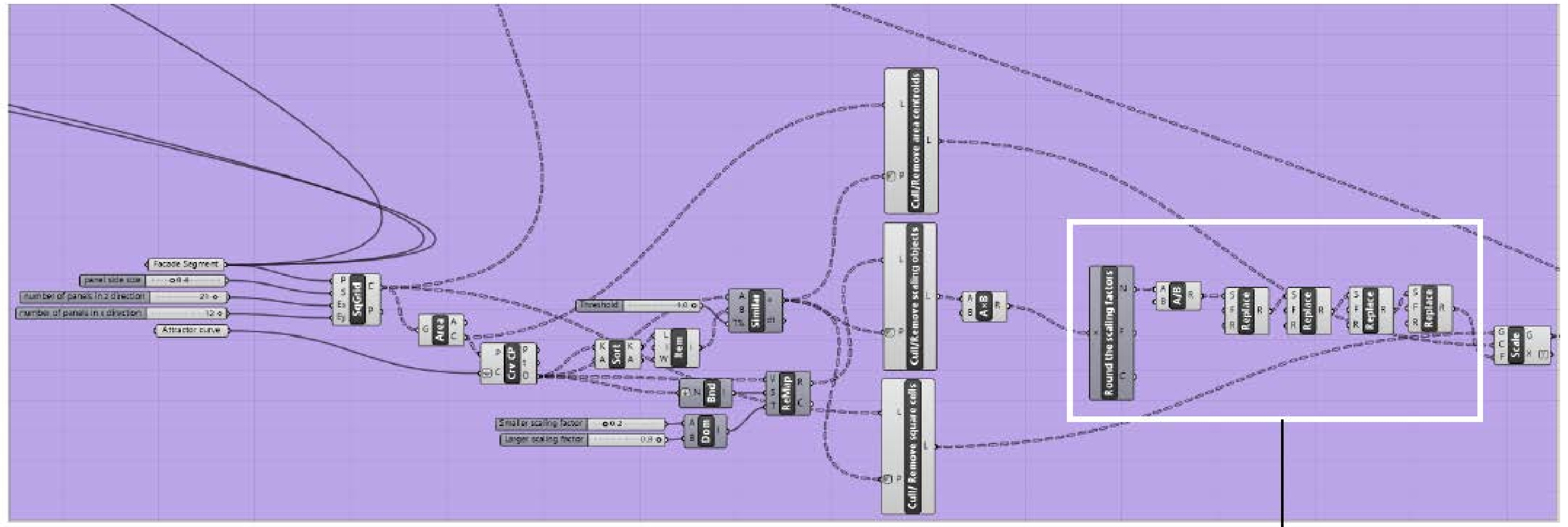
Height of each floor

Distance of the column from the facade



FACADE PATTERN | CREATION OF GLAZING ELEMENTS

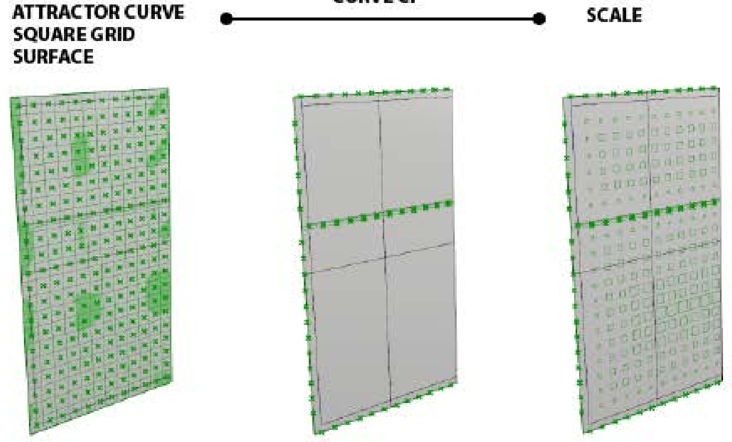
ATTRACTOR CURVE LOGIC



INPUT DATA
ATTRACTOR CURVE
SQUARE GRID
SURFACE

CURVE CP

OUTPUT
SCALE

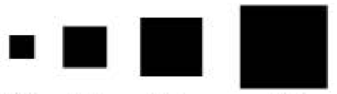


RESTRICTIONS
DOMAIN/SCALING FACTOR
0.2 0.8

7 DIFFERENT GLAZING ELEMENTS

REPLACE 4 DATA ITEMS: **0.1, 0.3 , 0.5 ,0.7**

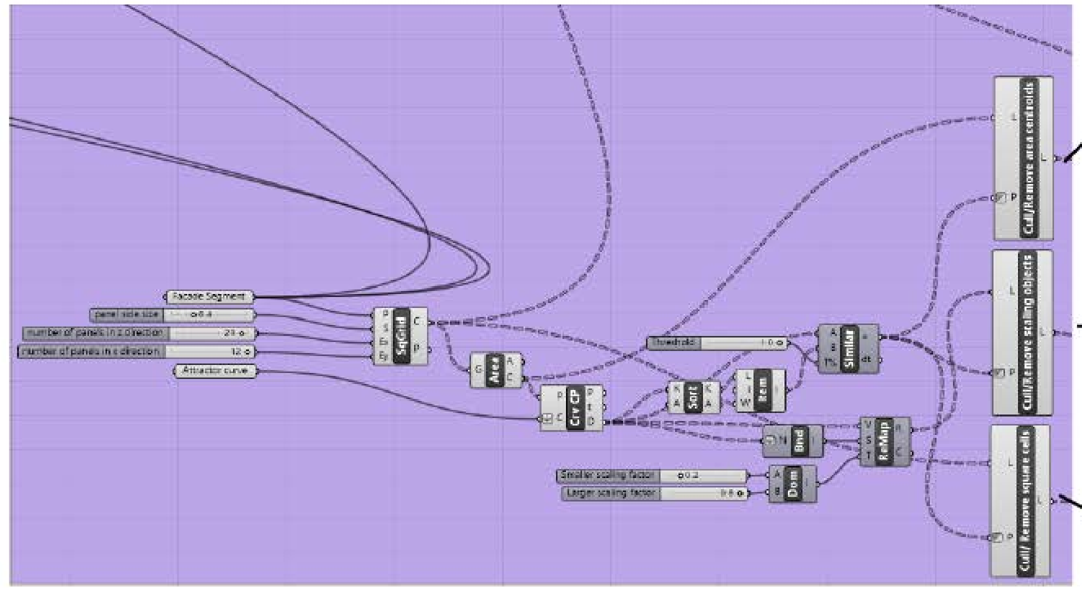
4 DIFFERENT GLAZING ELEMENTS = REMAINING SCALING VALUES: 0.2, 0.4, 0.6, 0.8

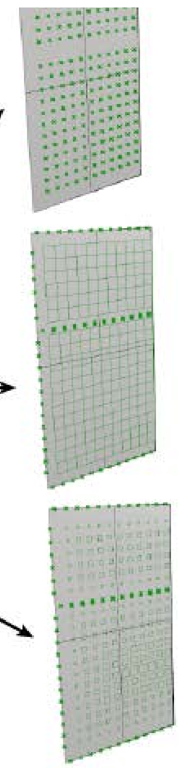


FACADE PATTERN | CREATION OF PCM BASED PANELS

ATTRACTOR CURVE LOGIC

Facade scale





TO THE ATTRACTOR CURVE

CULL PATTERN 1

REMOVE THE AREA CENTROIDS WHICH BELONG TO THE SQUARE CELLS CLOSEST TO THE ATTRACTOR LINE

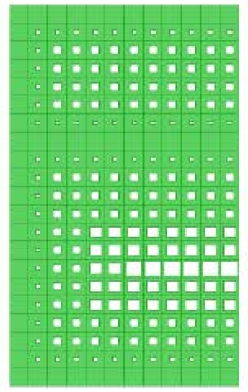
CULL PATTERN 2

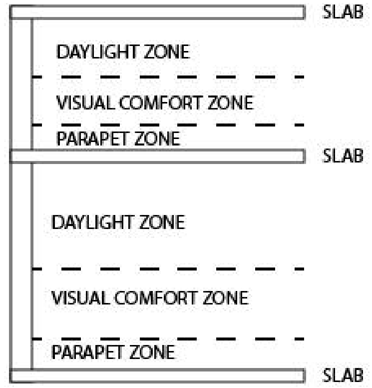
REMOVE THE SQUARE CELLS CLOSEST TO THE ATTRACTOR CURVE

CULL PATTERN 3

REMOVE THE SCALING SQUARES CLOSEST TO THE ATTRACTOR CURVE

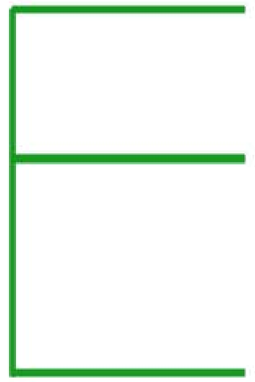
FACADE PATTERN 1



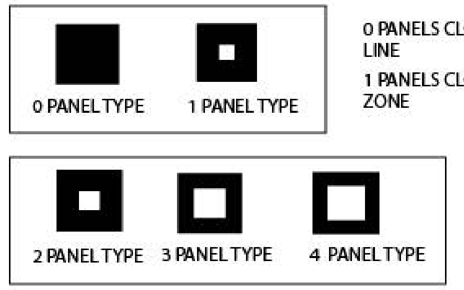


ATTRACTOR CURVE

THE ATTRACTION CURVE INFRONT OF THE STRUCTURAL ELEMENTS



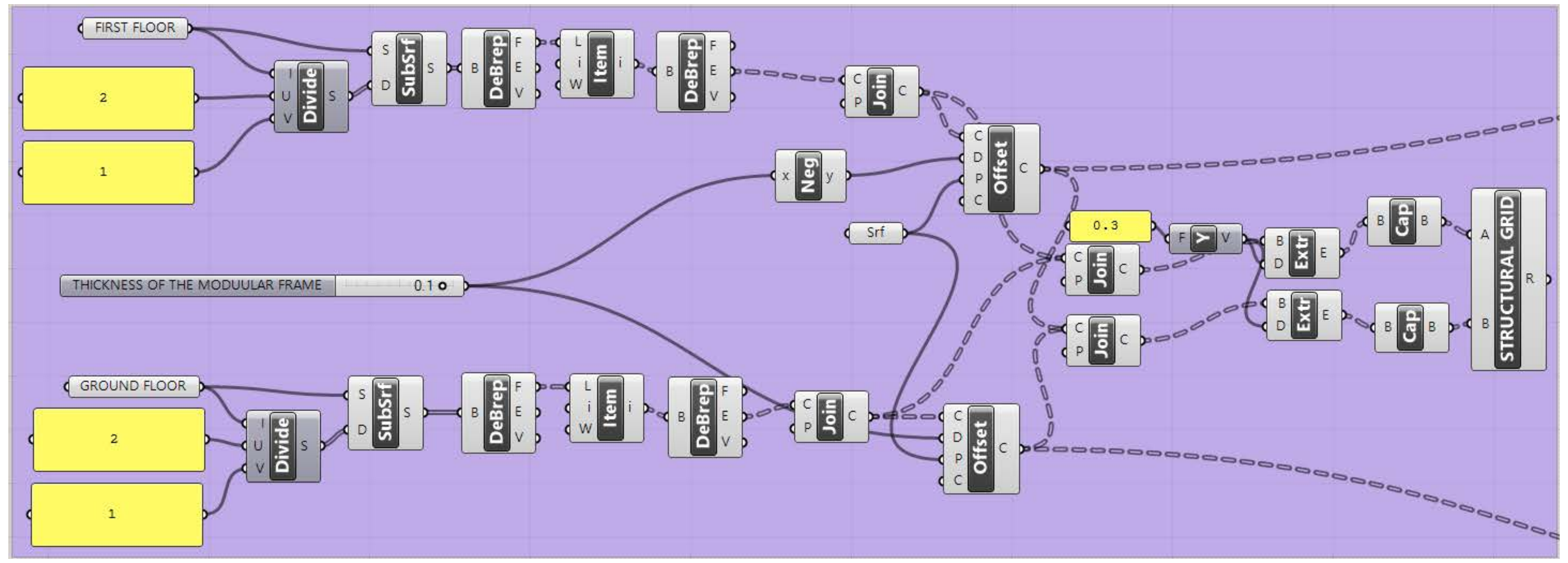
PANEL TYPES

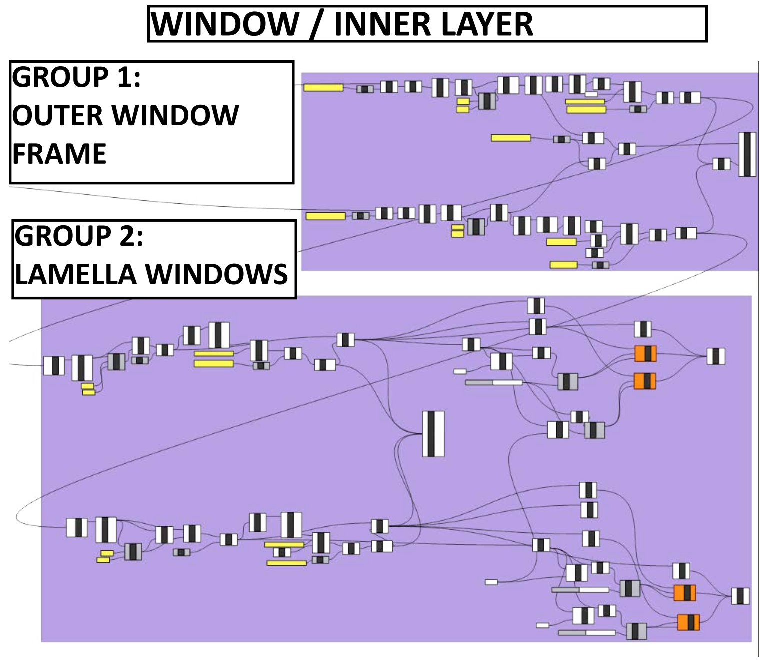


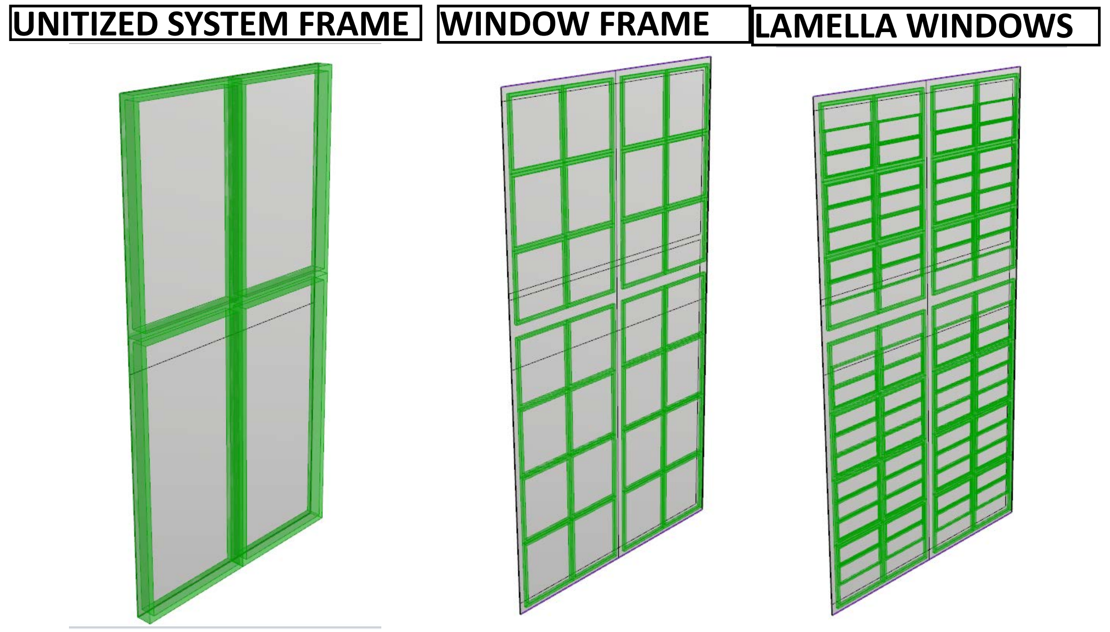
0 PANELS CLOSEST TO THE ATTRACTOR LINE
1 PANELS CLOSEST TO THE PARAPET ZONE

2,3,4 PANELS CLOSEST TO THE VISUAL COMFORT AND THE DAYLIGHT ZONE

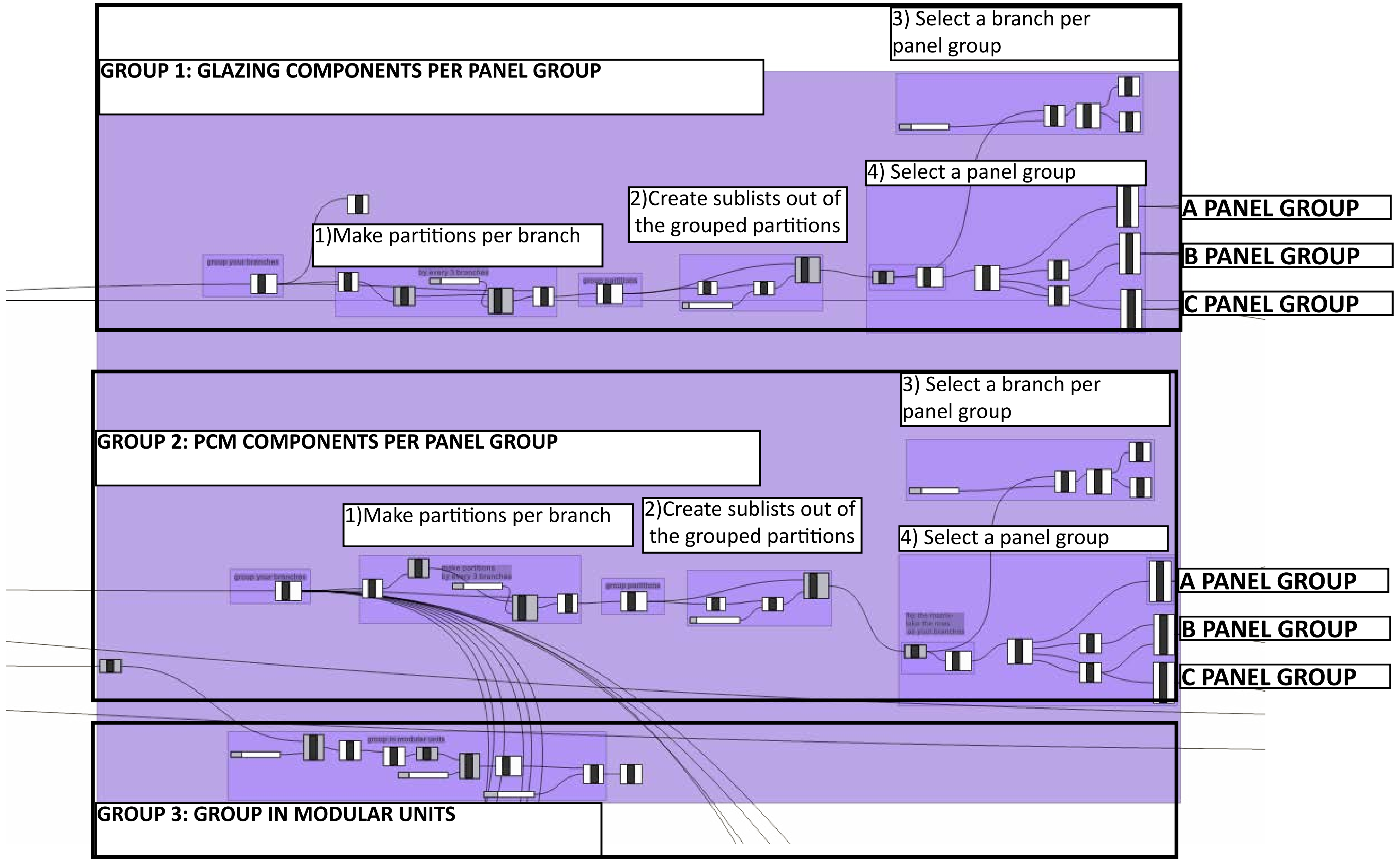
INTERNAL FACADE COMPONENTS



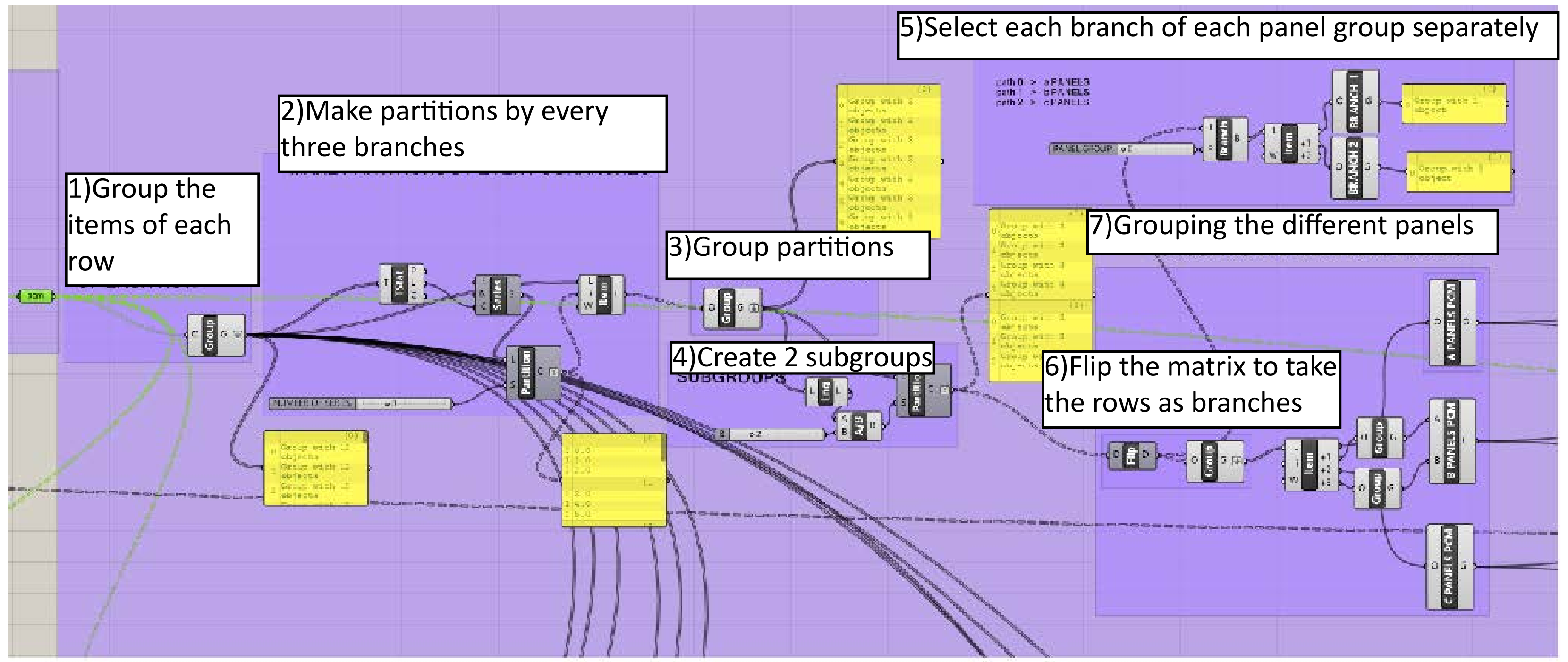




GENERAL GROUPING LOGIC



GROUPING LOGIC|HOW TO DIVIDE THE FACADE INTO SEGMENTS WITH DIFFERENT PCM TYPES

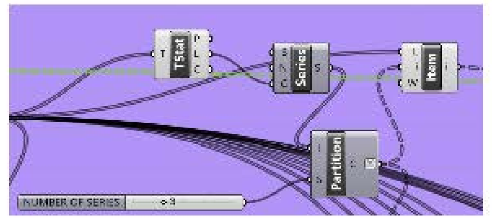


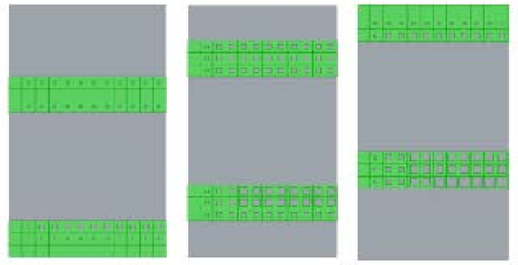
INPUT DATA
PCM PANELS

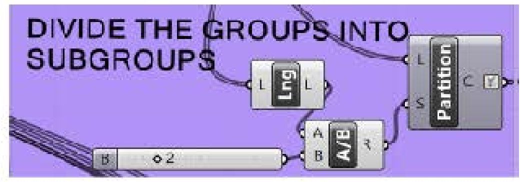
SERIES/ PARTITION LIST

OUTPUT
3 DIFFERENT GROUPS WITH 2 BRANCHES

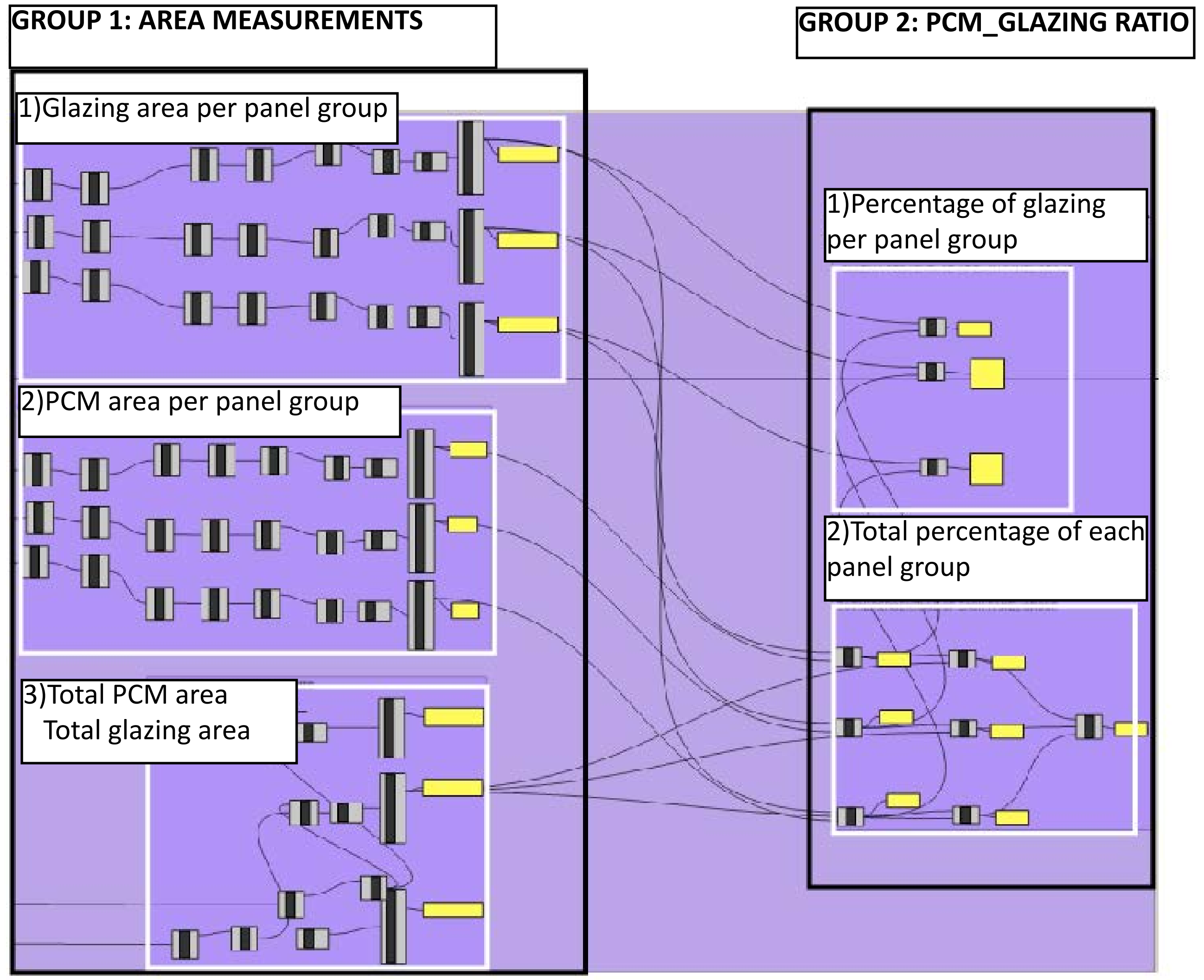
NUMBER OF SERIES OF ELEMENTS PER GROUP = NUMBER OF ROWS





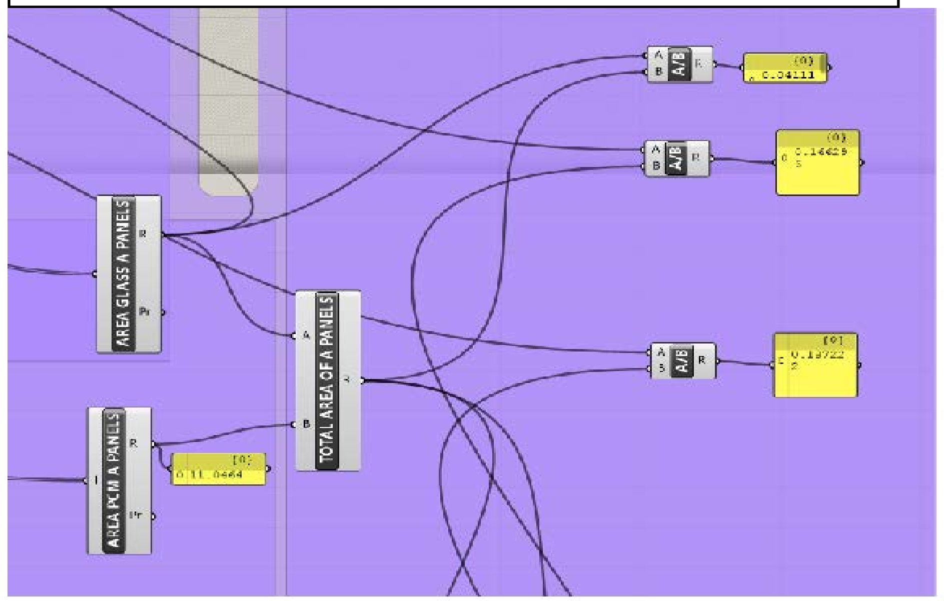


GLAZING AND PCM AREA MEASUREMENTS



PCM TO GLAZING RATIO| HOW TO CALCULATE THE GLAZING PERCENTAGE

GROUP 1: GLAZING PERCENTAGE PER PANEL GROUP

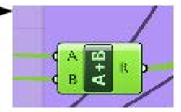


SELECT THE PANEL GROUP/ BOTH GLAZING AND PCM PARTS

CALCULATE THE TOTAL AREA PER PANEL GROUP

TOTAL AREA PANELS: AREA OF GLAZING PART (A) + AREA OF PCM COMPONENTS (B)

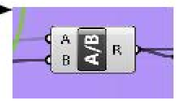
MATHEMATICAL ADDITION



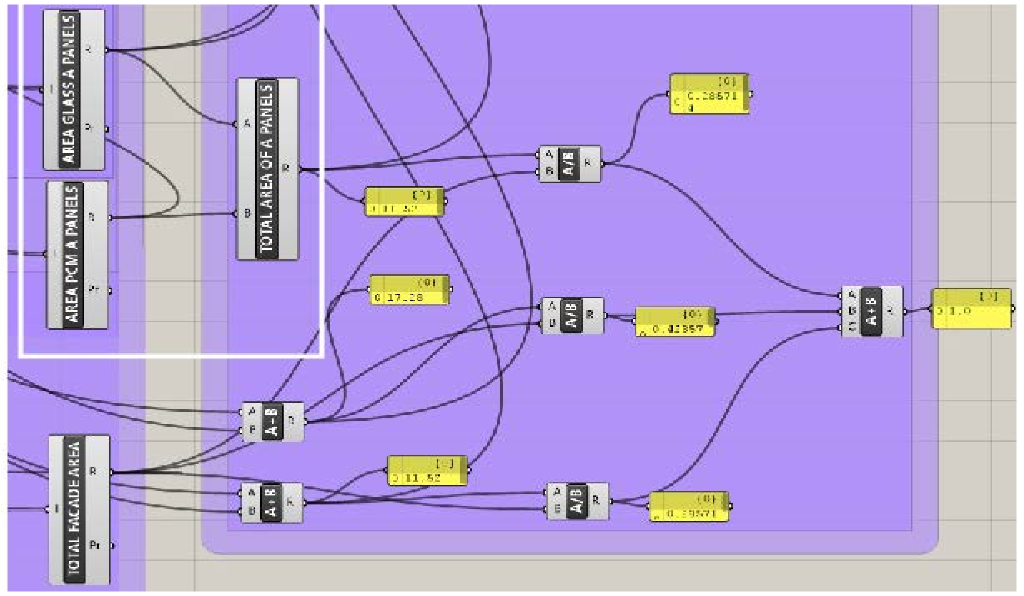
CALCULATE THE PERCENTAGE OF THE GLAZING PARTS PER PCM GROUP

AREA GLAZING PARTS (A) / TOTAL AREA PANELS (B)

MATHEMATICAL DIVISION



GROUP 1: GLAZING PERCENTAGE OF THE FACADE SEGMENT

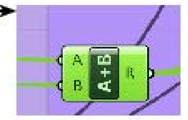


SELECT THE PANEL GROUP/ BOTH GLAZING AND PCM PARTS

CALCULATE THE TOTAL AREA PER PANEL GROUP

TOTAL AREA PANELS: AREA OF GLAZING PART (A) + AREA OF PCM COMPONENTS (B)

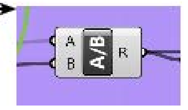
MATHEMATICAL ADDITION



CALCULATE THE PERCENTAGE OF THE A PANELS IN THE FACADE

TOTAL AREA PANELS (A) / TOTAL AREA FACADE (B)

MATHEMATICAL DIVISION



Commands: how to measure the glazing percentages per panel group and the total glazing percentage of the facade.

PART 2| PCMs USED FOR THE EXPERIMENT AND THE ENERGY SIMULATIONS

SP21EK

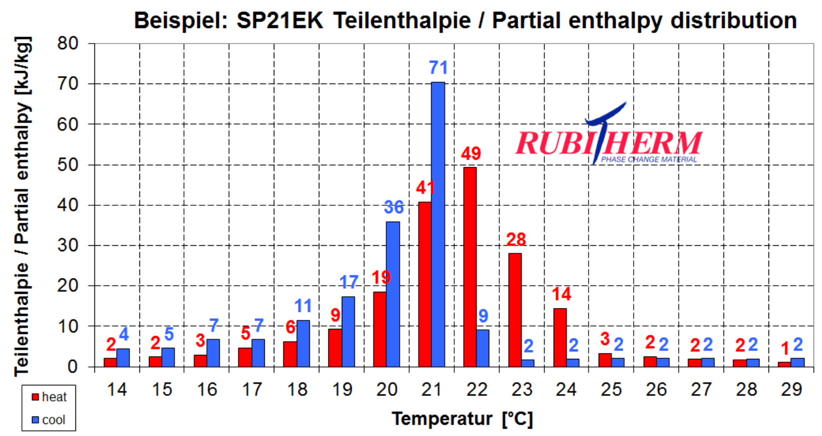
The creation of the latent heat blended material RUBITHERM® SP has led to a new and innovative class of low flammability PCM. RUBITHERM® SP consists of a unique composition of inorganic components.
RUBITHERM® SP is preferably used as macroencapsulated material. Densities of 1,0 kg/l and more can be achieved. 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. in wall elements and 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 dependig on volume and cooling rate),
- low flammability, non toxic
- different melting temperatures between -21°C und 70°C are available

The most important data:	**Typical Values**	
Melting area	**22-23** main peak: 22	**[°C]**
Congealing area	**21-19** main peak: 21	**[°C]**
Heat storage capacity ± 7,5% Combination of sensible and latent heat in a temperatur range of °C to 13 °C. 28	**170**	**[kJ/kg]**
	47	**[Wh/kg]***
Specific heat capacity	**2**	**[kJ/kg·K]***
Density solid at 15 °C	**1,5**	**[kg/l]**
Density liquid at 35 °C	**1,4**	**[kg/l]**
Volume expansion	**3-4**	**[%]**
Heat conductivity	**0,6**	**[W/(m·K)]**
Max. operation temperature	**45**	**[°C]**
Corrosion	**corrosive effect on metals**	

Attention

Note: The product must be initialized (melt, homogenize and cool to 0 ° C) once before use to achieve the specified properties.
Many SP-product are hygroscopic and may absorb moisture if stored improperly. This can result in a change of the physical properties given.



*Measured with 3-layer-calorimeter.

Datasheet exported by RUBITHERM for SP21

Rubitherm Technologies GmbH
Sperenberger Str. 5a
D-12277 Berlin
Tel: +49 30 720004-62
Fax: +49 30 720004-99
E-Mail: info@rubitherm.com
Internet: www.rubitherm.com

The product information given is a non-binding planning aid, subject to technical changes without notice. Version: 30.09.2016

SP25E2

The creation of the latent heat blended 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 preferably 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. in wall elements and air conditioners.

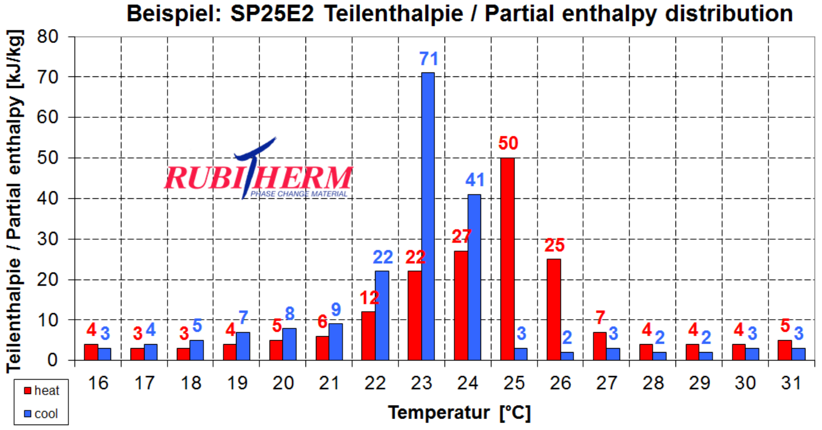
We look forward to discussing your particular questions, needs and interests with you.
Properties:
- stable performance throughout the phase change cycles
- high thermal storage capacity per volume
- limited supercooling, low flammability, non toxic
- different melting temperatures between -21°C und 70°C are available

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	**1,5**	**[kg/l]**
Density liquid at 30 °C	**1,4**	**[kg/l]**
Volume expansion	**3-4**	**[%]**
Heat conductivity	**0,6**	**[W/(m·K)]**
Max. operation temperature	**45**	**[°C]**
Corrosion	**corrosive effect on metals**	


Achtung

Note: The product must be initialized (melt, homogenize and cool to 0 ° C) once before use to achieve the specified properties.
All SP-product are hygroscopic and may absorb moisture if stored improperly. This can result in a change of the physical properties given.

Beispiel: SP25E2 Teilenthalpie / Partial enthalpy distribution



**Measured with 3-layer-calorimeter.*

Rubitherm Technologies GmbH
Sperenberger Str. 5a
D-12277 Berlin
Tel: +49 30 720004-62
Fax: +49 30 720004-99
E-Mail: info@rubitherm.com
Internet: www.rubitherm.com

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SP31

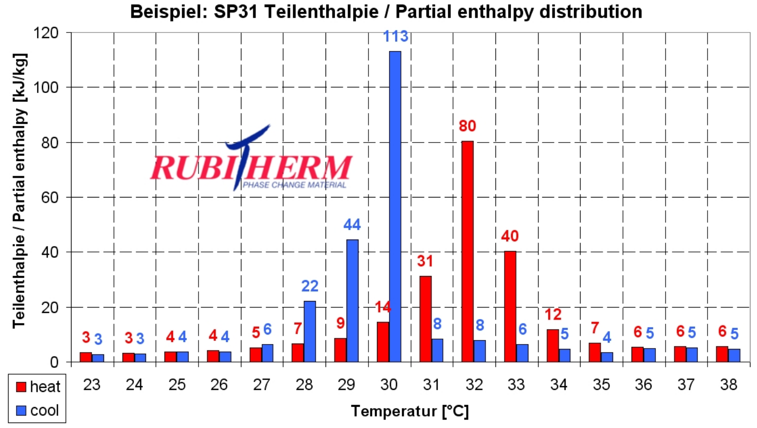
The creation of the latent heat blended material RUBITHERM® SP has led to a new and innovative class of low flammability PCM. RUBITHERM® SP consists of a unique composition of inorganic components.
RUBITHERM® SP is preferably used as macroencapsulated material. Densities of 1,0 kg/l and more can be achieved. 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. in wall elements and 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, low flammability, non toxic
- different melting temperatures between -21°C und 70°C are available

The most important data:	Typical Values	
Melting area	**31-33** (main peak: 32)	**[°C]**
Congealing area	**28-30** (main peak: 30)	**[°C]**
Heat storage capacity ± 7,5% Combination of sensible and latent heat in a temperatur range of 23°C to 38°C.	**210**	**[kJ/kg]**
	58	**[Wh/kg]***
Specific heat capacity	**2**	**[kJ/kg·K]***
Density solid at 15 °C	**1,35**	**[kg/l]**
Density liquid at 35 °C	**1,3**	**[kg/l]**
Volume expansion	**3-4**	**[%]**
Heat conductivity	**n.b.**	**[W/(m·K)]**
Max. operation temperature	**50**	**[°C]**
Corrosion	**corrosive effect on metals**	

Note: The product must be initialized (melt, homogenize and cool to 0 ° C) once before use to achieve the specified properties.
All SP-product are hygroscopic and may absorb moisture if stored improperly. This can result in a change of the physical properties given.

Beispiel: SP31 Teilenthalpie / Partial enthalpy distribution



**Measured with 3-layer-calorimeter.*

Rubitherm Technologies GmbH
Sperenberger Str. 5a
D-12277 Berlin
Tel: +49 30 720004-62
Fax: +49 30 720004-99
E-Mail: info@rubitherm.com
Internet: www.rubitherm.com

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Datasheet exported by RUBITHERM for SP31

150610-1

ClimSel™ C10

Typically used for temperature stabilized transports of refrigerated products and other payloads at around 11°C / 52°F.

Transport

Typical temperature stabilization span

6°C ⟷ 11°C
43°F ⟷ 52°F

Product description

ClimSel™ C10 is a salt hydrate based Phase Change Material that works by either the charging or discharging of energy at different temperatures. ClimSel™ C10 is delivered in various sizes of aluminium foil pouches. Its main components are sodium sulphate, water and additives.

Physical data

Phase change temperature: Solid	6°C / 43°F
Phase change temperature: Liquid	11°C / 52°F
Latent heat of fusion (see curve)	32 Wh/kg – 116 kJ/kg
Specific gravity	1.4 kg/litre
Thermal conductivity: Solid	0.83 W/m/°K
Thermal conductivity: Liquid	0.70 W/m/°K

Estimated functionality time

If the products are handled correctly, and the packaging is kept uncompromised, the product will continue to cycle as intended over time, with no known lifetime limit.

Note: ClimSel™ C10 will only work as declared for as long as the pouch is intact.

Usage guidelines

- *Recommended storage temperature: 10-15°C / 50-60°F.*
- *Preparation before use depends on application conditions.*
- *Handle the ClimSel™ C10 pouch with care and do not bend when solid.*
- *Do not use damaged pouch, as the product functionality will be compromized.*

Damaged products

- *If damaged pouch is suspected, it shall be thoroughly inspected before use.*
- *Damaged products shall be discarded and treated in accordance with federal, state and local requirements for EWC (=European Waste code) = 060314.*

Climator is one of the world´s leading companies within PCM and temperature stabilization solutions.

Through our know-how, PCM expertise and innovation power, we develop project-based solutions that solve our customers' temperature stabilization and control problems.

We operate within four application areas.

Transport

Room

Body

Equipment

Climator Sweden AB
Mejselvägen 15
SE-541 34 Skövde
SWEDEN

+46 (0)500 48 23 50
www.climator.com
climator@climator.com

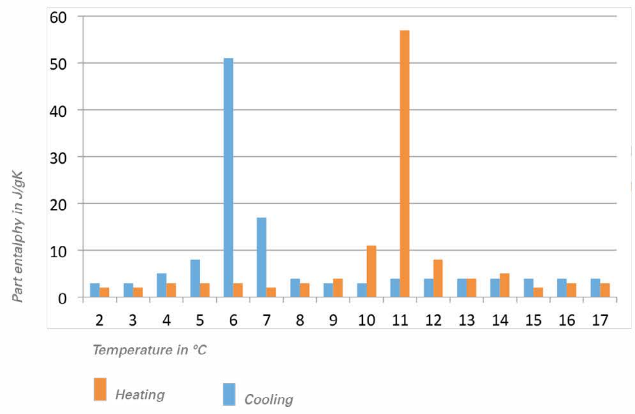
Climator
moving energy in time

150610-1

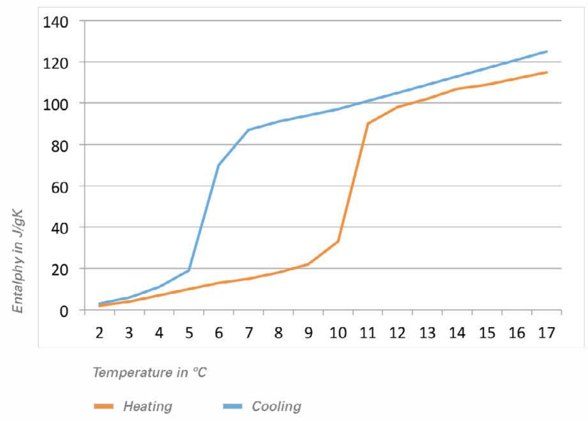
ClimSel™ C10

Phase change performance curves

Part entalphy



Entalphy



Orange curve shows performance during melting (to be read from left to right).
Blue curve shows performance during crystallisation (to be read from right to left).

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Mejselvägen 15
SE-541 34 Skövde
SWEDEN

+46 (0)500 48 23 50
www.climator.com
climator@climator.com

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moving energy in time

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bibliography

THE SOURCES

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