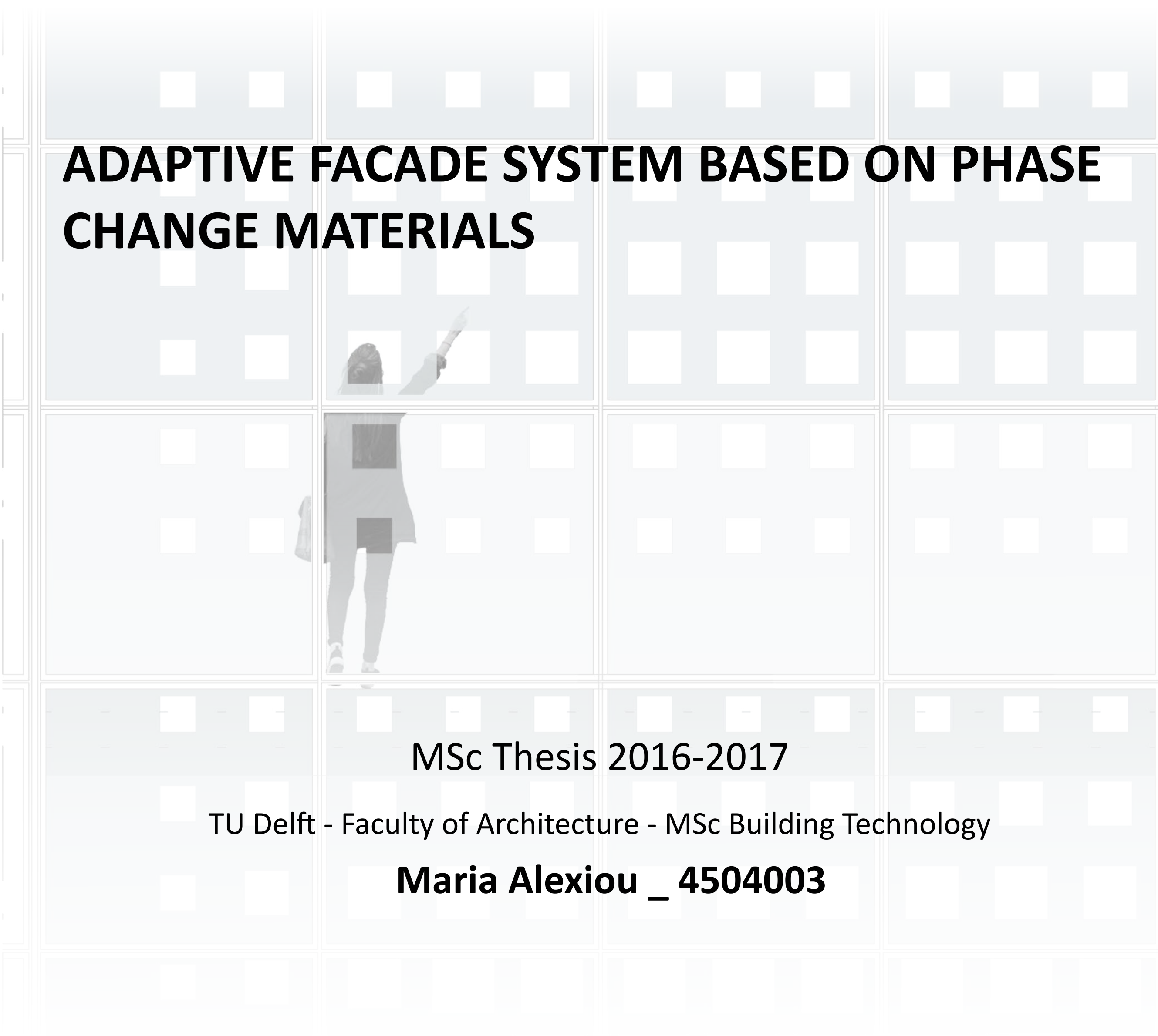


ADAPTIVE FACADE SYSTEM BASED ON PHASE CHANGE MATERIALS

MSc Thesis 2016-2017

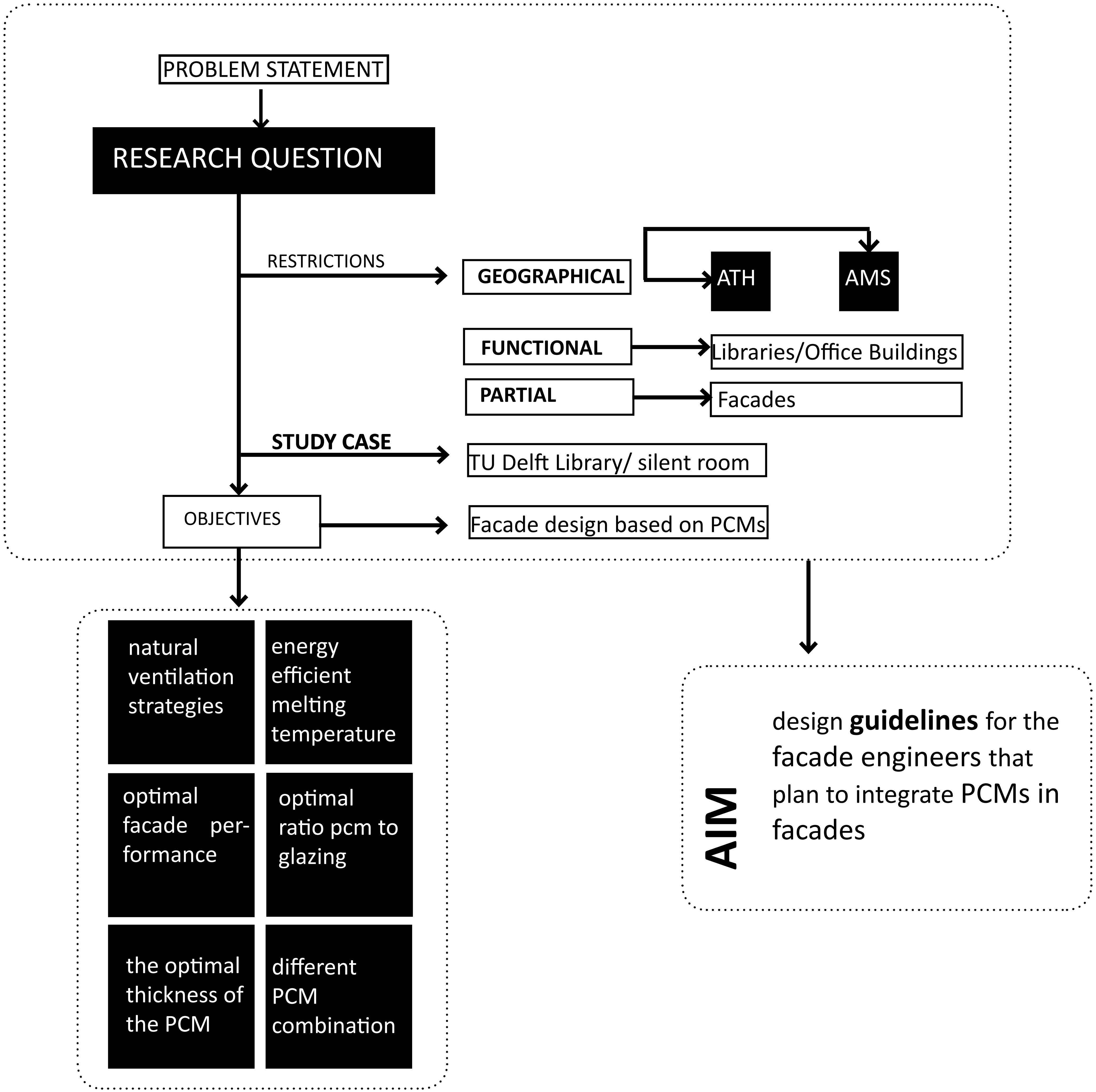
TU Delft - Faculty of Architecture - MSc Building Technology

Maria Alexiou _ 4504003

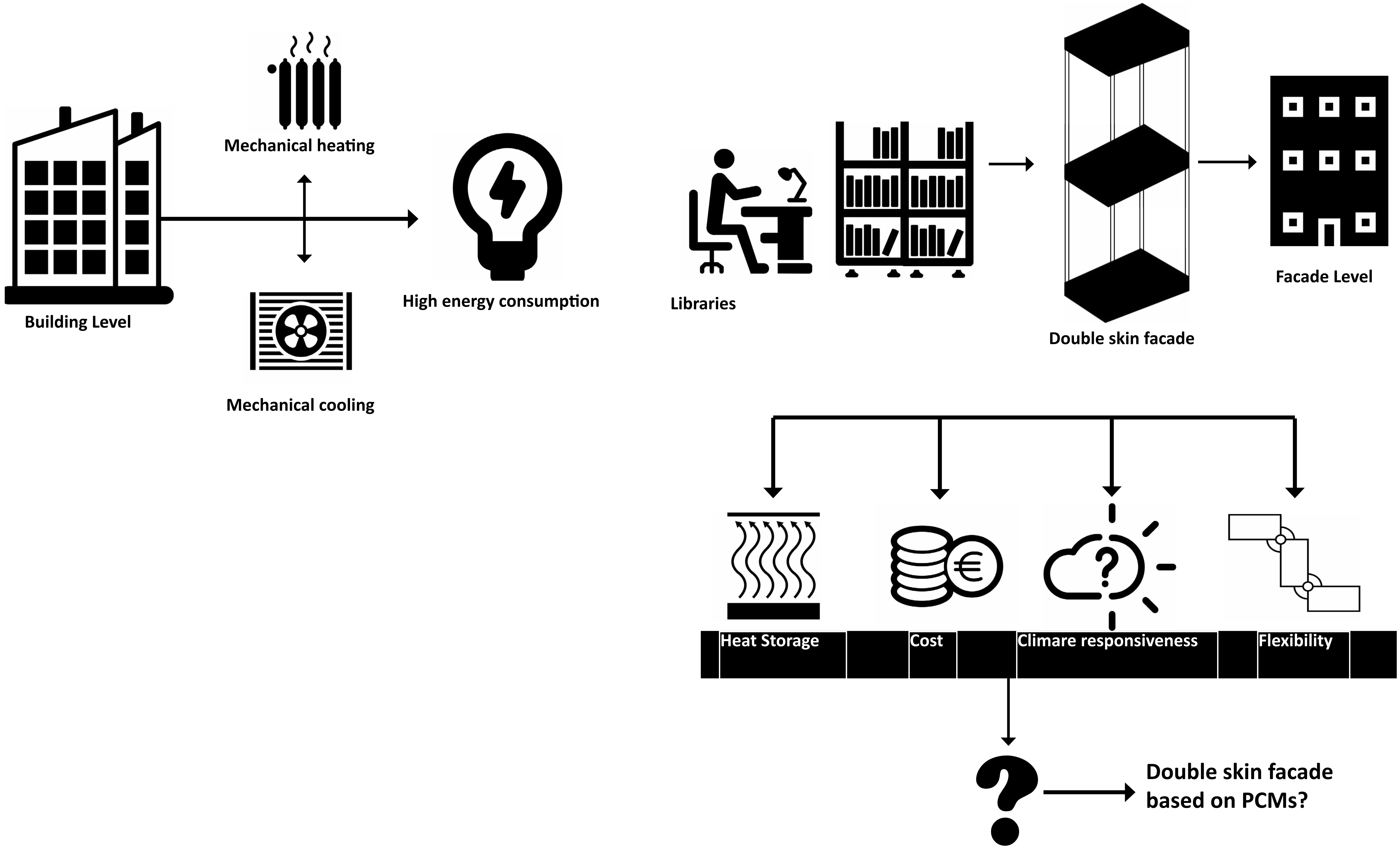
Mentors:

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

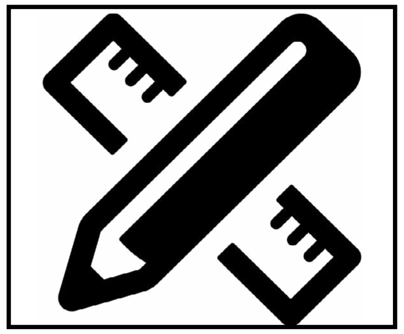
RESEARCH AIM



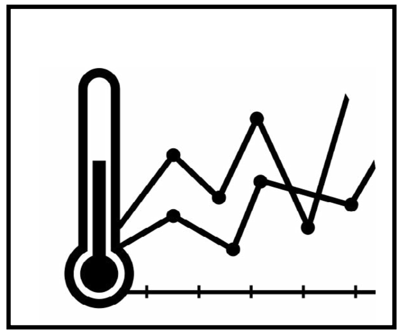
PROBLEM STATEMENT



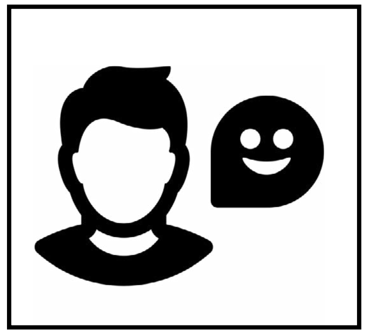
What should be the design of **an adaptive façade system based on PCMs** and how should it **respond to different climate conditions** so as to provide **thermal comfort** in the indoor space of **libraries** whilst **minimising the energy use** for heating, cooling and lighting?



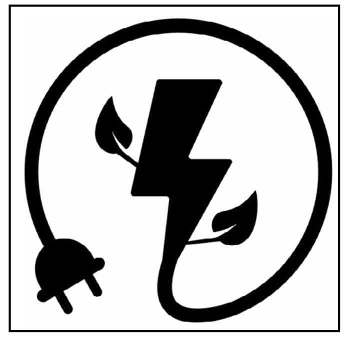
Design



Climate responsiveness



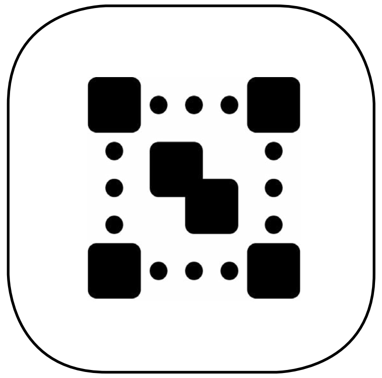
Thermal Comfort



Energy efficiency

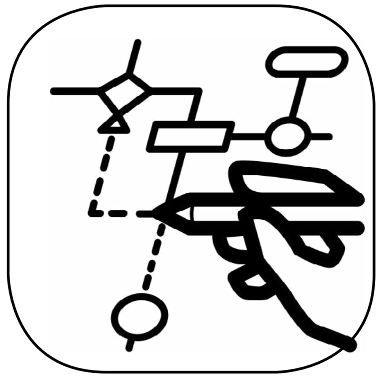
RESEARCH METHODOLOGY

LITERATURE REVIEW

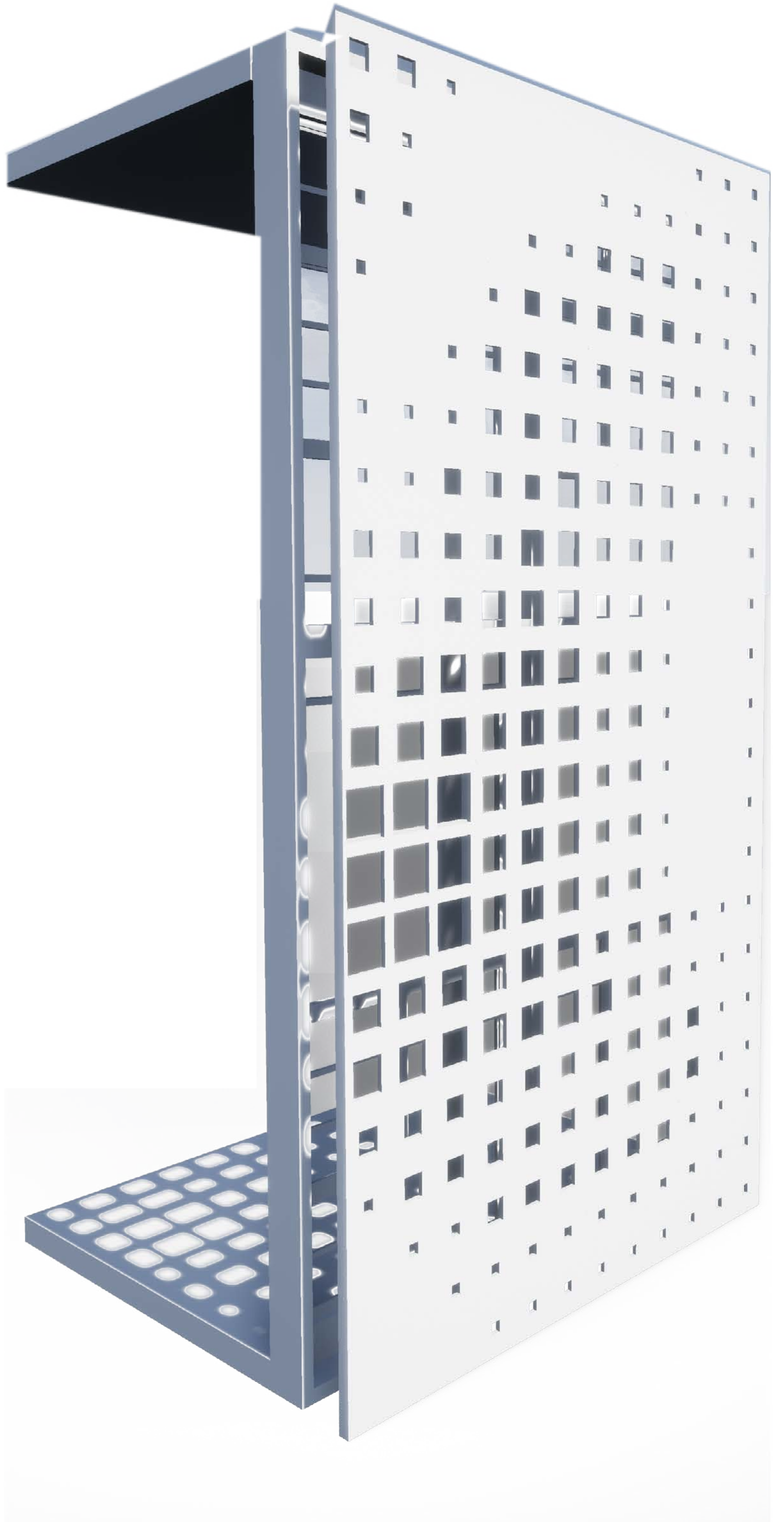


DESIGN STRATEGIES/
BOUNDARY CONDITIONS

HAND CALCULATIONS
WEATHER DATA ANALYSIS



COMPUTATIONAL DESIGN



ENERGY SIMULATIONS

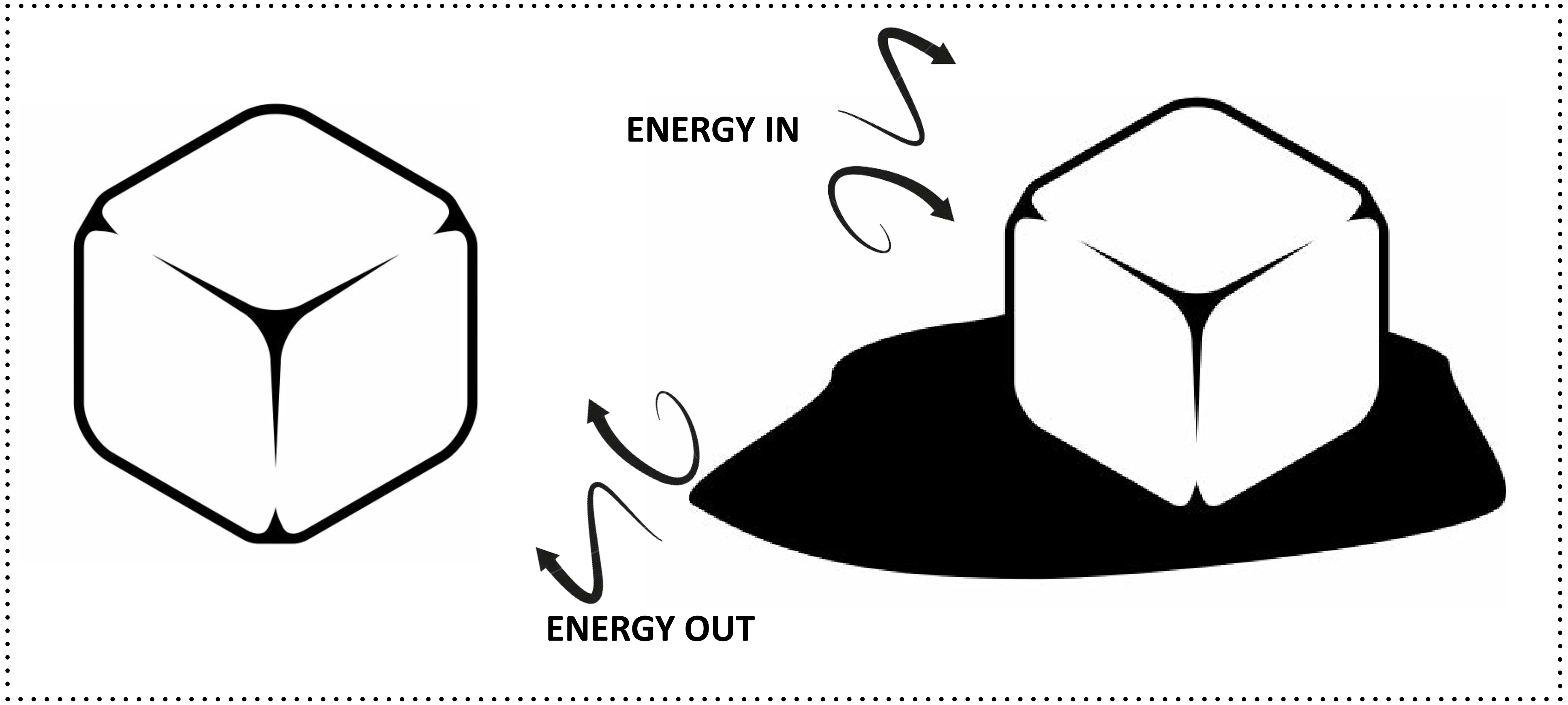
THE EXPERIMENT

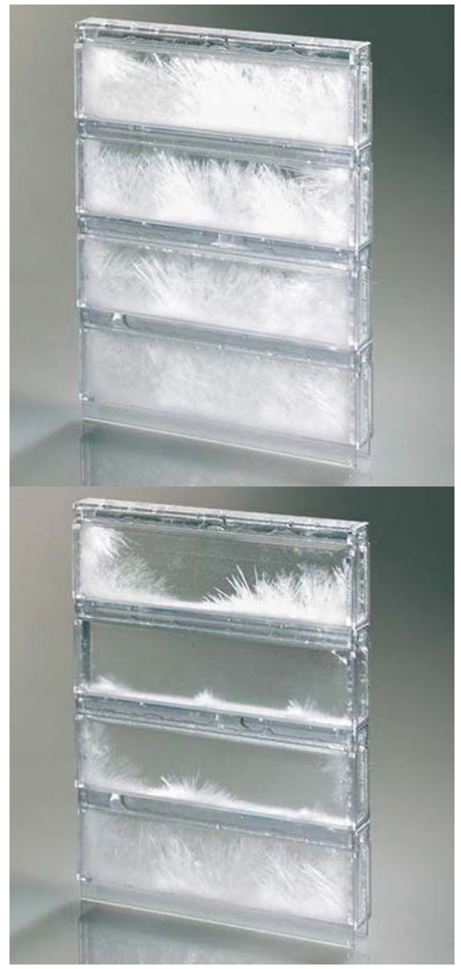
FACADE SYSTEM
PERFORMANCE| CONSTRUCTION

DESIGNER S MANUAL| CONCLUSIONS

PCMs

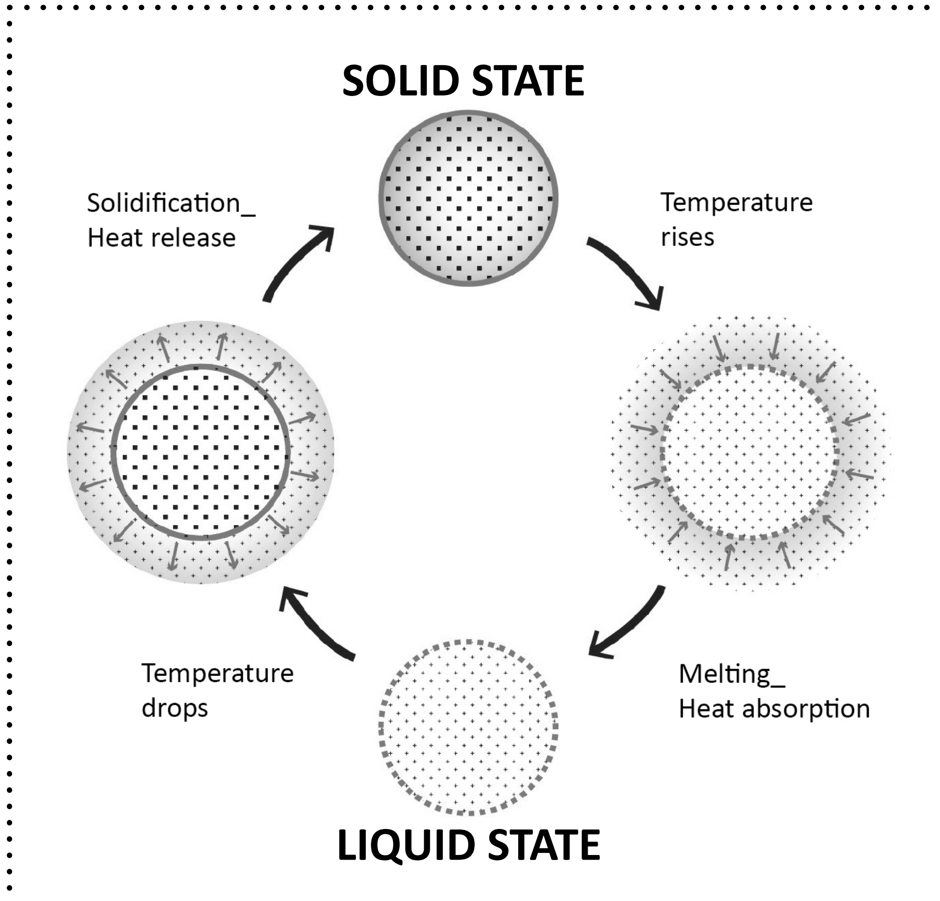
PHASE TRANSITION FOR ICE

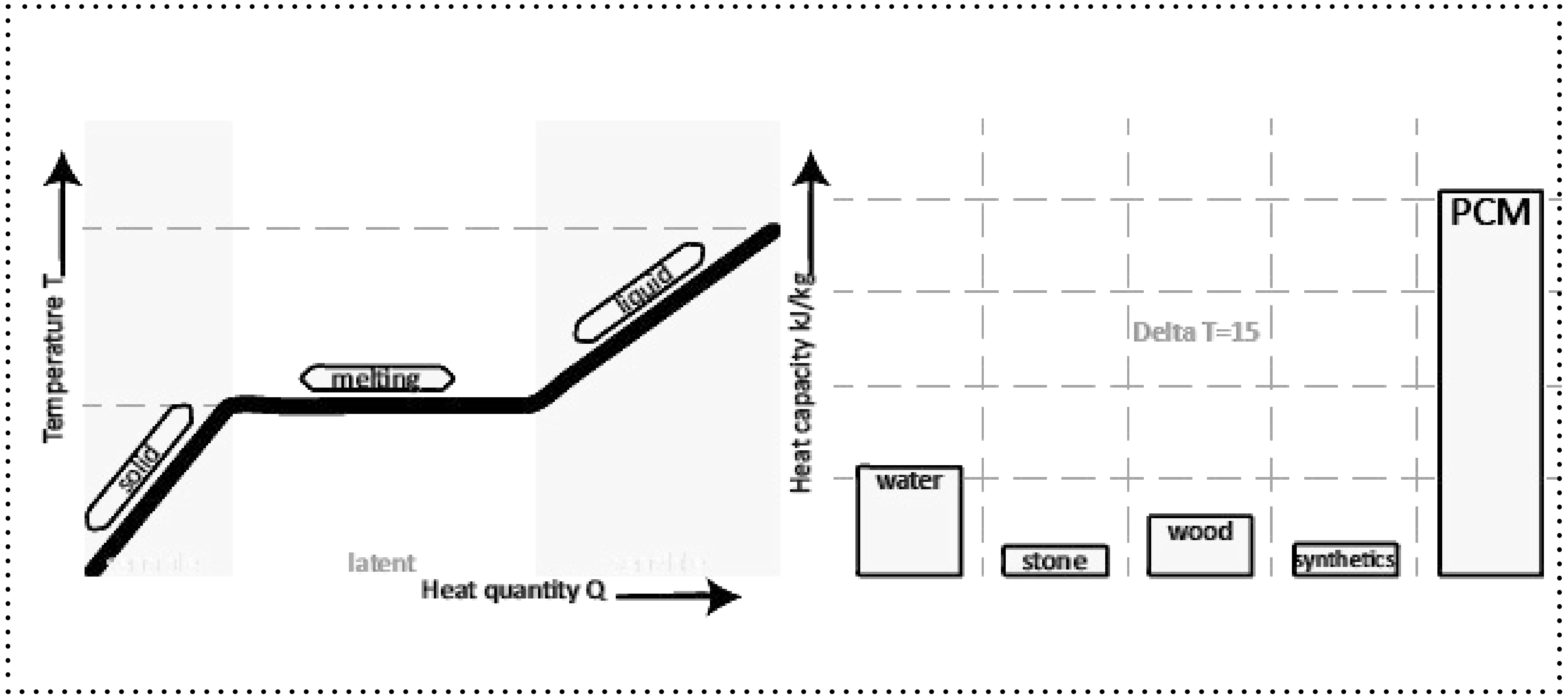




PCM based product /GLASS X

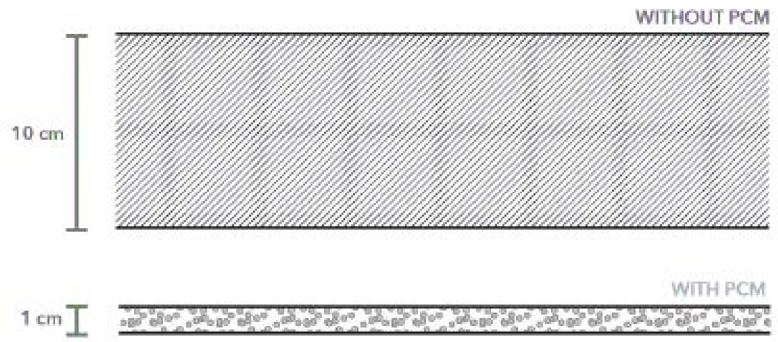
THERMAL CYCLE





REDUCE THE THICKNESS OF THERMAL

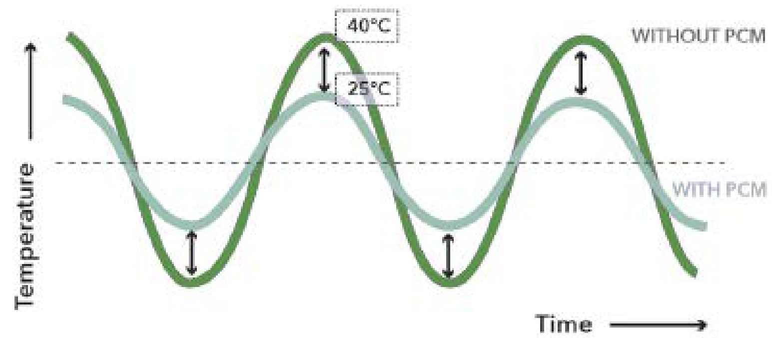
1



→ **CREATION OF LIGHTWEIGHT STRUCTURES WITH HIGH THERMAL MASS**

REDUCE TEMPERATURE PEAKS

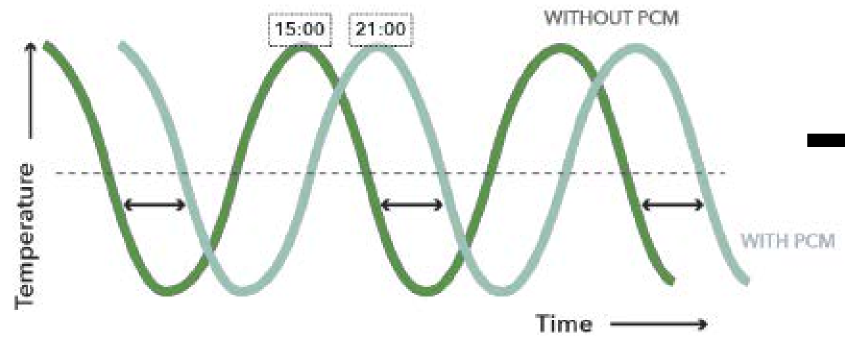
2



→ **ENERGY SAVINGS FOR COOLING SYSTEMS**

SHIFT TEMPERATURE PEAKS

3

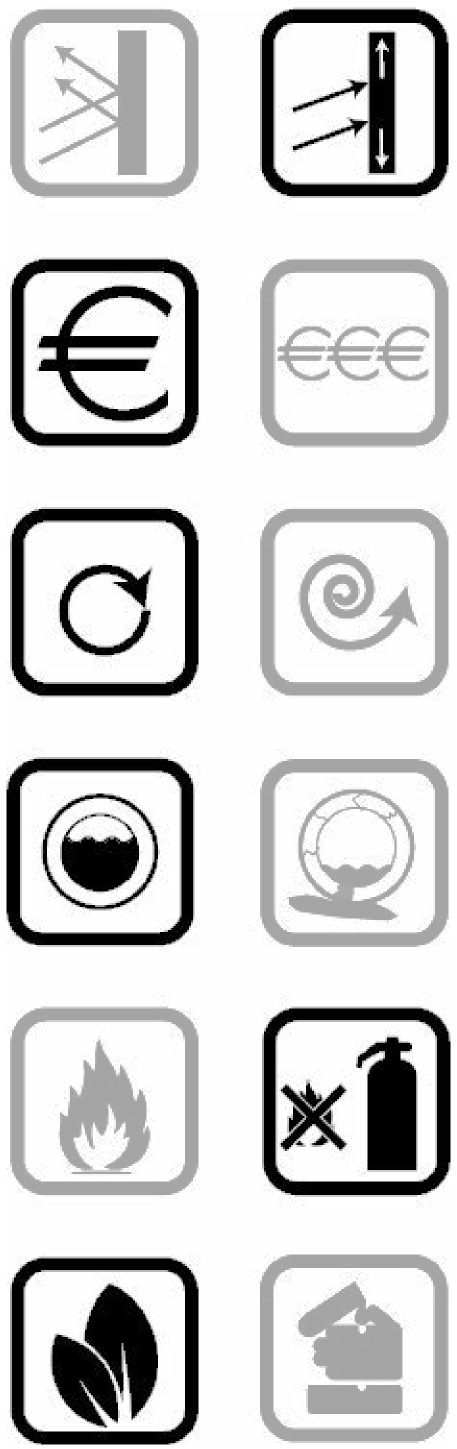


→ **ENERGY SAVINGS FOR HEATING SYSTEMS**

PCMs ++

SELECTION CRITERIA

FACADE LEVEL



CONDUCTIVE

COST EFFECTIVE

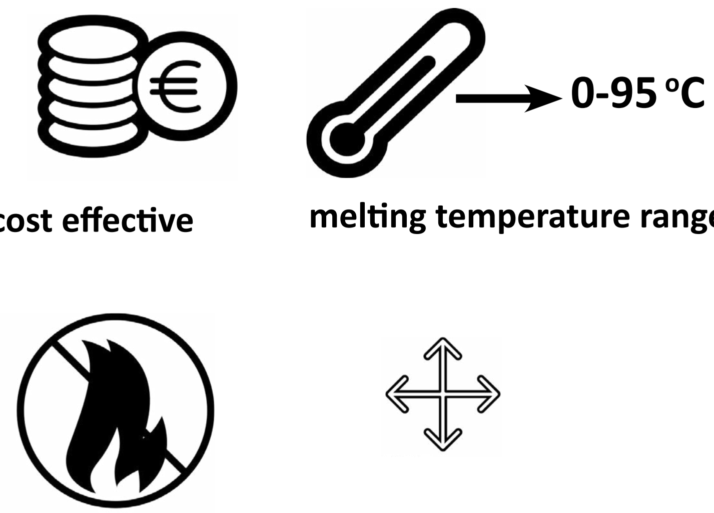
STABLE CYCLE

LOW VOLUME CHANGE

NON FLAMMABLE

NON TOXIC

SALT HYDRATES



cost effective

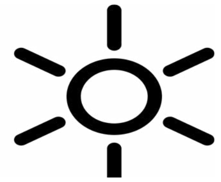
melting temperature range

non- flammable

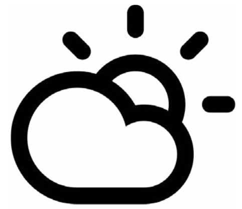
small volume alter-
ation in the phase
change

RESTRICTIONS

CLIMATE



MEDITERRANEAN



TEMPERATE

GEOGRAPHY

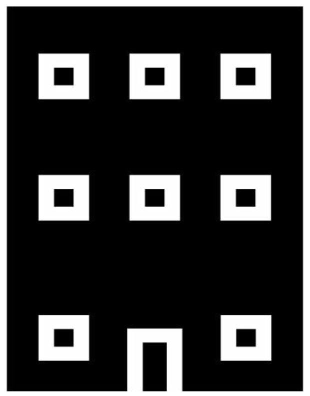
GREECE

THE NETHERLANDS

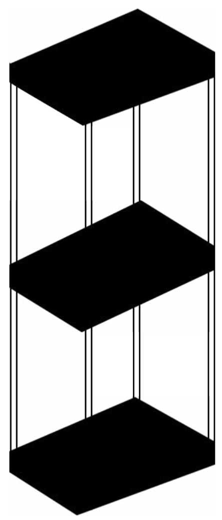
BUILDING USE

LIBRARIES

BUILDING COMPONENT



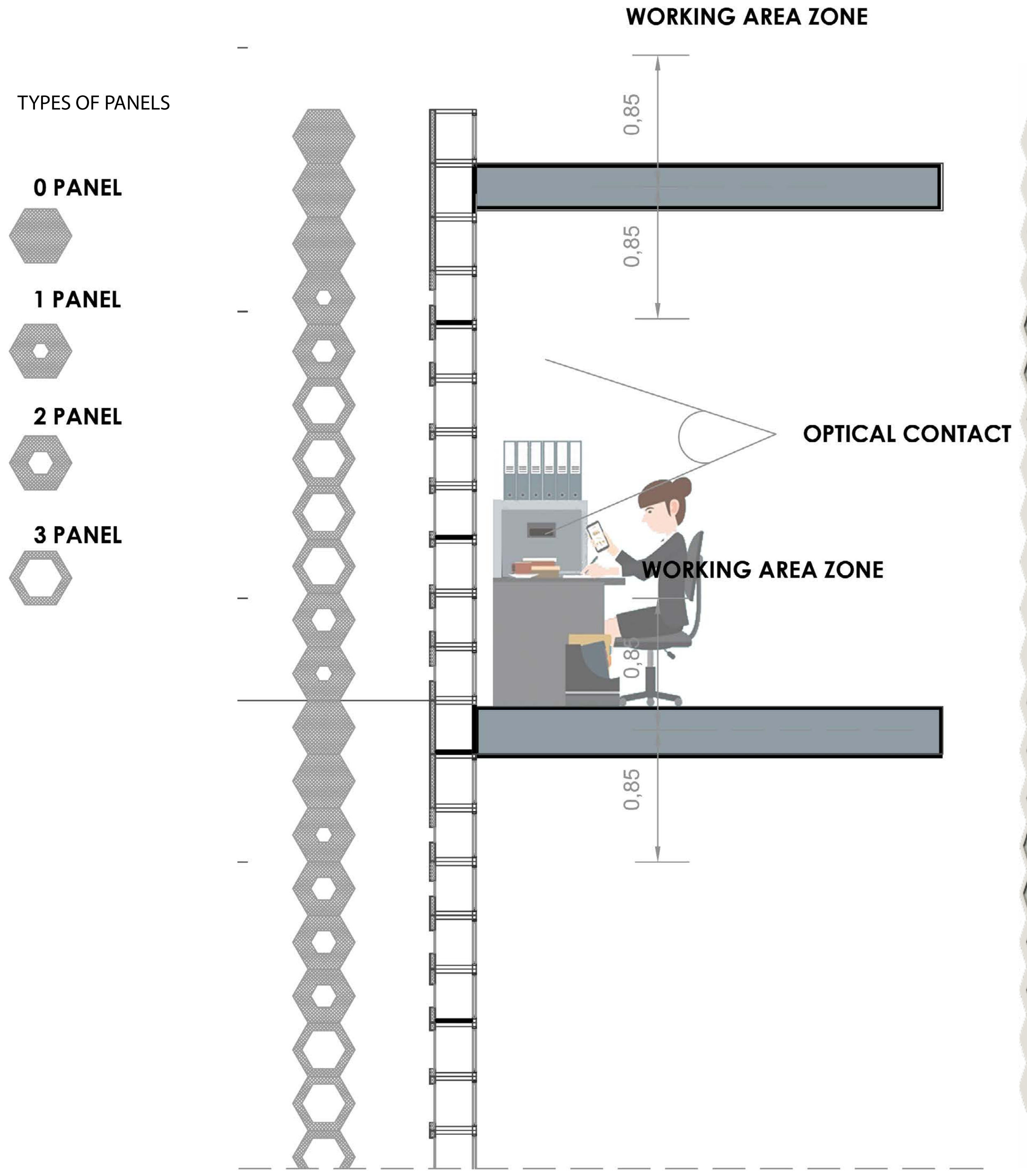
FACADE

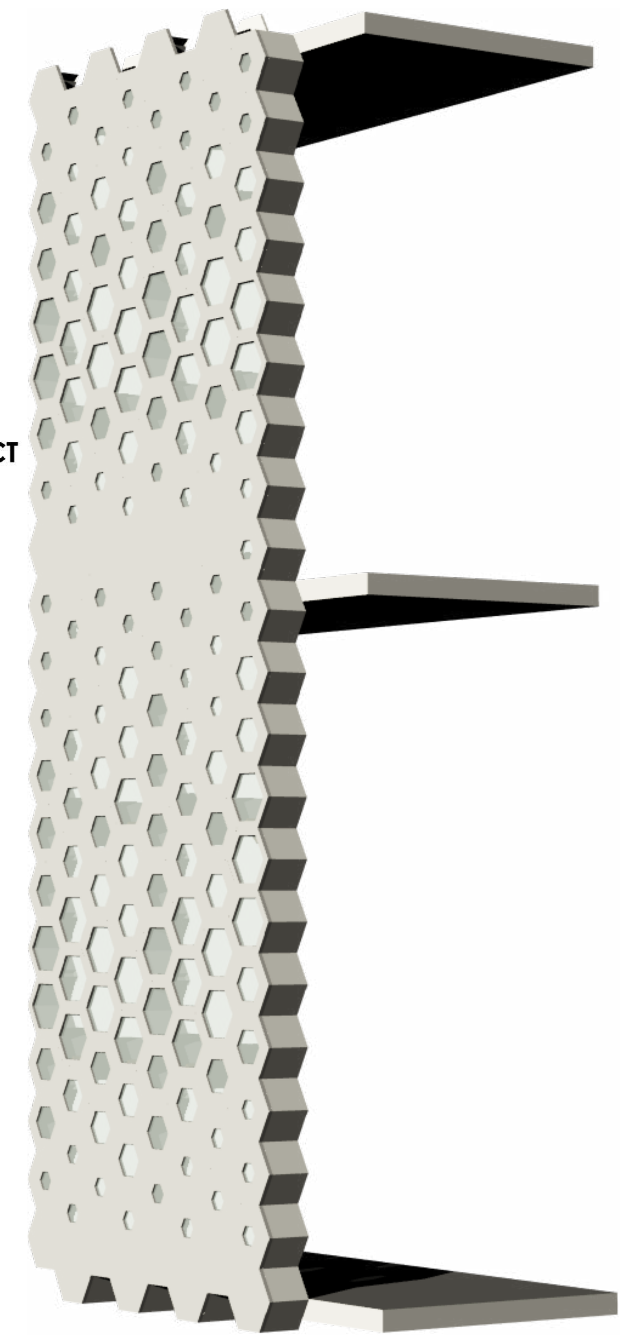


DOUBLE SKIN
FACADE

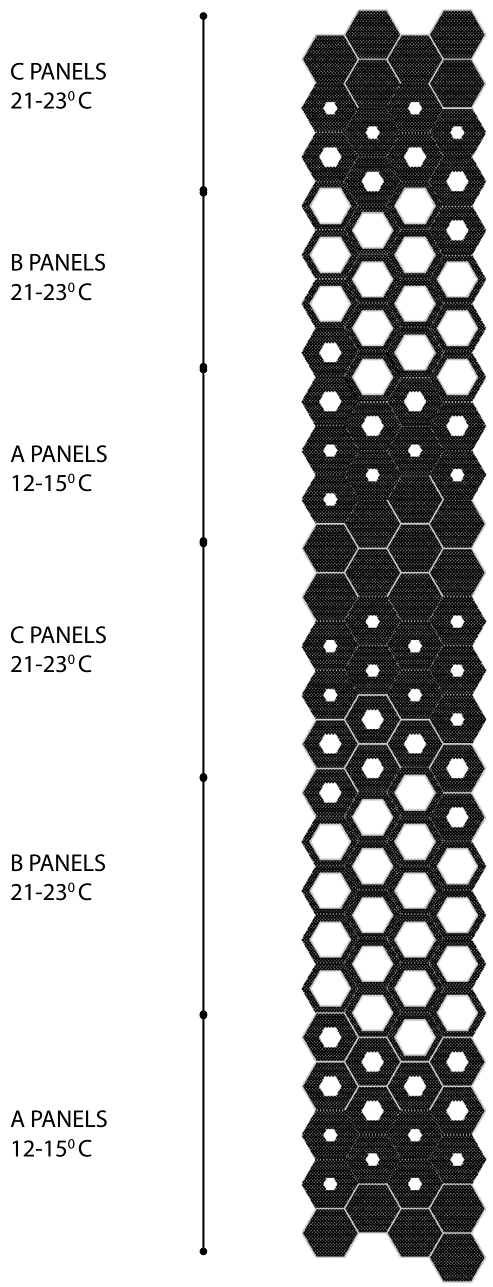
PANEL PLACEMENT

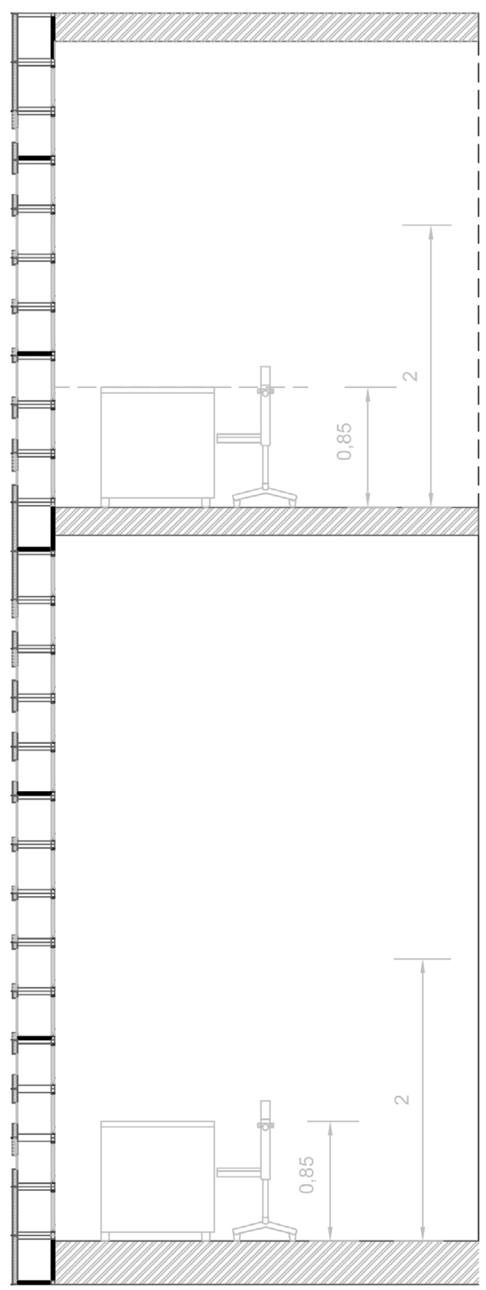
OPTICAL CONTACT WITH THE EXTERIOR

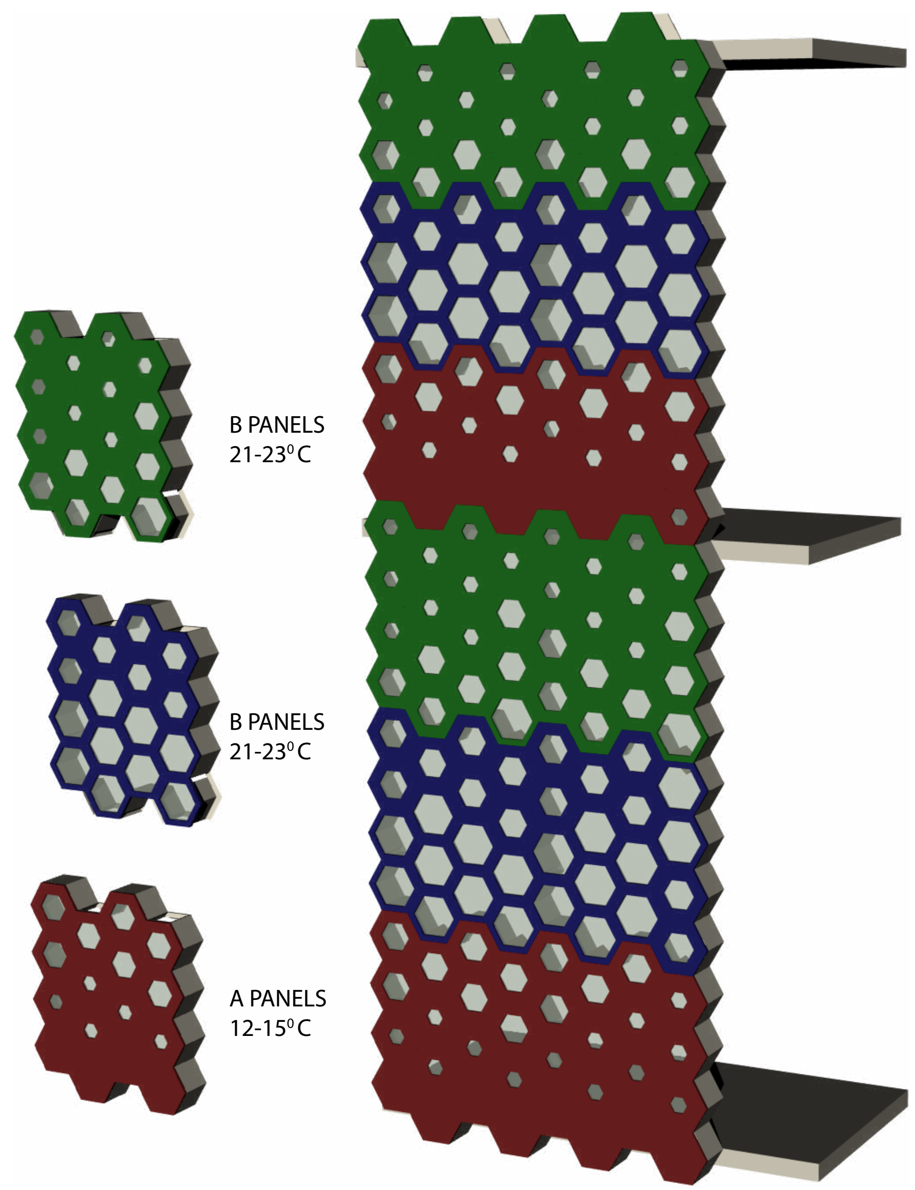




THERMAL COMFORT





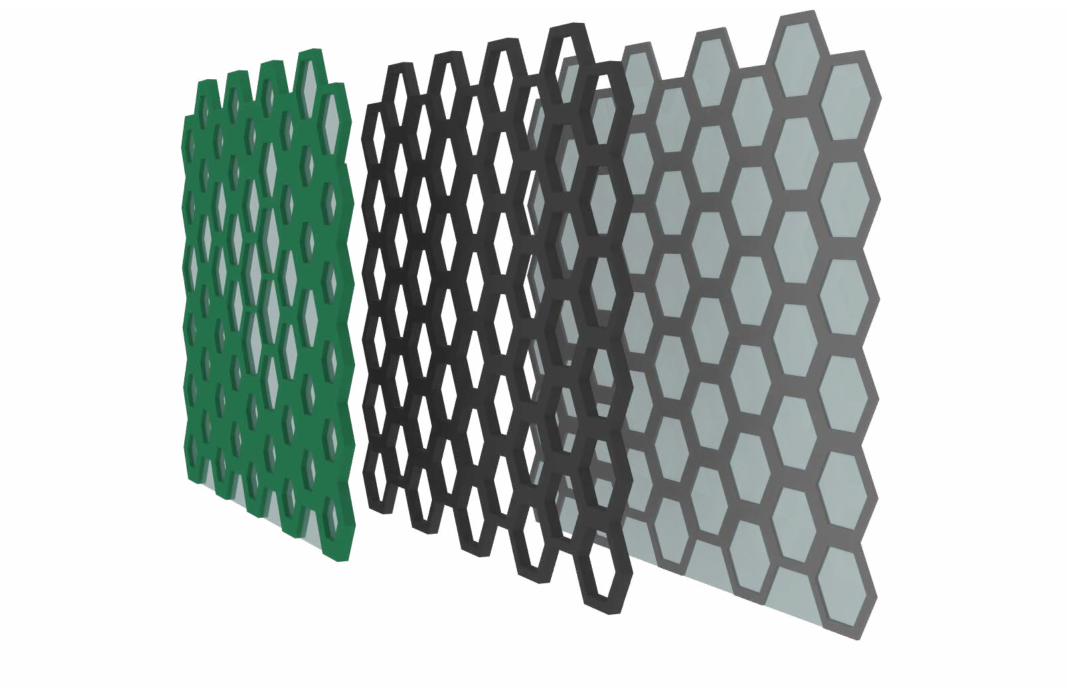


DESIGN CONCEPT

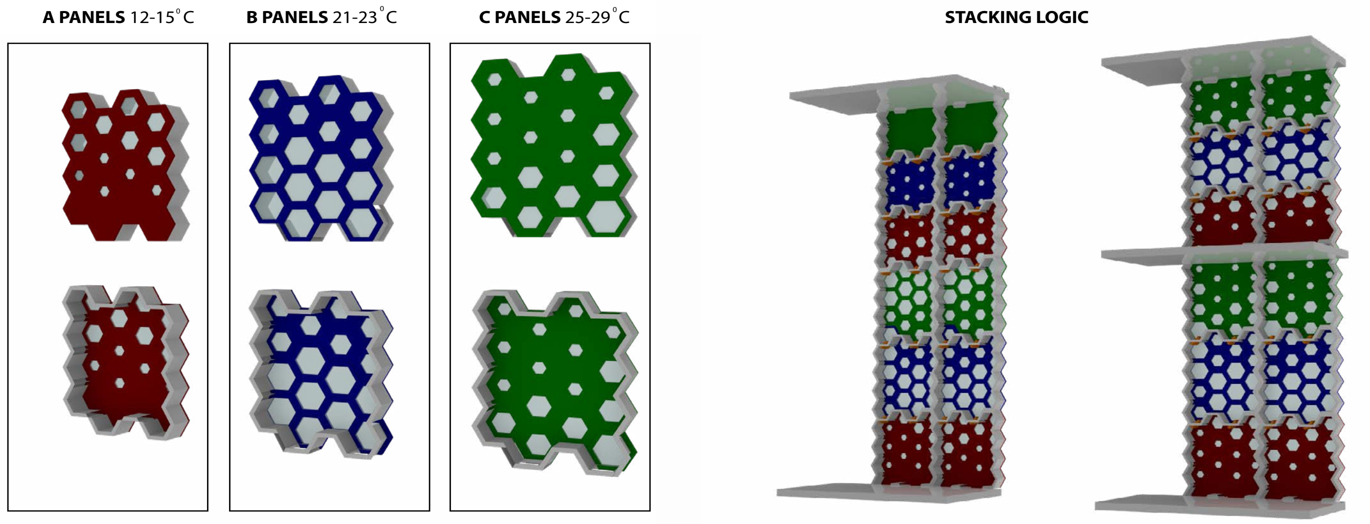
FIRST LOGIC : MODULAR UNITS PER PANEL

SECOND LOGIC : MODULAR UNITS PER MULTIPLE PANELS

PERSPECTIVE VIEW AND DRAWINGS



PERSPECTIVE VIEW AND DRAWINGS



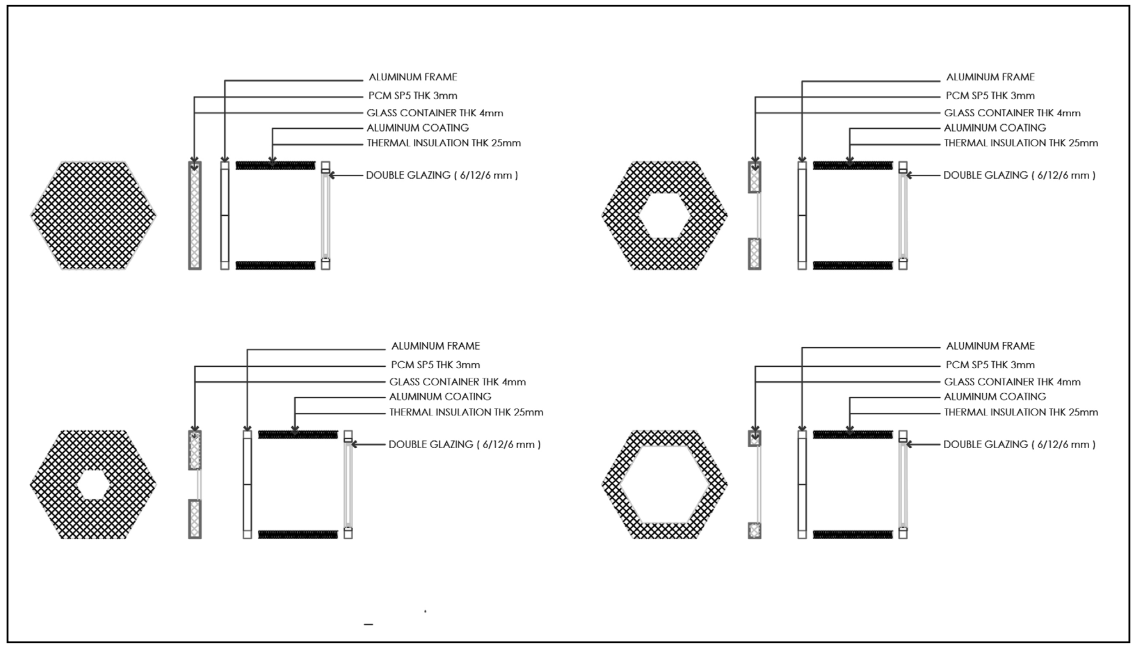
Placed in the lower part of each floor

Placed in the central part of each floor

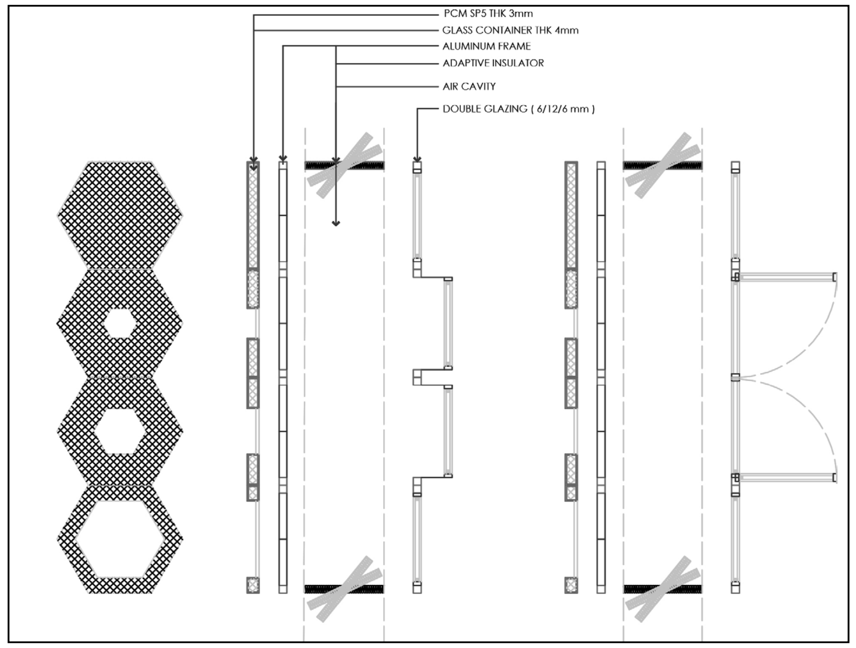
Placed in the higher part of each floor

Each modular unit is composed by PCM panels with the same melting temperature ans is placed on the top of another unit.

1ST LOGIC
EACH MODULE CONTAIN ONE PANEL

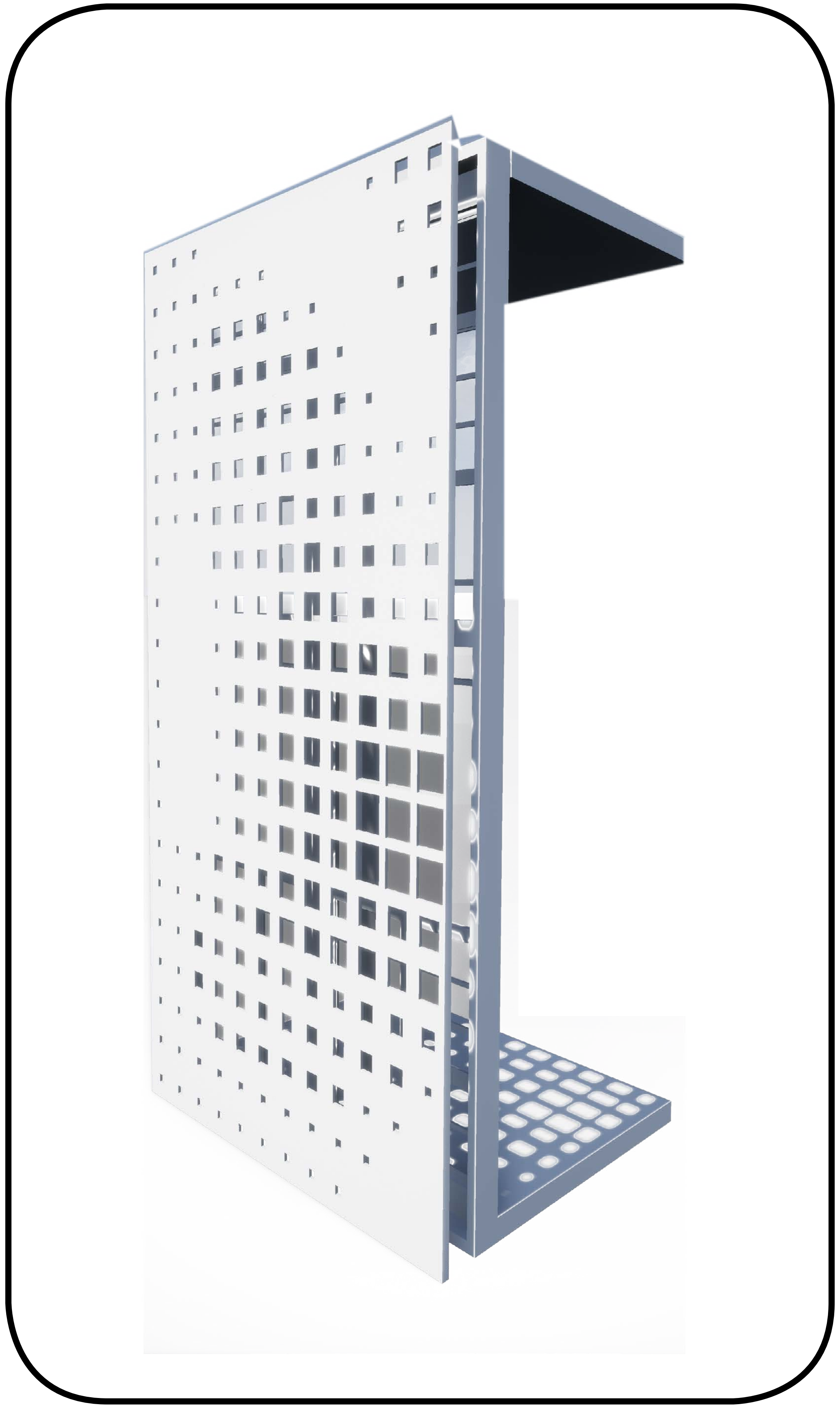


2ND LOGIC
EACH MODULE CONTAIN MULTIPLE PANELS

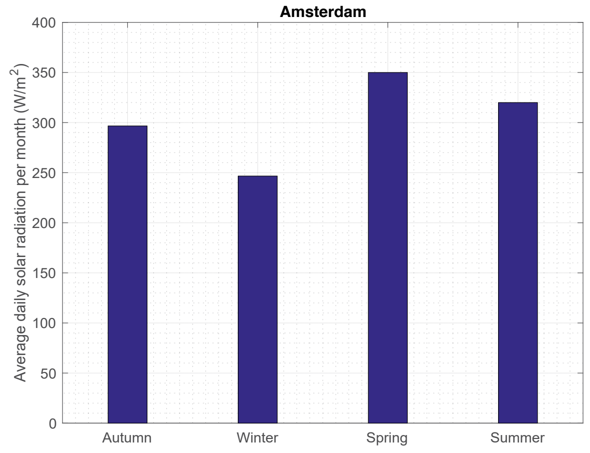


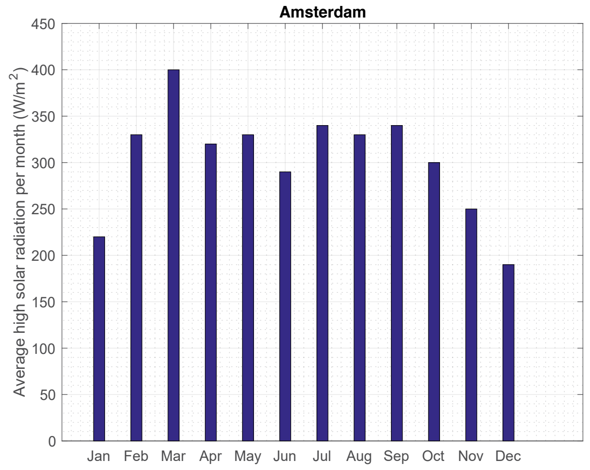
FACADE DESIGN CHOICE

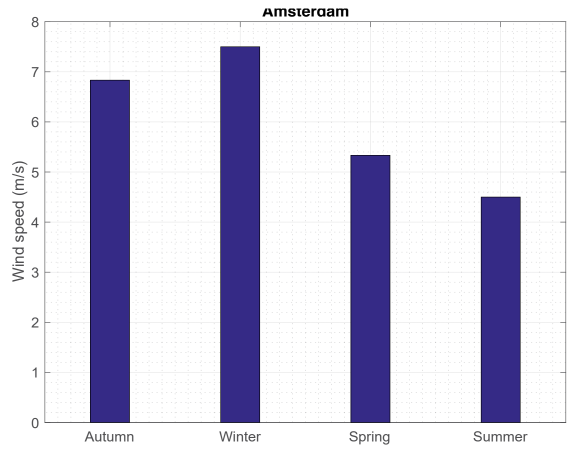
VS

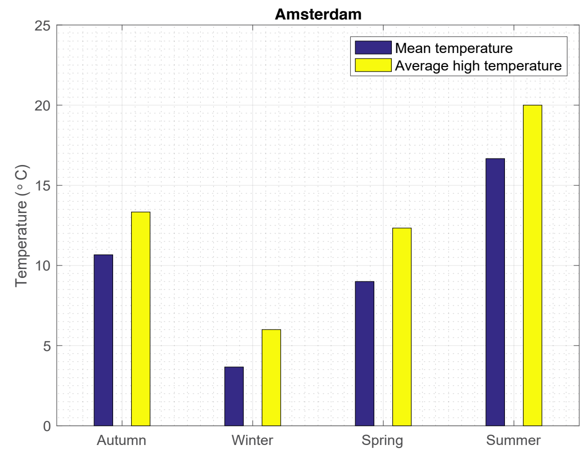


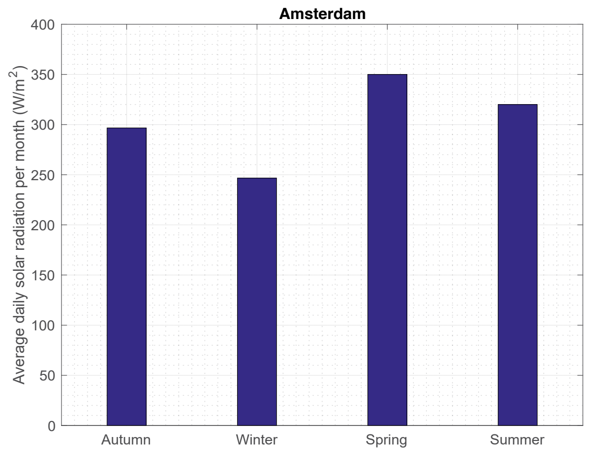
CLIMATE ANALYSIS

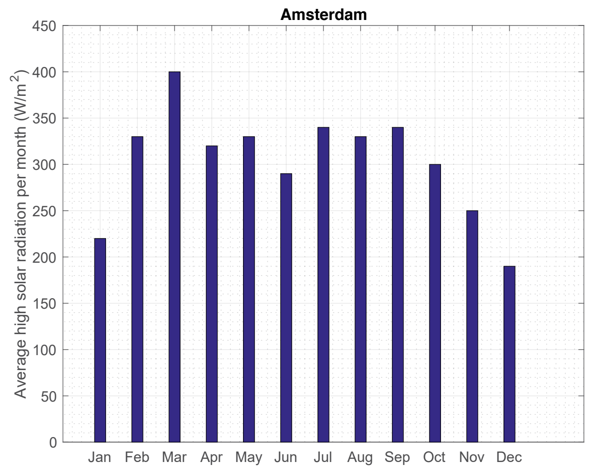


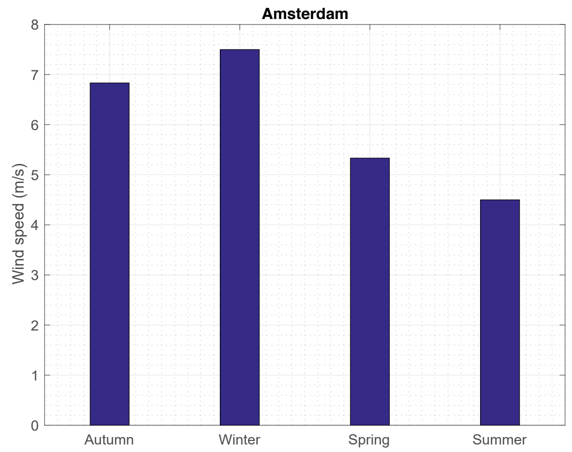


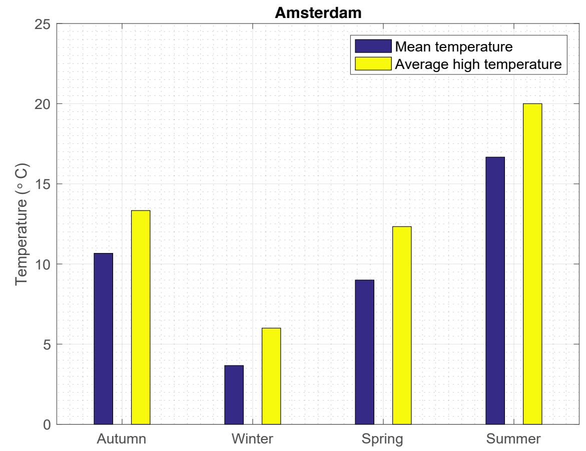


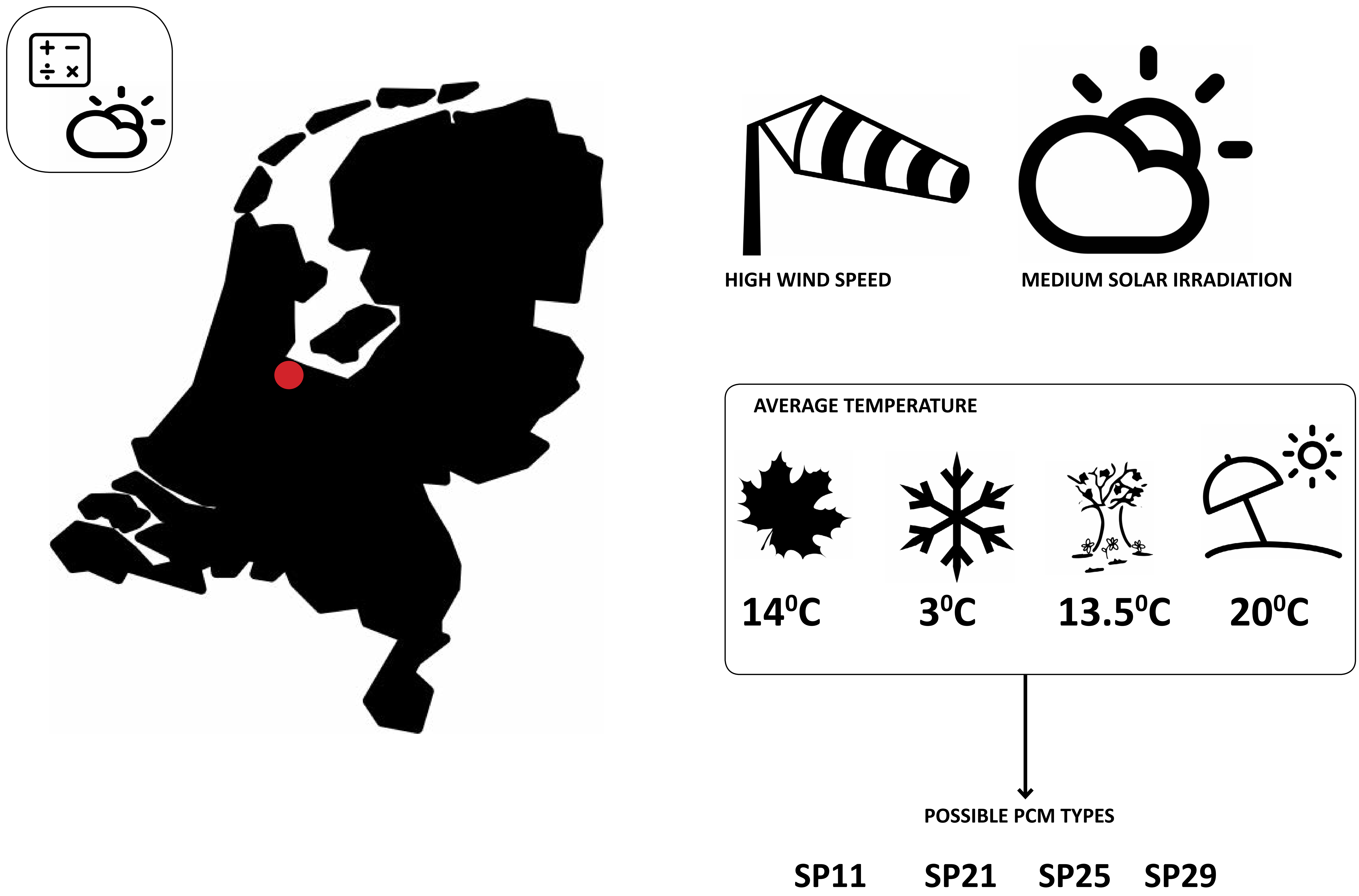


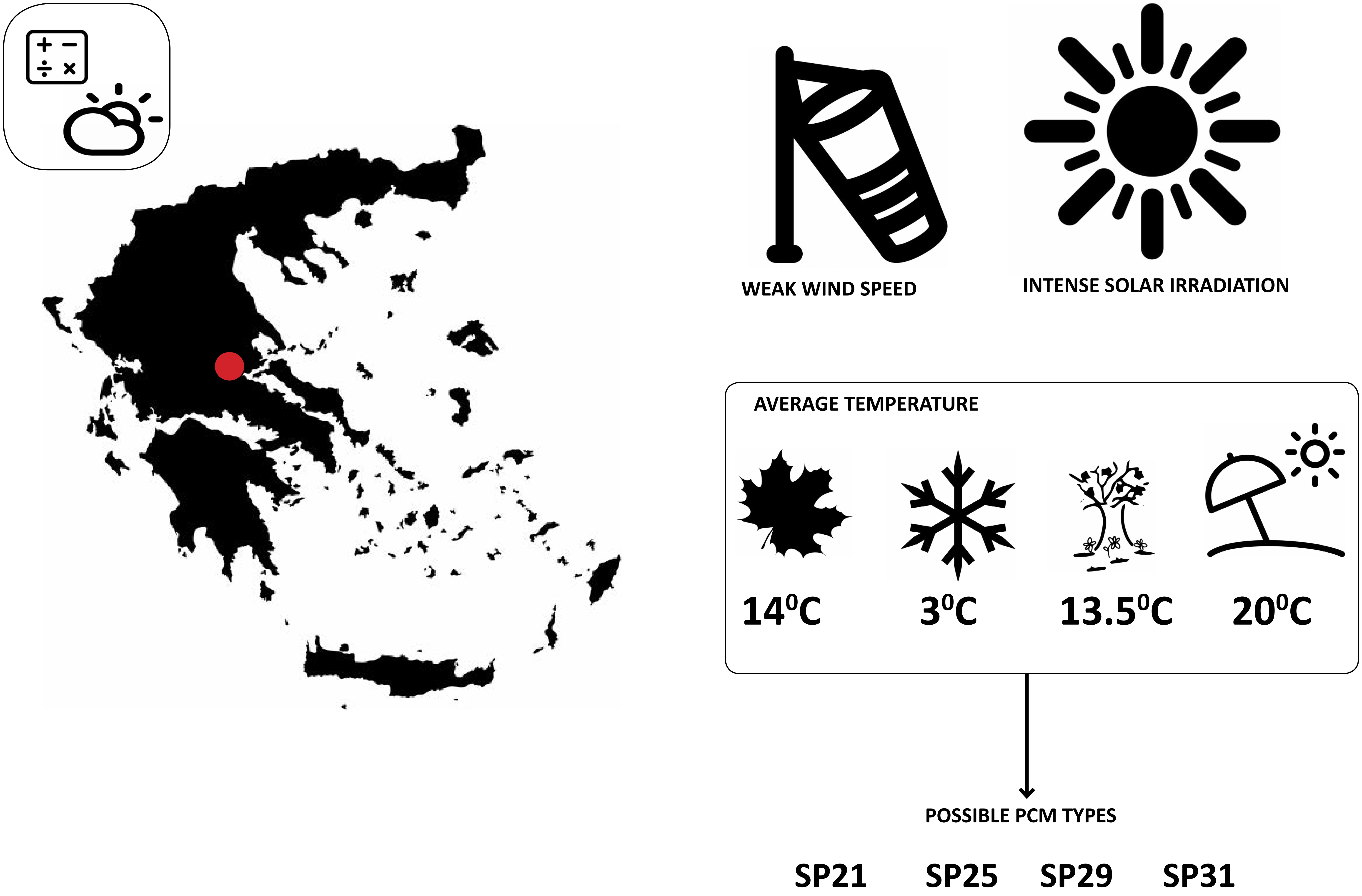






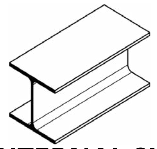



HIGH WIND SPEED
MEDIUM SOLAR IRRADIATION
AVERAGE TEMPERATURE
14^{0}C
3^{0}C
13.5^{0}C
20^{0}C
POSSIBLE PCM TYPES
SP11
SP21
SP25
SP29

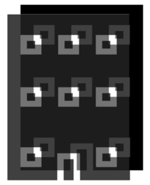

WEAK WIND SPEED
INTENSE SOLAR IRRADIATION
AVERAGE TEMPERATURE
14^{0}C
3^{0}C
13.5^{0}C
20^{0}C
POSSIBLE PCM TYPES
SP21
SP25
SP29
SP31

GENERAL DEFINITION

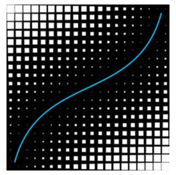
1.STRUCTURE



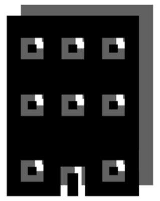
2.INTERNAL SKIN



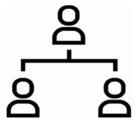
3.FACADE PATTERN



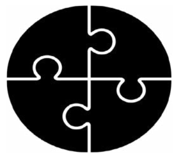
4.EXTERNAL SKIN



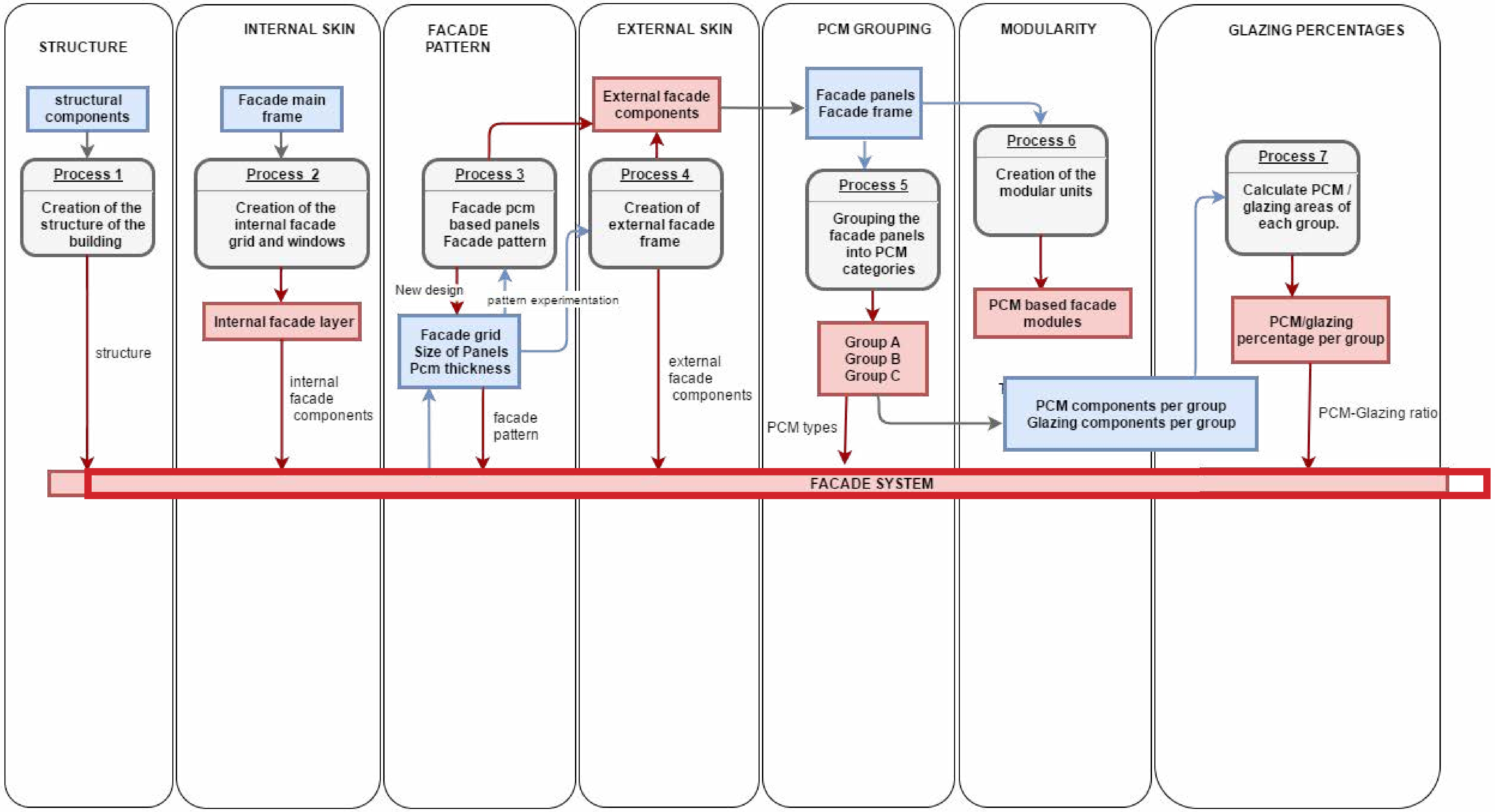
5.PCM GROUPING

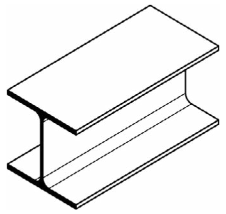


6.MODULAR UNITS

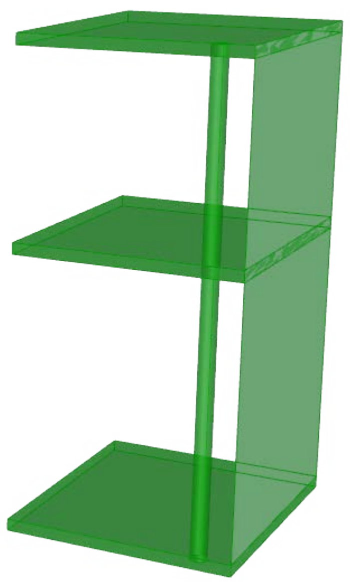


7.GLAZING PERCENTAGE

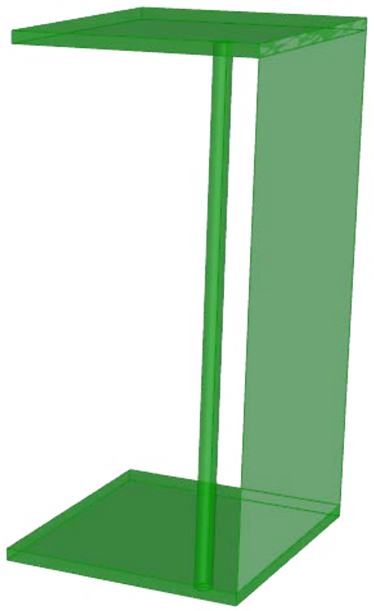




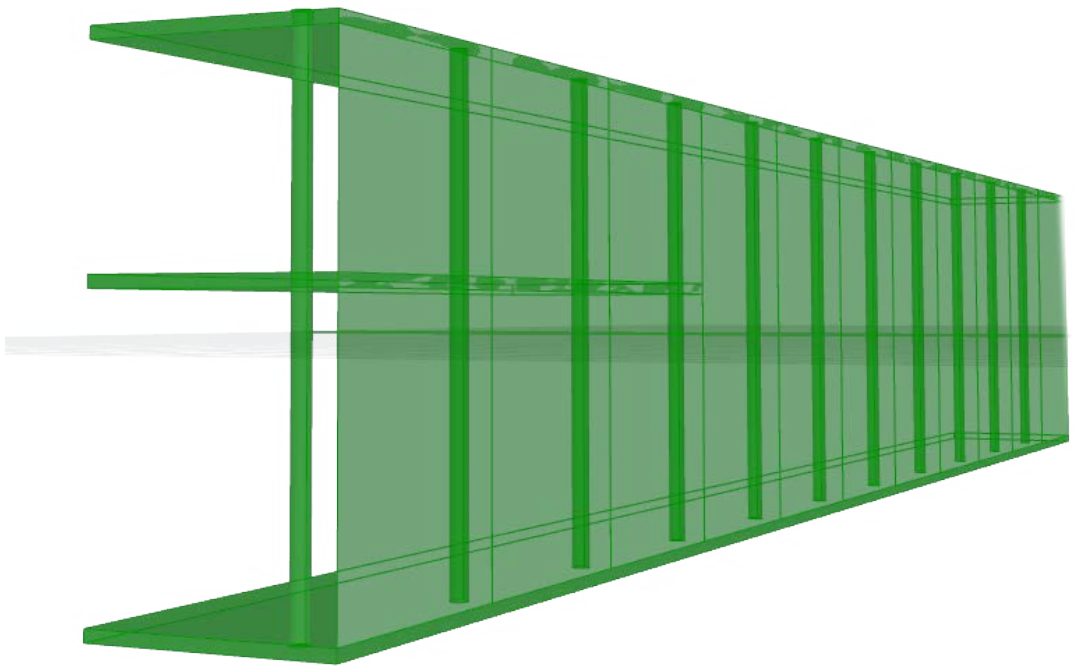
STRUCTURE



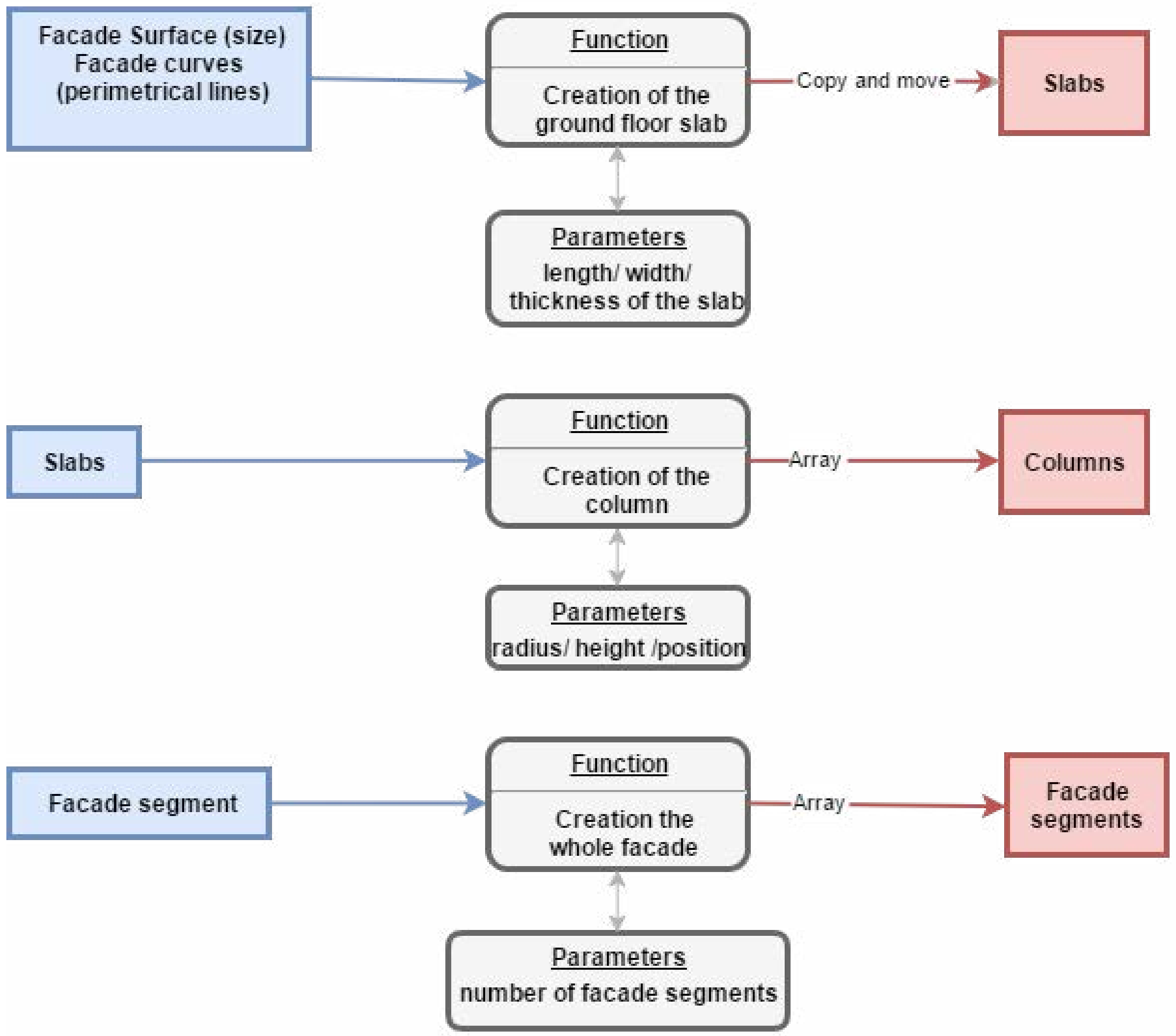
SEGMENT 1(2 FLOORS)



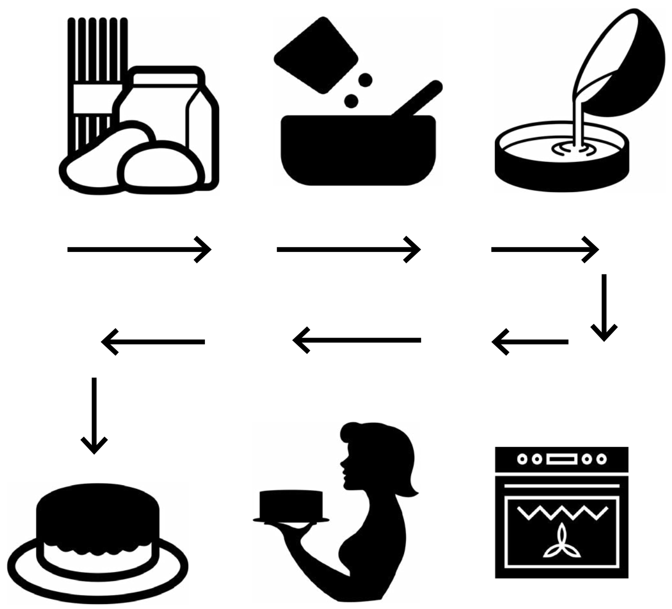
SEGMENT 2 (1 FLOOR)

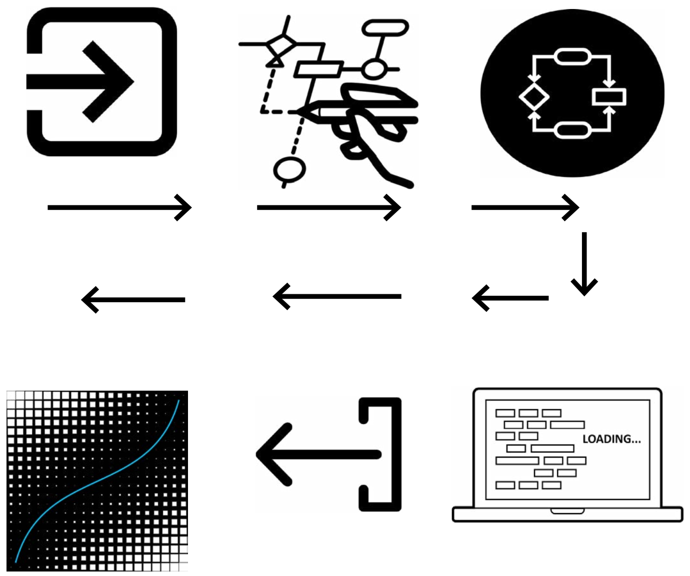


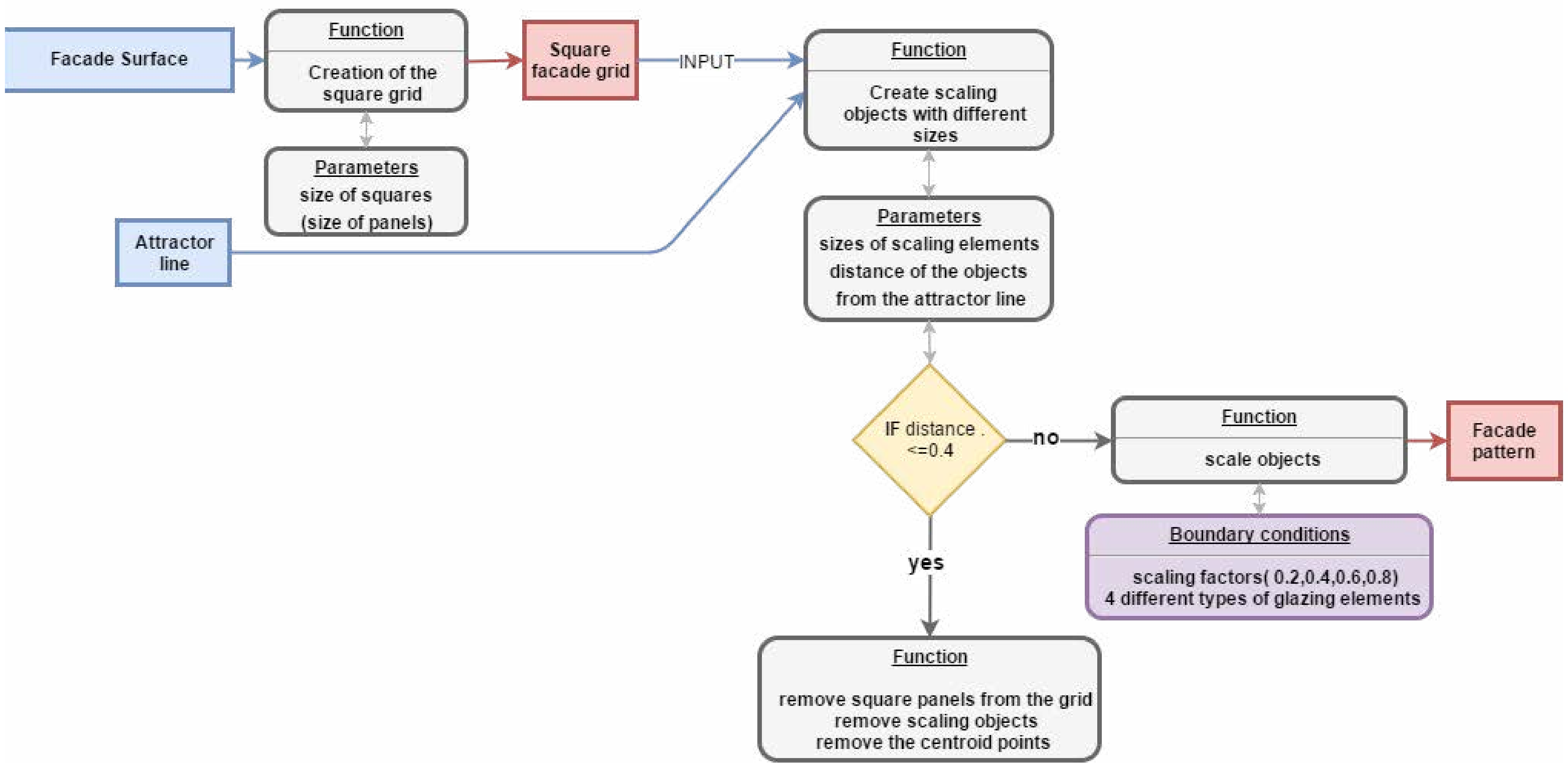
THE WHOLE FACADE



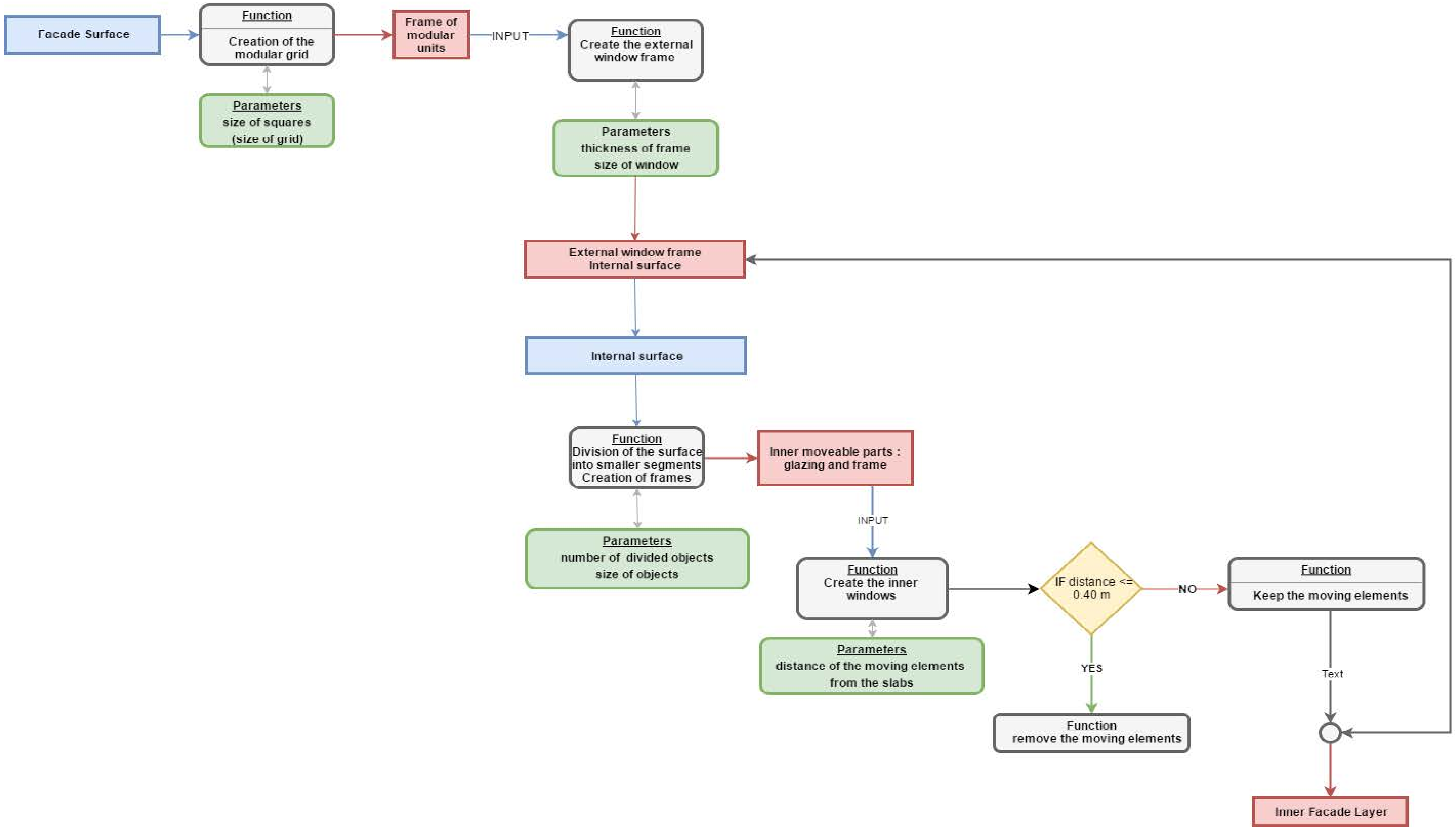
FACADE PATTERN



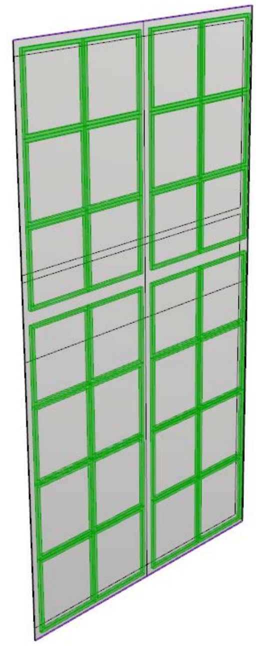




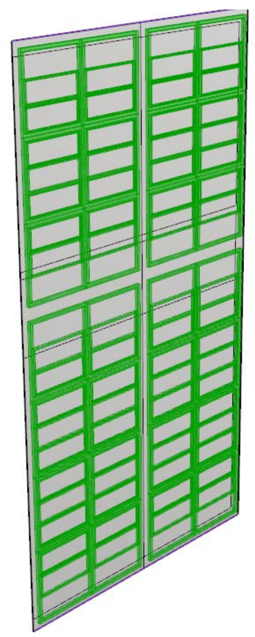
INNER FACADE LAYER



UNITIZED SYSTEM FRAME

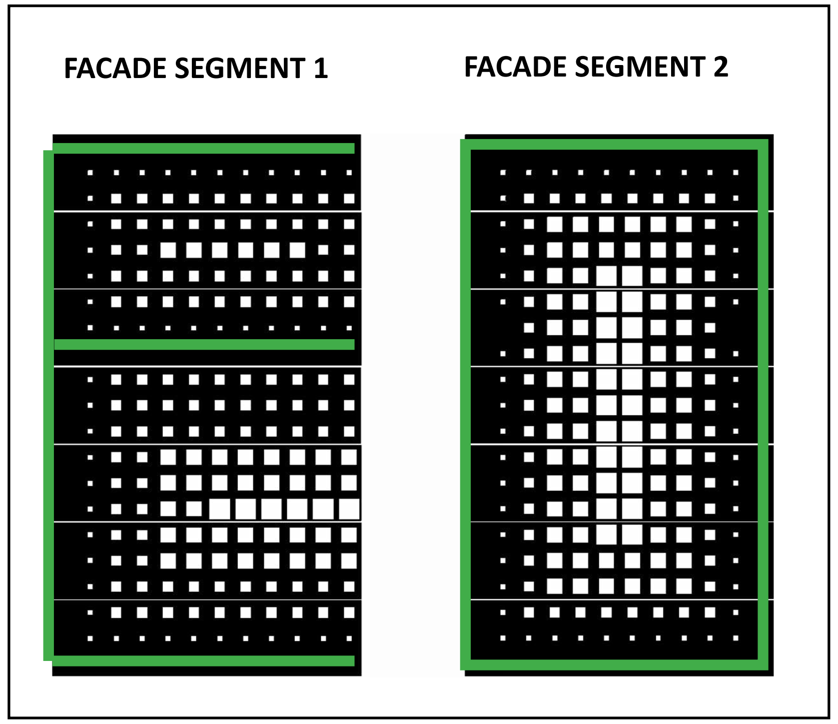


WINDOW FRAME

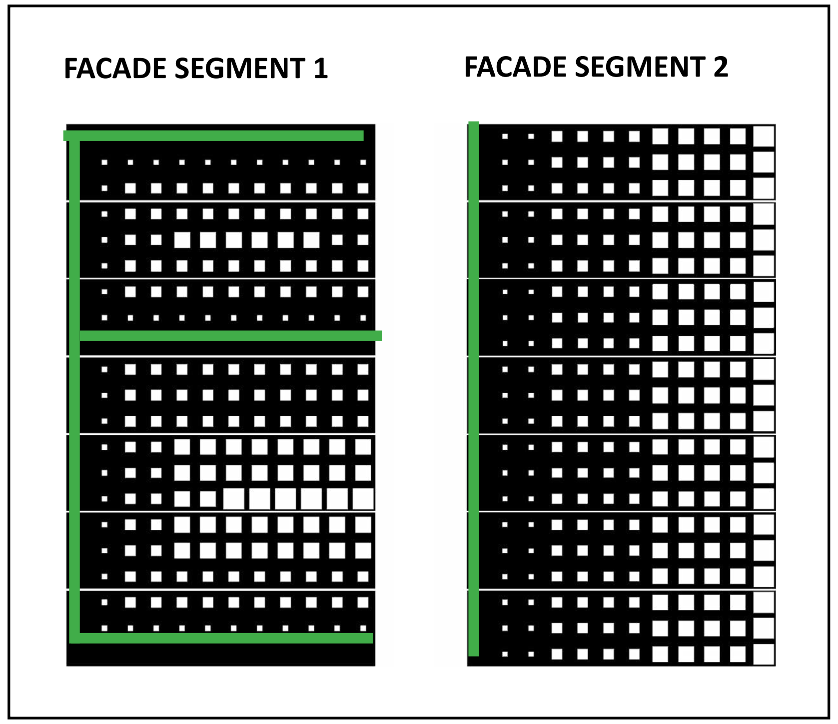


LAMELLA WINDOWS

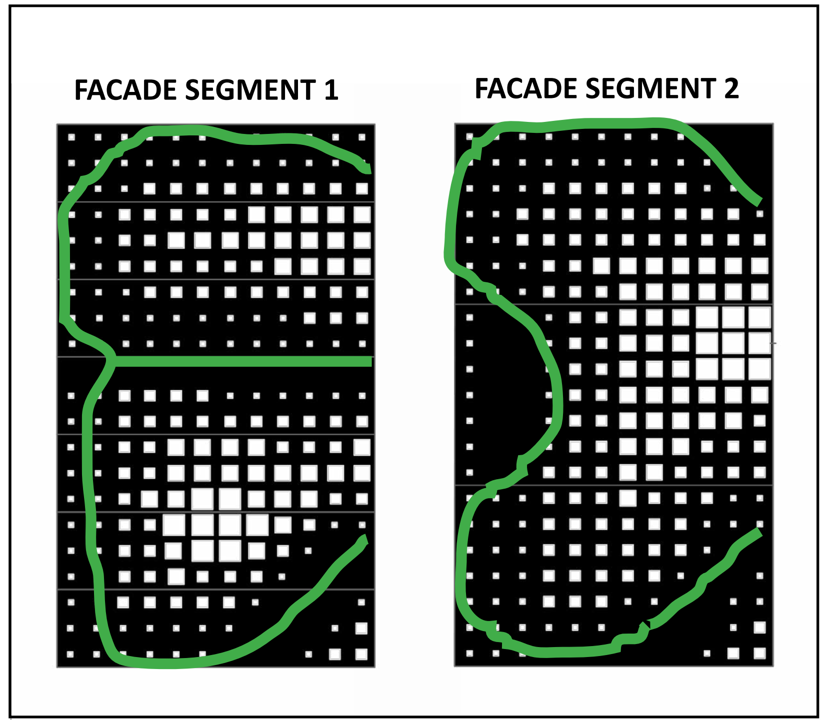
ATHENS



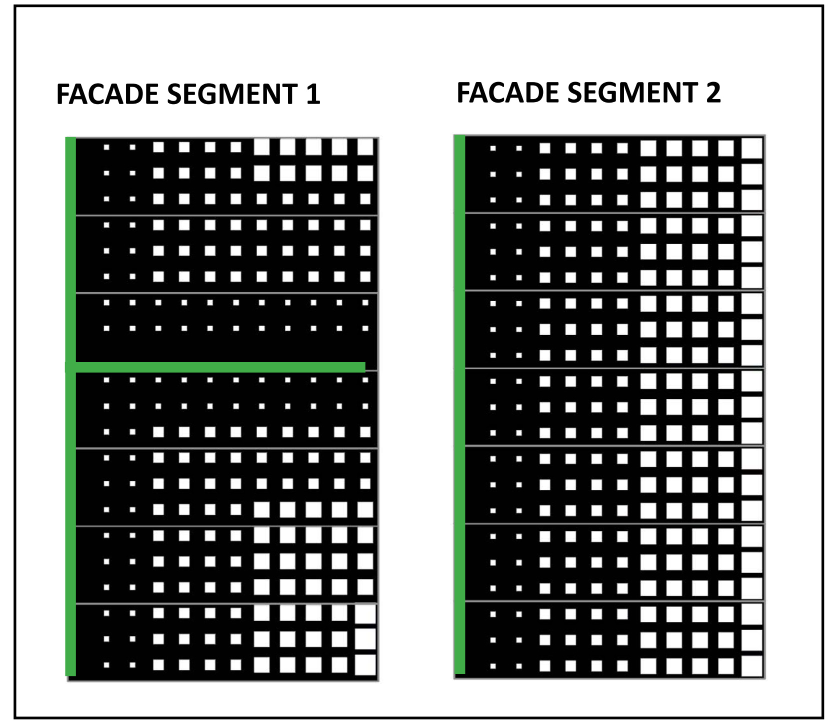
FACADE PATTERN 1



FACADE PATTERN 2

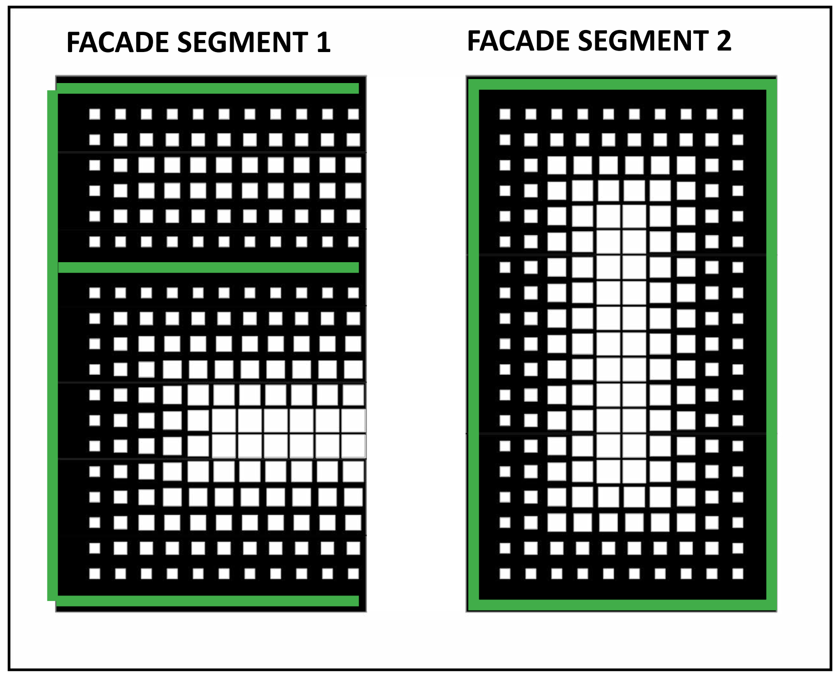


FACADE PATTERN 3

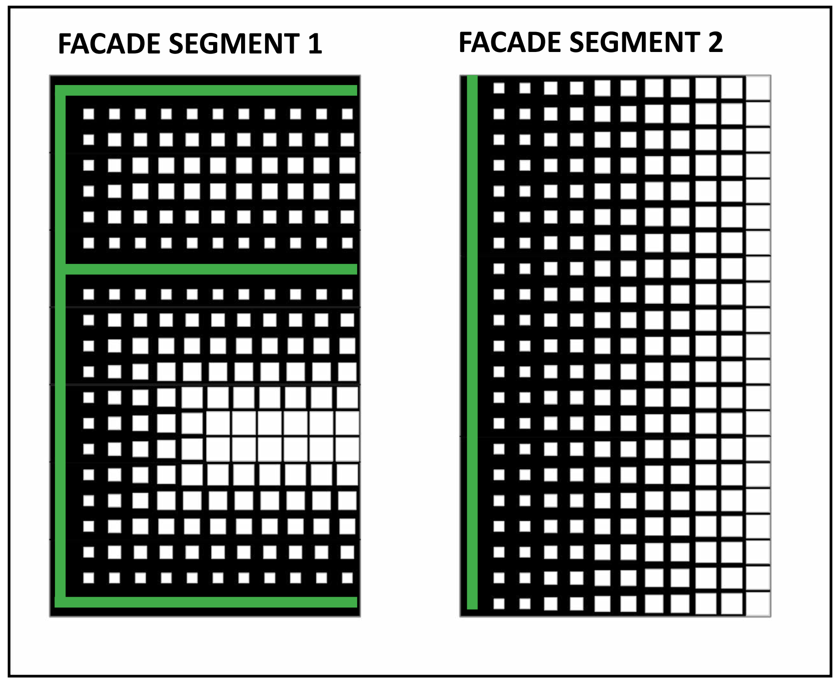


FACADE PATTERN 4

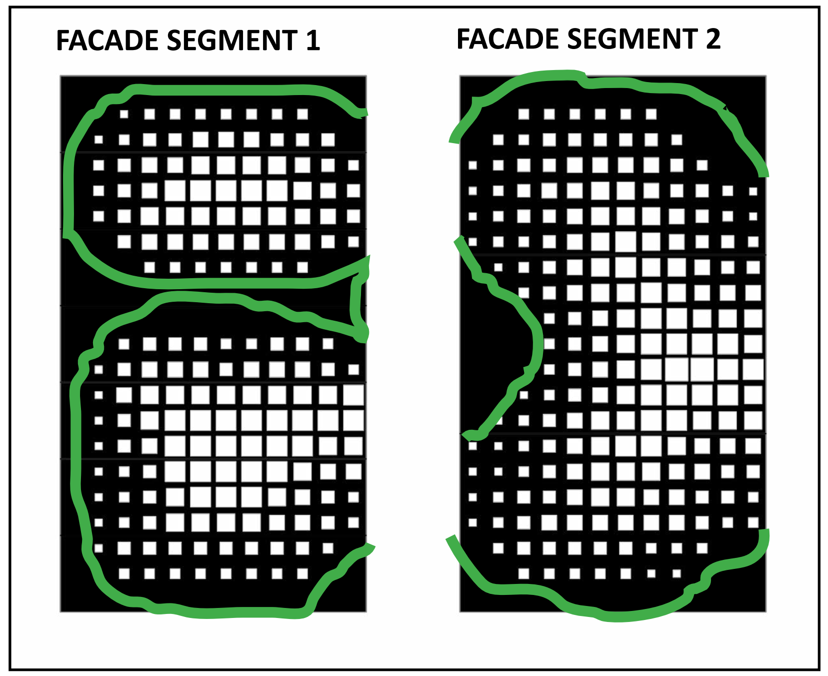
AMSTERDAM



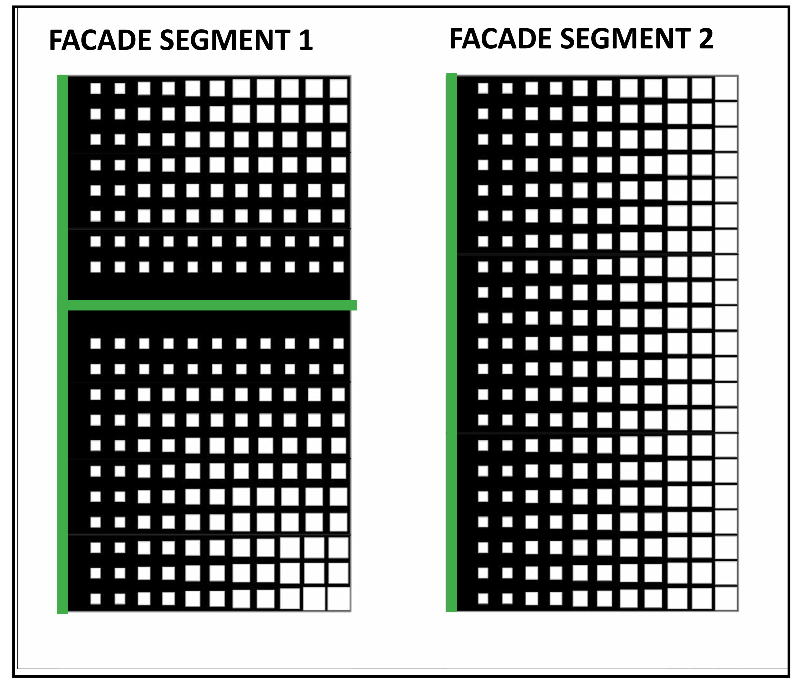
FACADE PATTERN 1



FACADE PATTERN 2



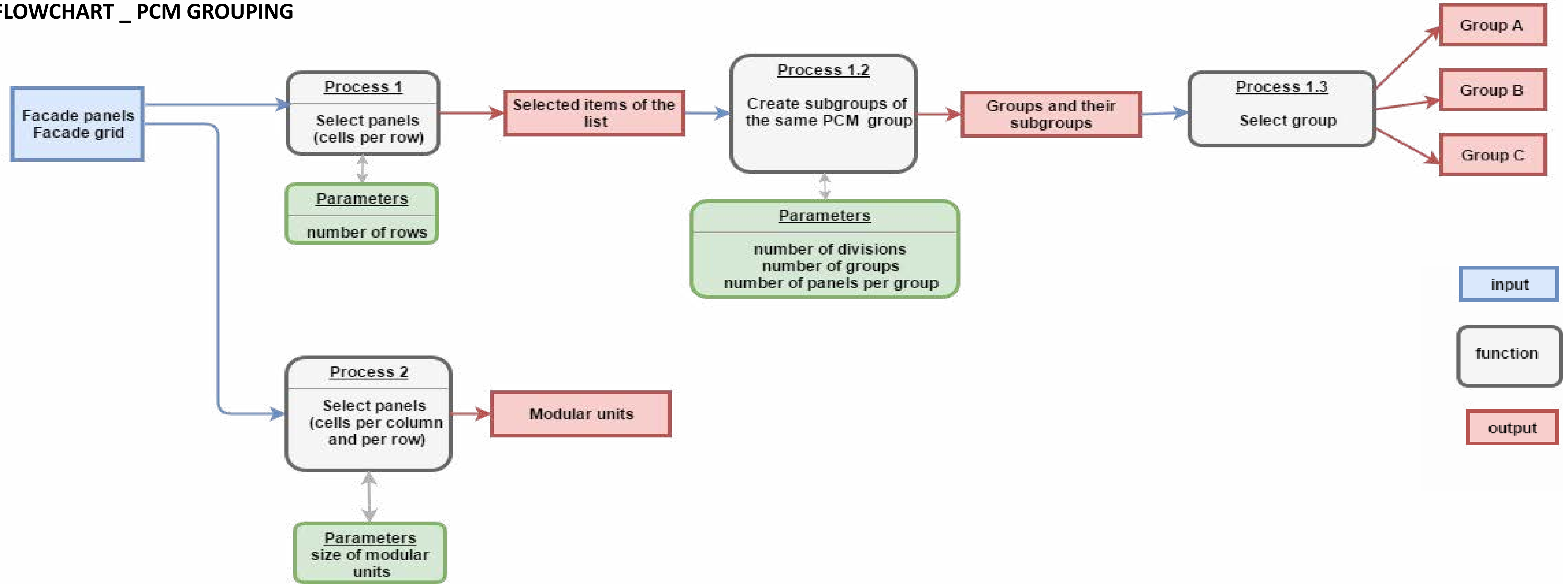
FACADE PATTERN 3



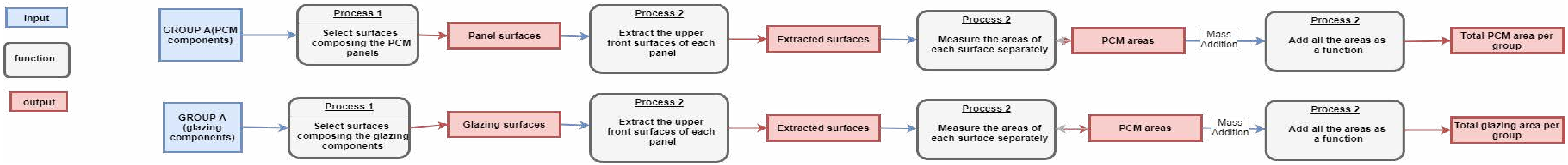
FACADE PATTERN 4

PCM GROUPING

FLOWCHART _ PCM GROUPING



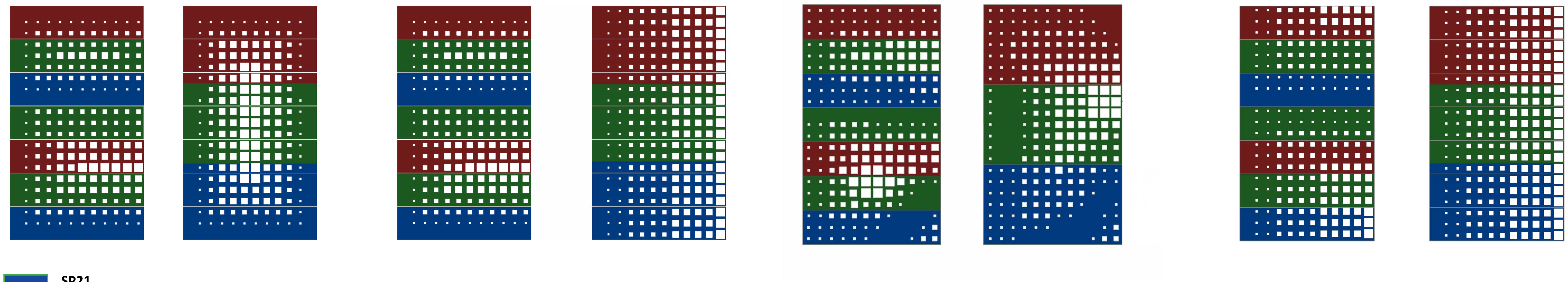
FLOWCHART _ PCM -GLAZING AREA MEASUREMENTS (example for group A)



PCM PLACEMENT

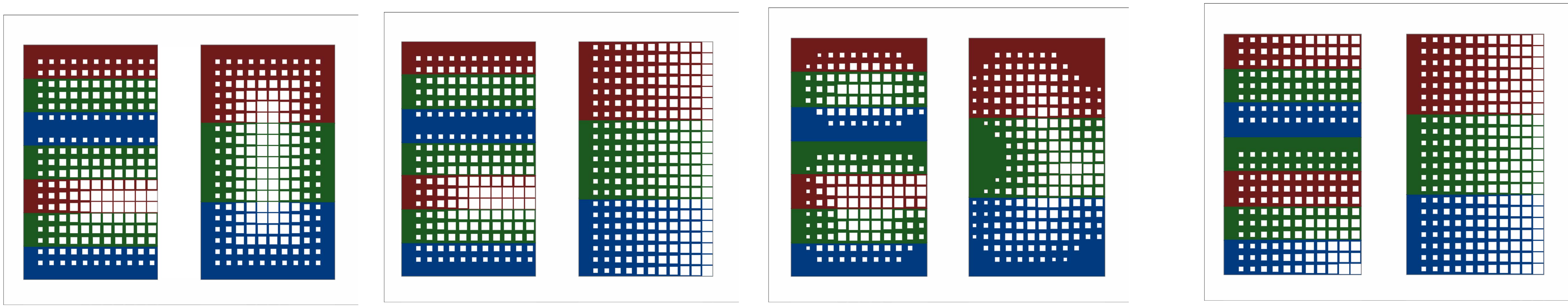
ATHENS

FACADE SEGMENT 1 | FACADE SEGMENT 2 | FACADE SEGMENT 1 | FACADE SEGMENT 2 | FACADE SEGMENT 1 | FACADE SEGMENT 2 | FACADE SEGMENT 1 | FACADE SEGMENT 2



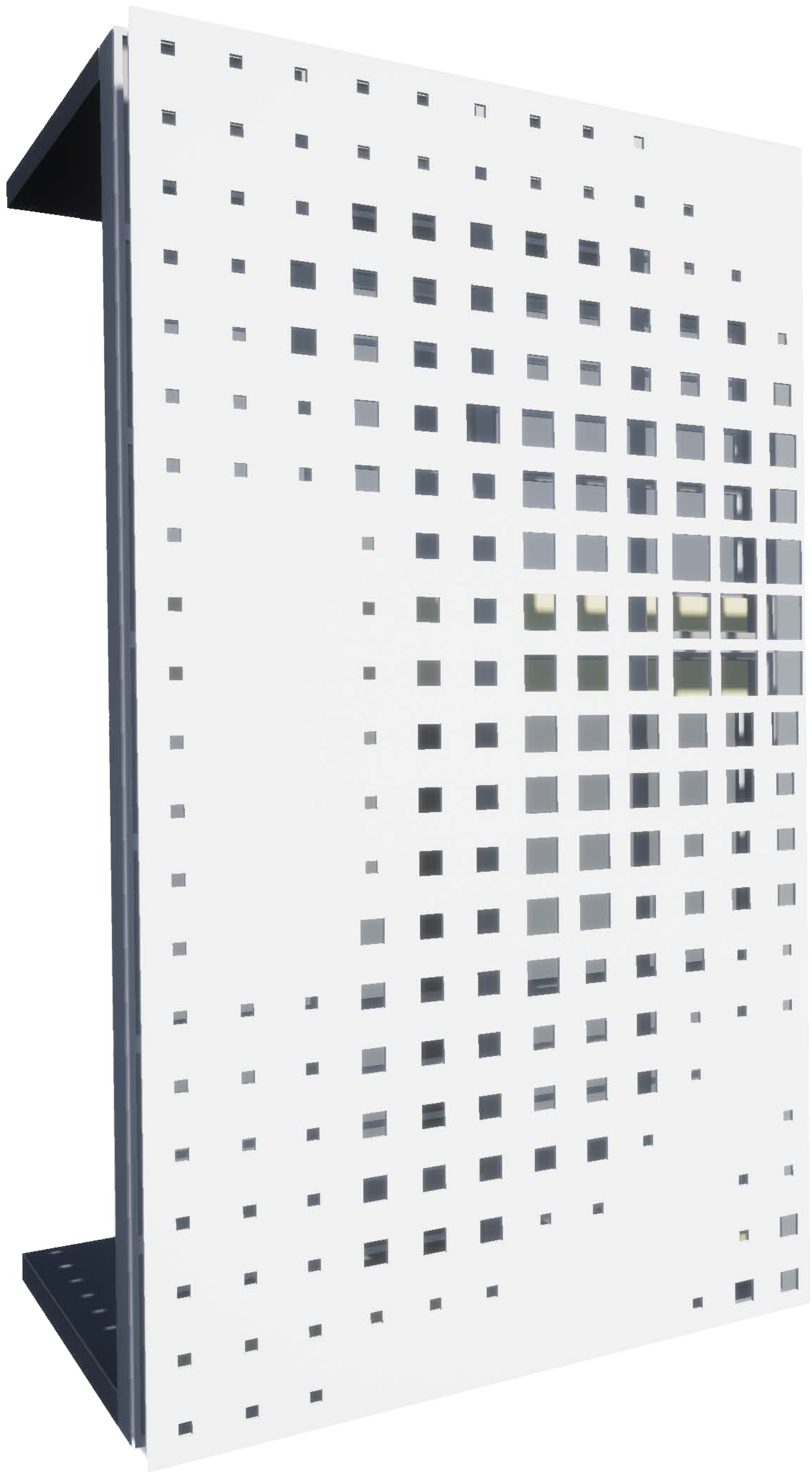
- SP21
- SP25
- SP29 or SP31

AMSTERDAM



- SP11
- SP21
- SP25 or SP29

ENERGY PERFORMANCE



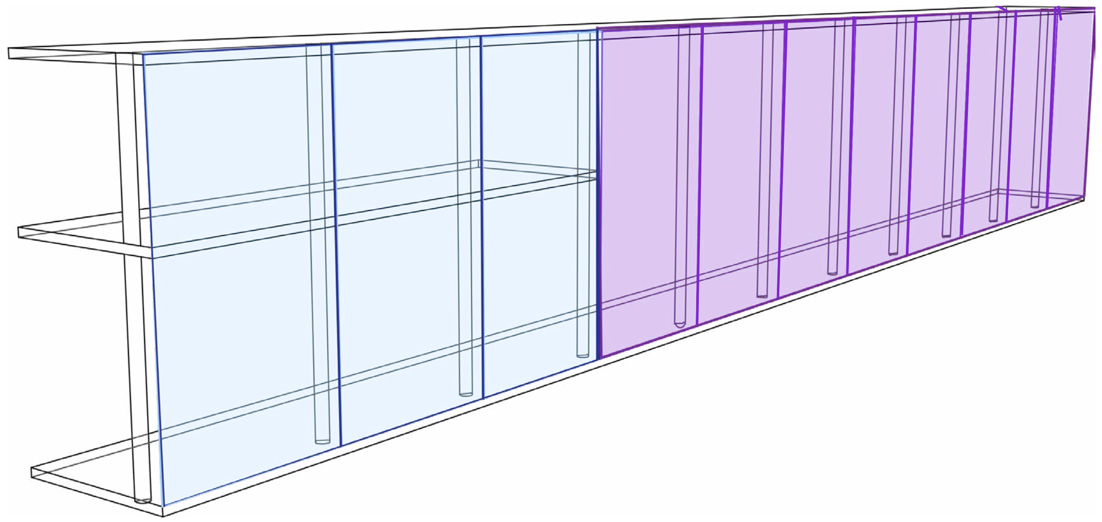
PCM BASED DOUBLE SKIN FACADE

VS

FULLY GLAZED DOUBLE SKIN FACADE

SET UP

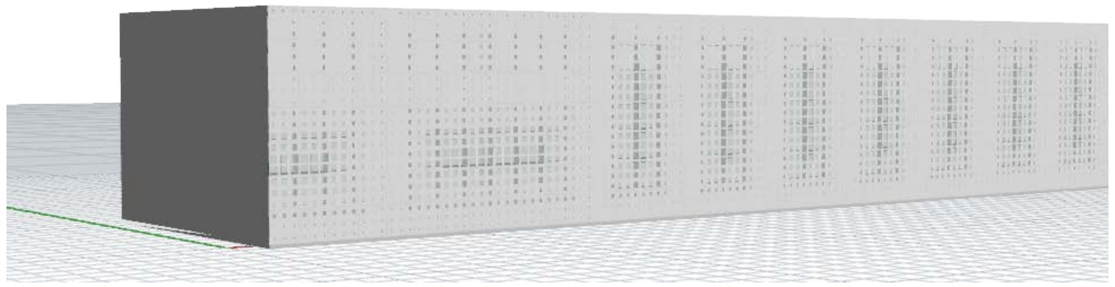
FACADE SEGMENTATION



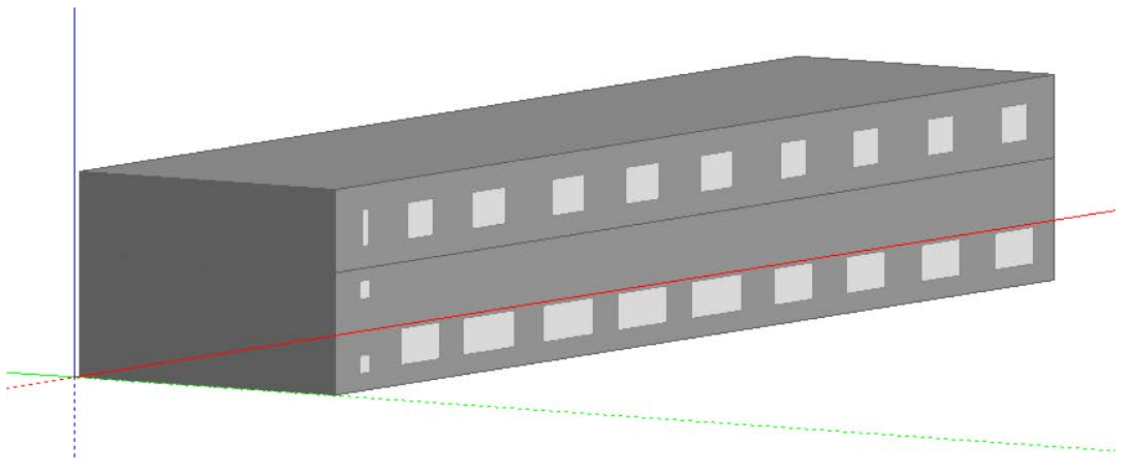
FACADE SEGMENT 1

FACADE SEGMENT 2

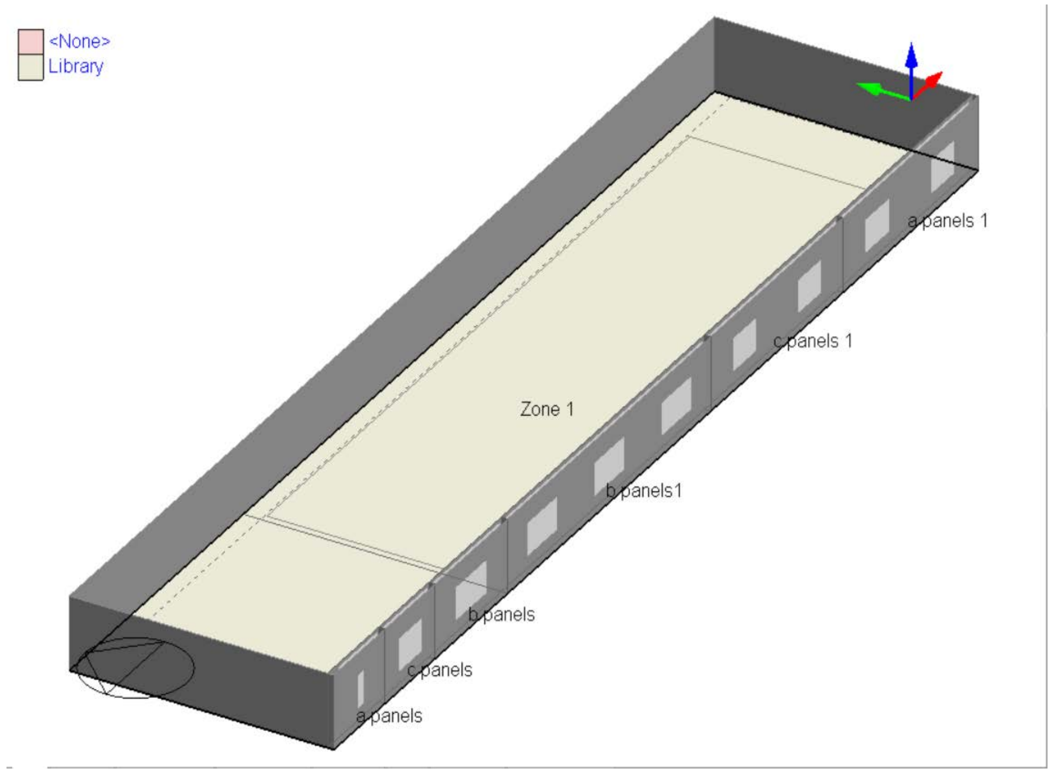
ACTUAL PATTERN



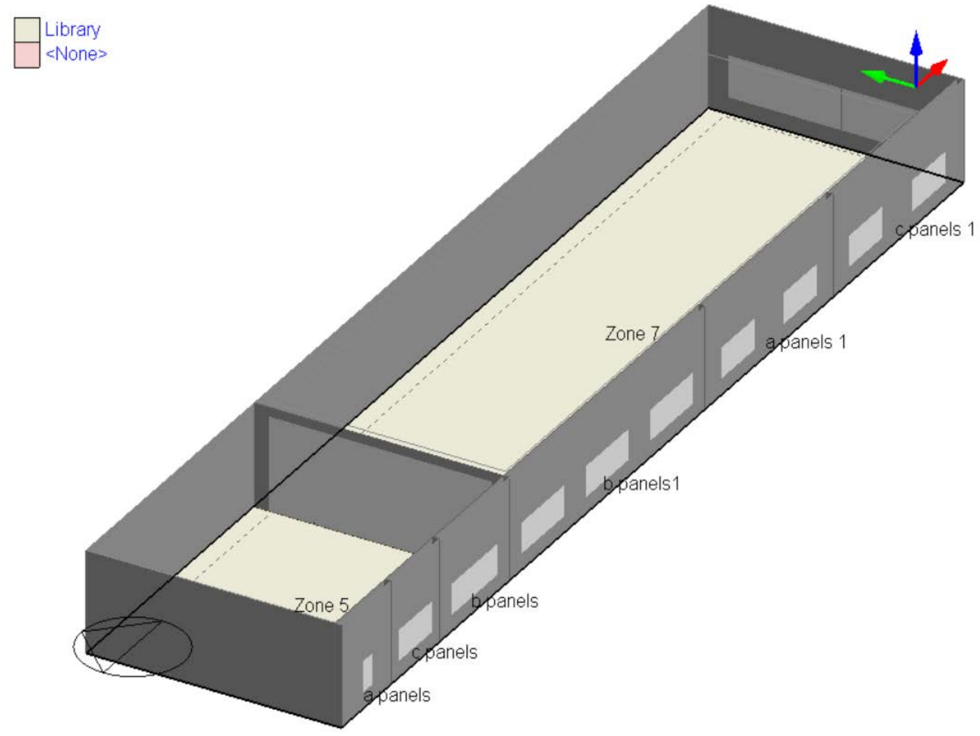
PATTERN TRANSLATED TO WINDOW TO WALL RATIO



FIRST FLOOR (1 THERMAL ZONE:INDOOR SPACE, 6 THERMAL ZONES : DOUBLE SKIN FACADE

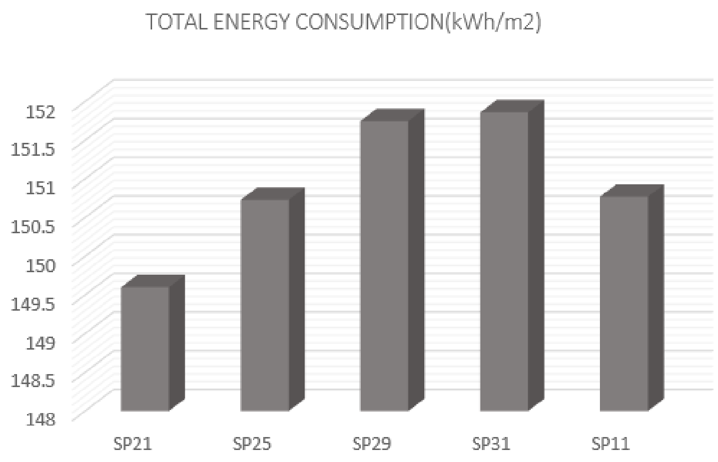


GROUND FLOOR (2 THERMAL ZONE:INDOOR SPACE, 6 THERMAL ZONES : DOUBLE SKIN FACADE

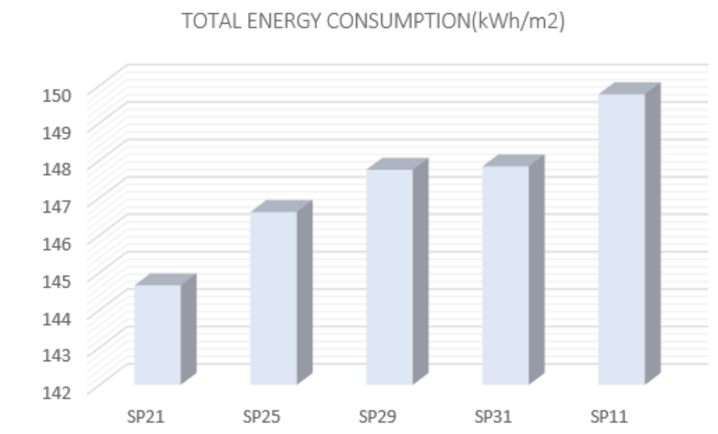


AMSTERDAM

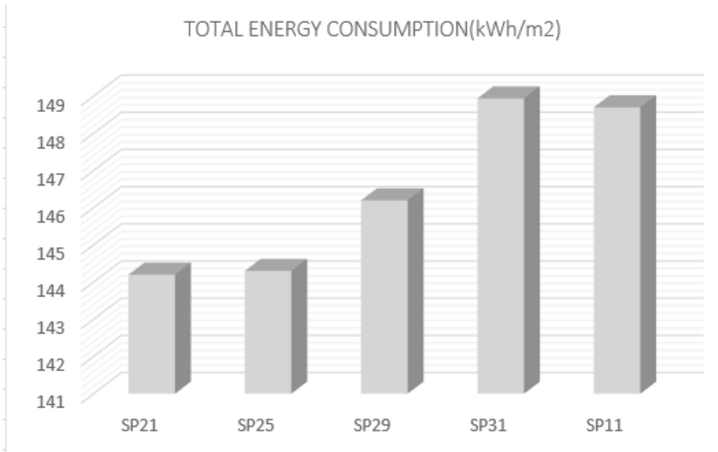
BOUNDARY CONDITIONS



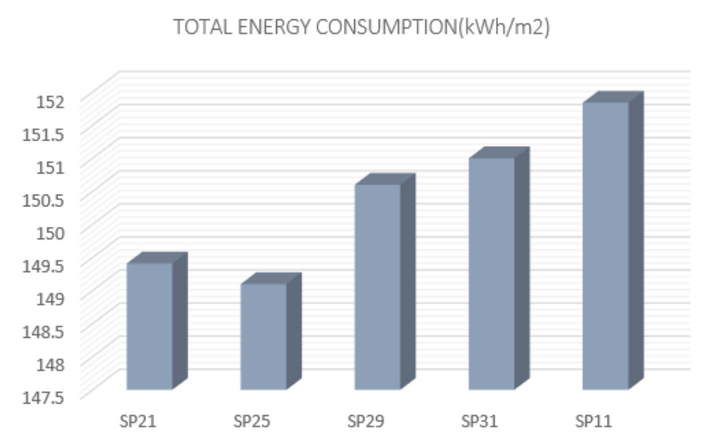
50% Glazing



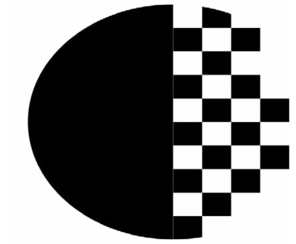
40% Glazing



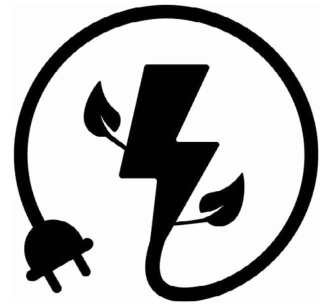
30% Glazing



20% Glazing



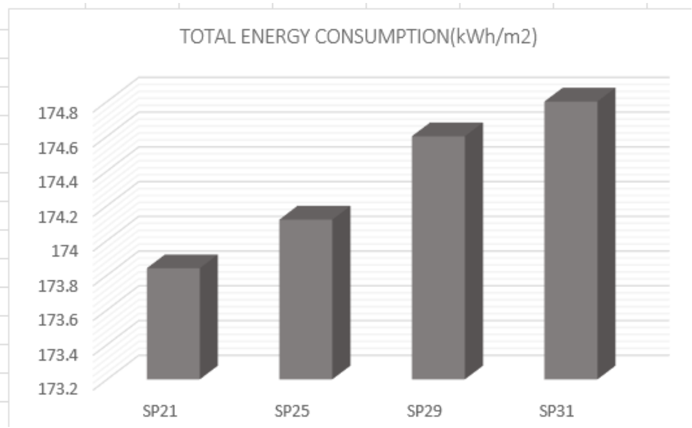
30-40 %



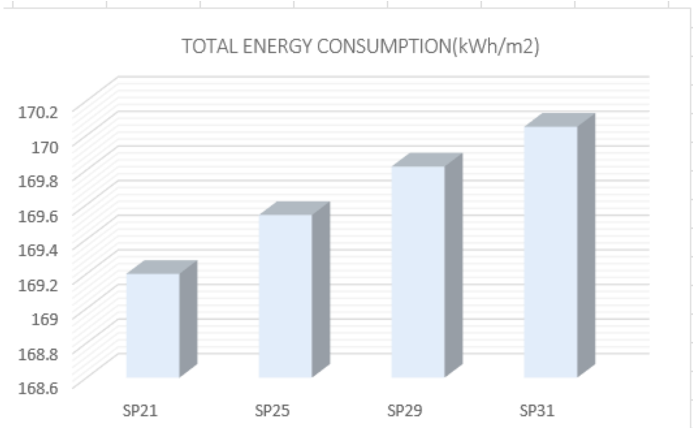
21 ^{0}C

ATHENS

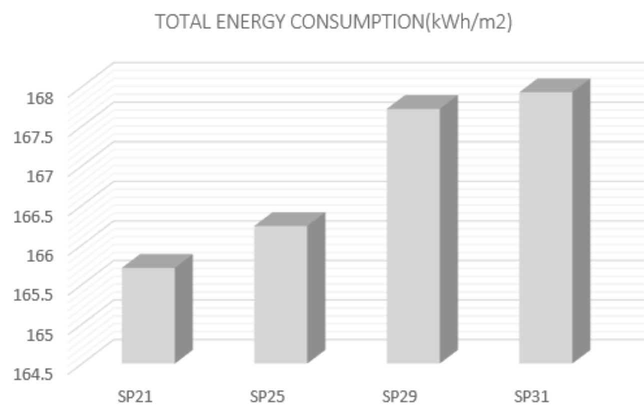
BOUNDARY CONDITIONS



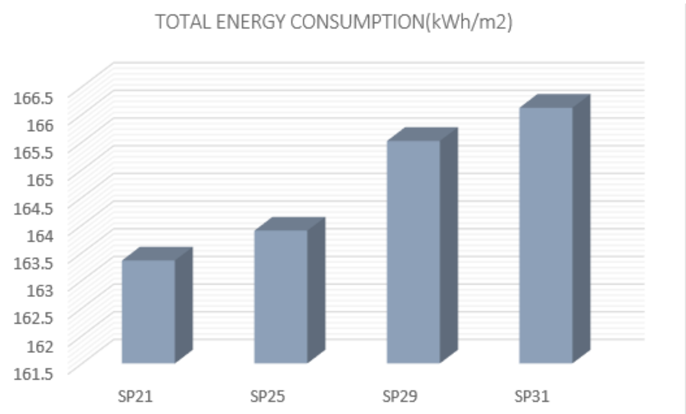
50% Glazing



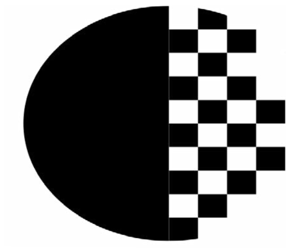
40% Glazing



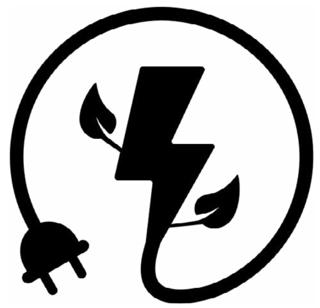
30% Glazing



20% Glazing



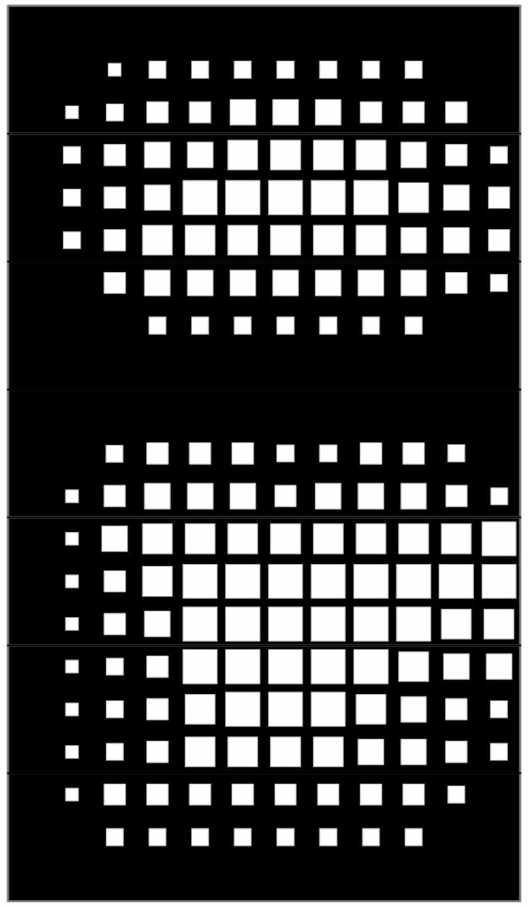
20 %



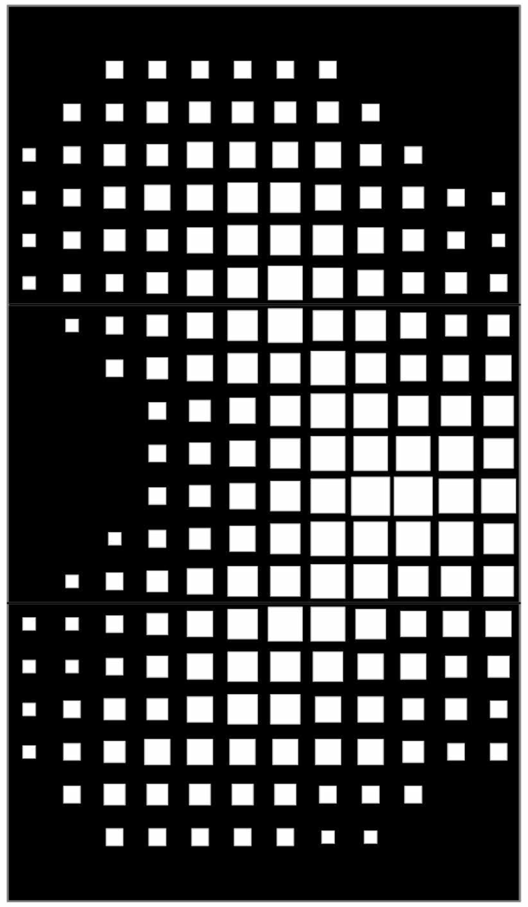
21 & 25 ^{0}C

PROPOSED DESIGN

PATTERN
FACADE SEGMENT 1

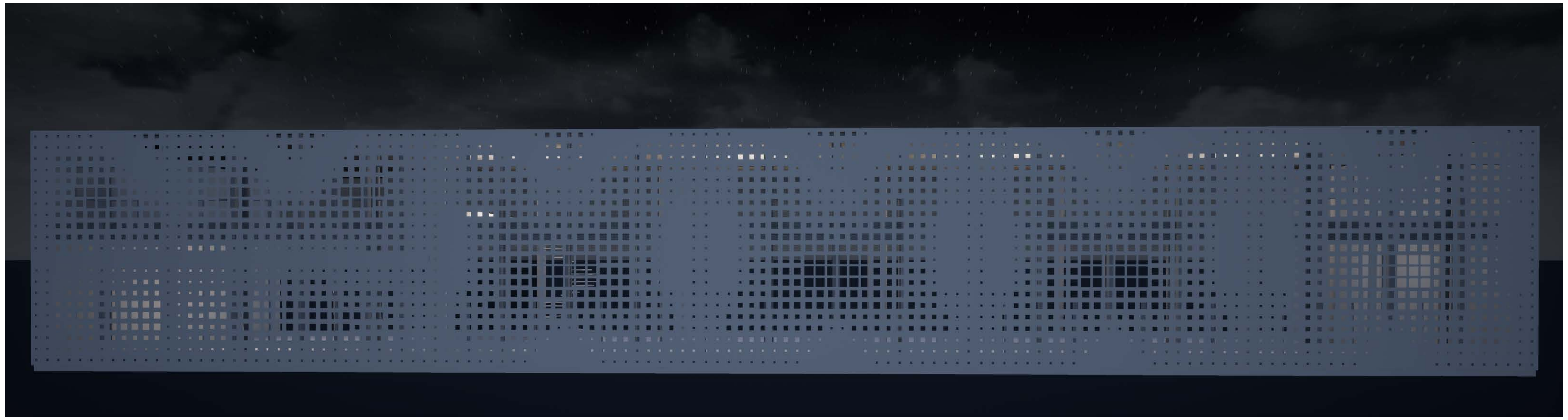


PATTERN
FACADE SEGMENT 2



INPUT DATA

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%



IMPORTANT POINTS

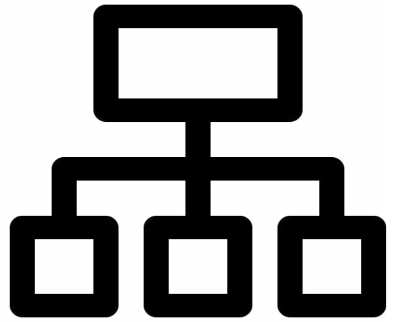
Glazing percentage

17.6%

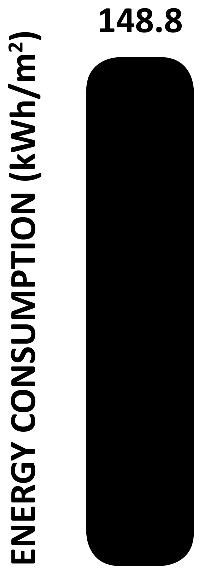
Annual energy consumption

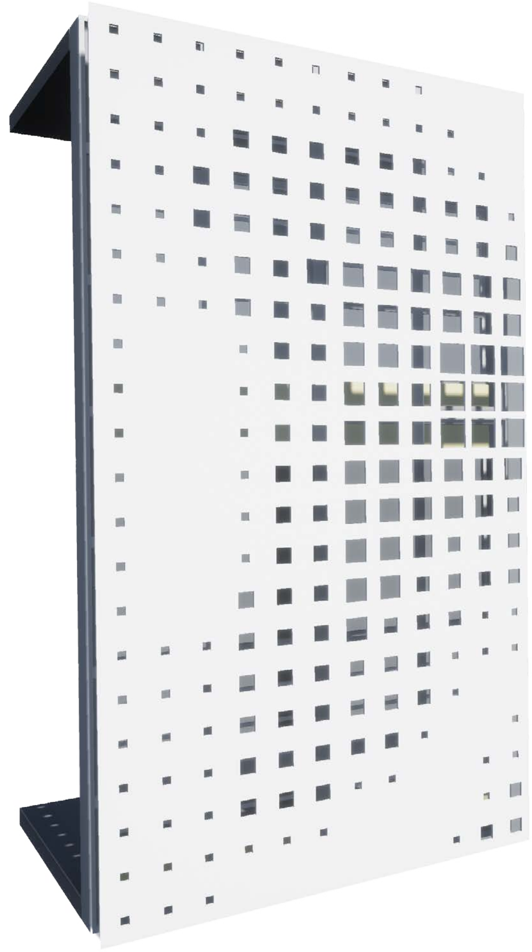
148.85 kWh/m²

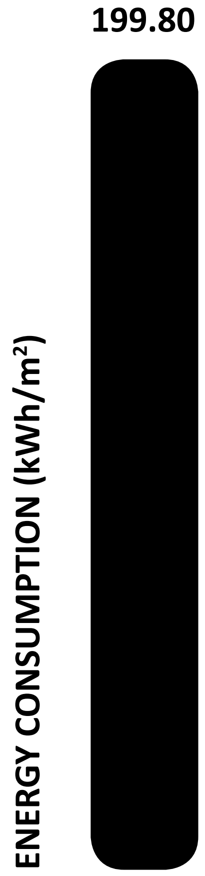
Energy efficient PCM combination

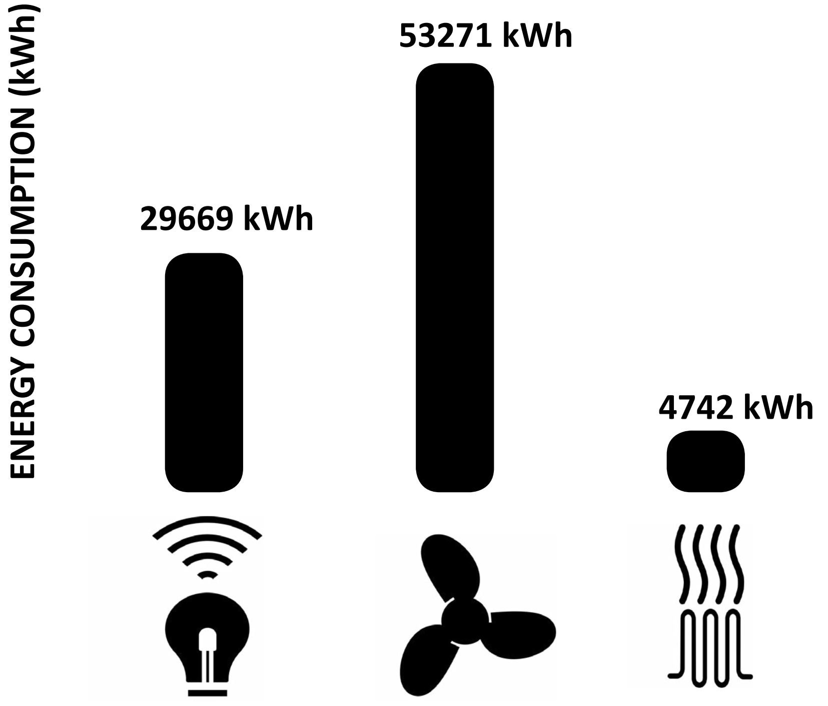


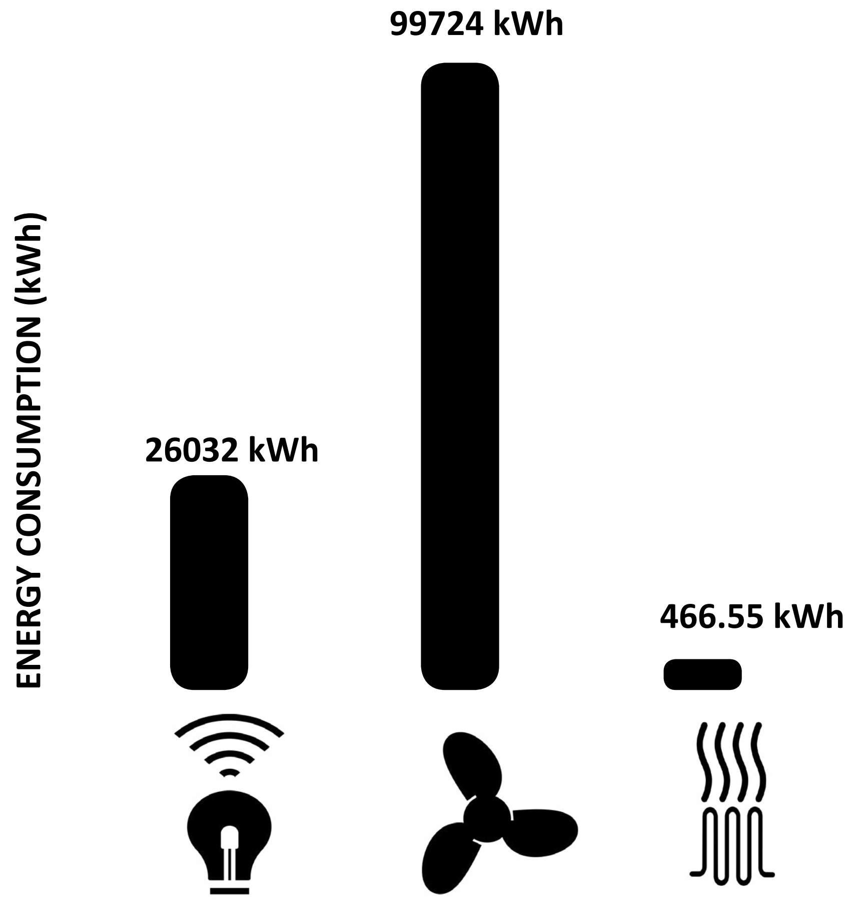
COMPARISON


148.8
ENERGY CONSUMPTION (kWh/m²)



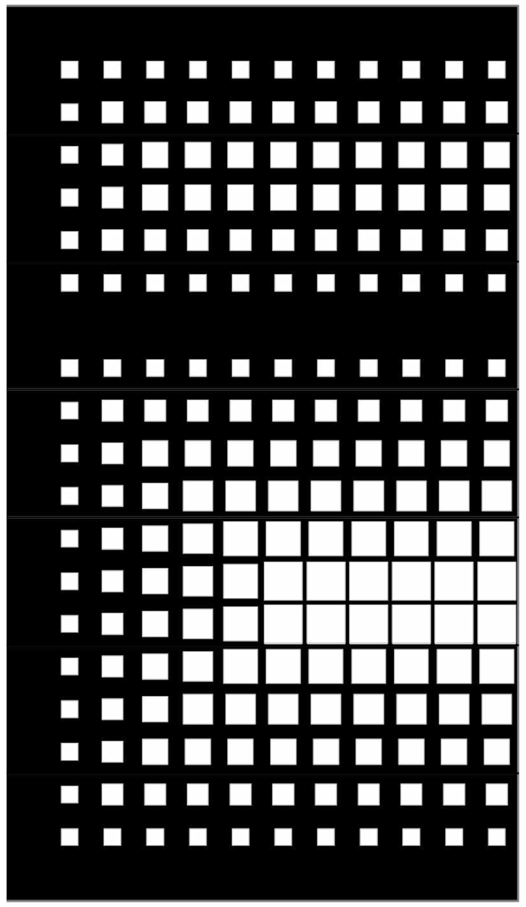

199.80
ENERGY CONSUMPTION (kWh/m²)


ENERGY CONSUMPTION (kWh)
29669 kWh
53271 kWh
4742 kWh

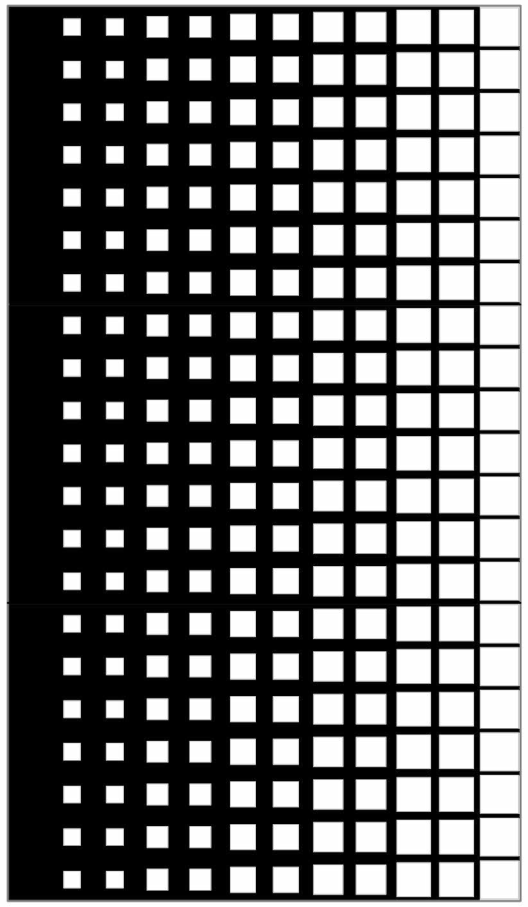

ENERGY CONSUMPTION (kWh)
26032 kWh
99724 kWh
466.55 kWh

PROPOSED DESIGN

PATTERN
FACADE SEGMENT 1



PATTERN
FACADE SEGMENT 2



INPUT DATA

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%

IMPORTANT POINTS

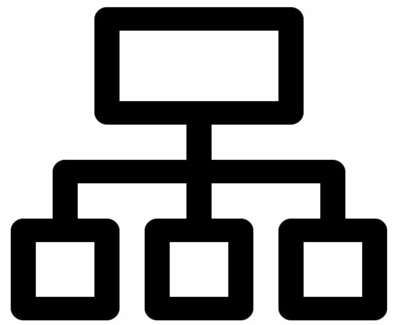
Glazing percentage

35.73%

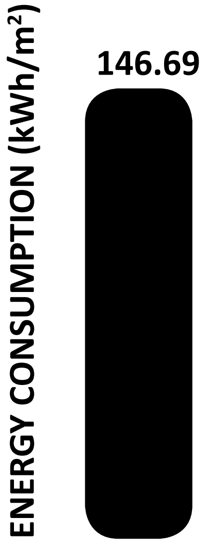
Annual energy consumption

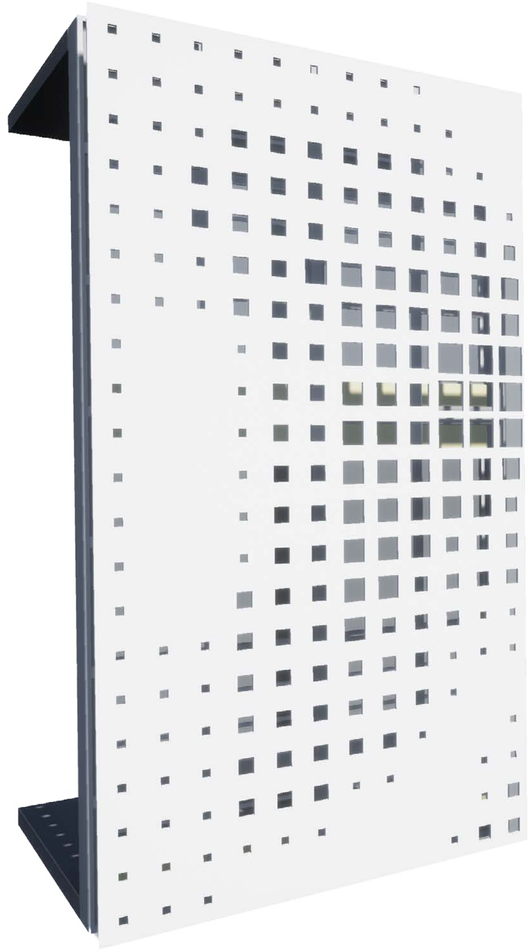
146.69 kWh/m^2

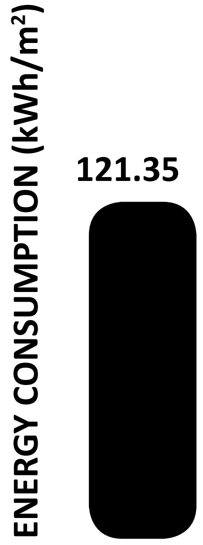
Energy efficient PCM combination

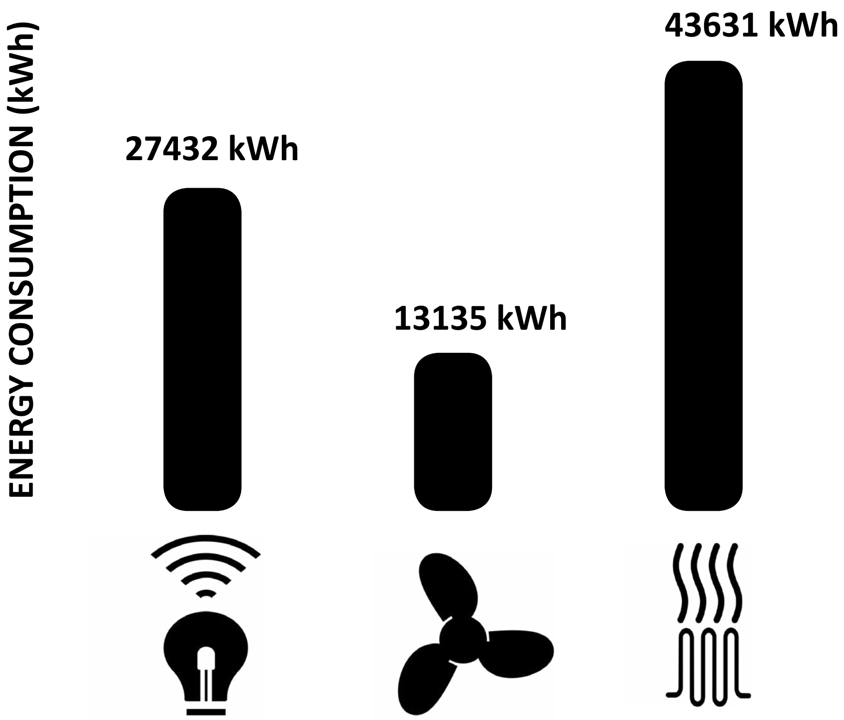


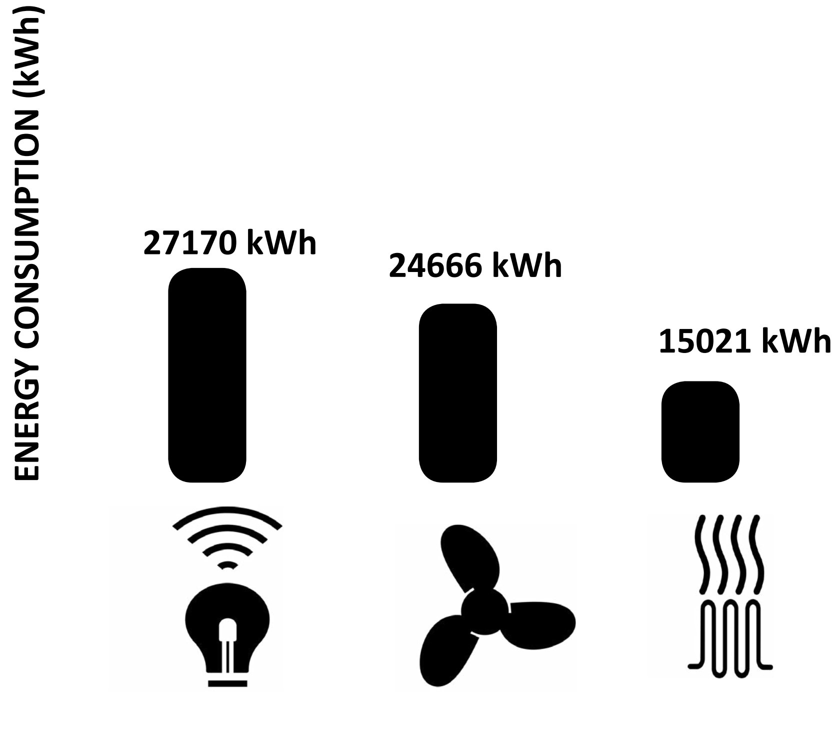
COMPARISON

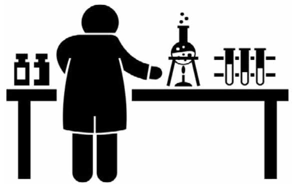

ENERGY CONSUMPTION (kWh/m²)
146.69



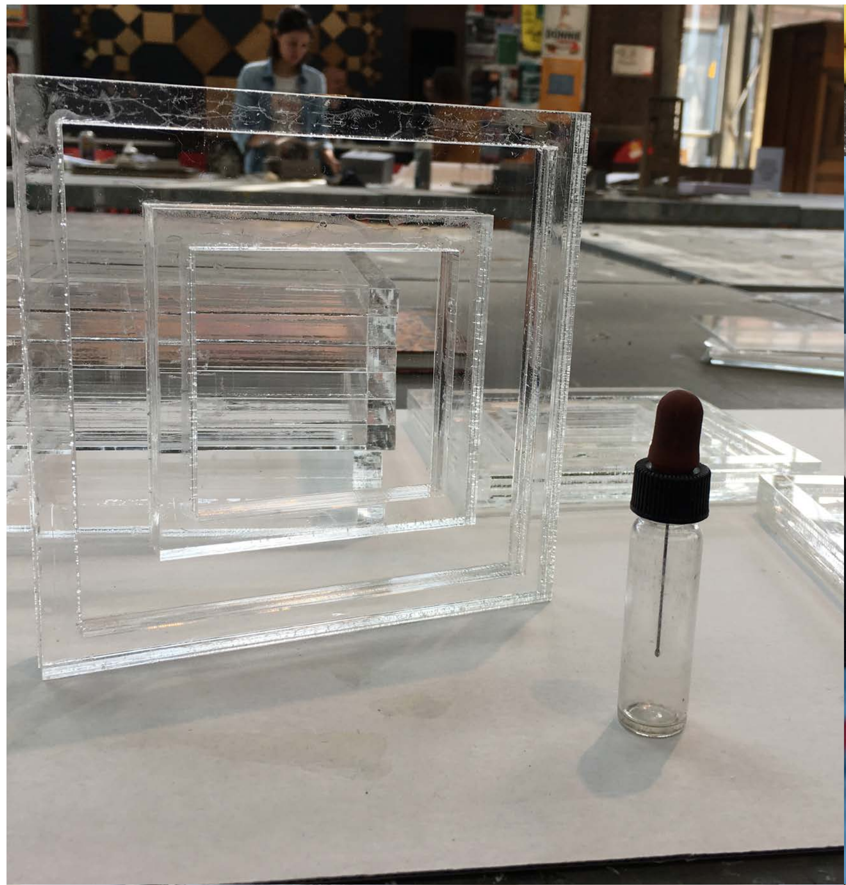

ENERGY CONSUMPTION (kWh/m²)
121.35

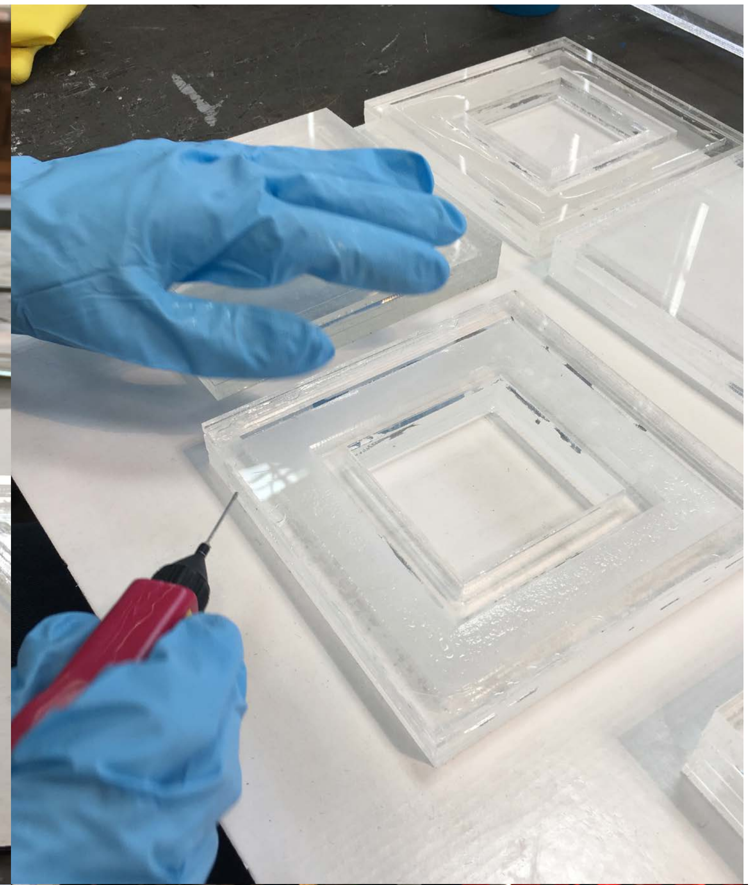

ENERGY CONSUMPTION (kWh)
27432 kWh
13135 kWh
43631 kWh

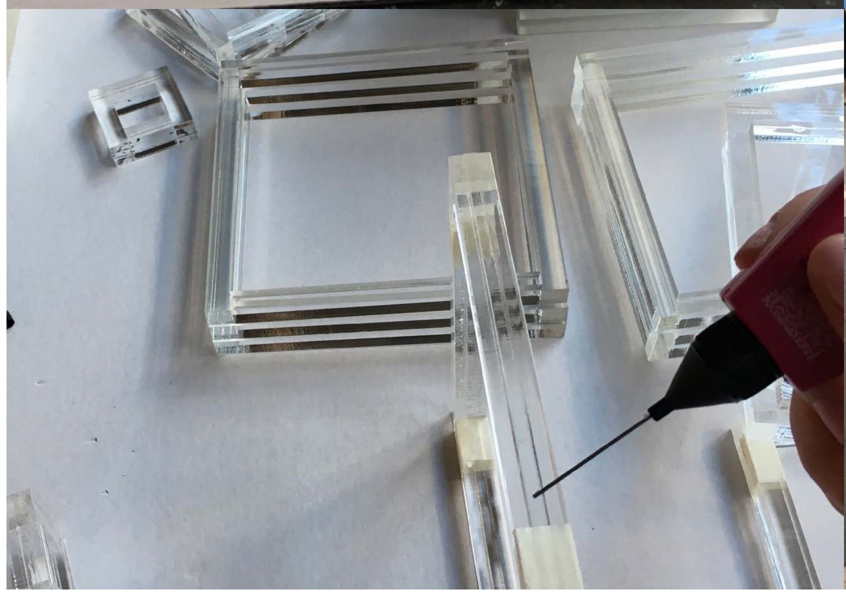

ENERGY CONSUMPTION (kWh)
27170 kWh
24666 kWh
15021 kWh

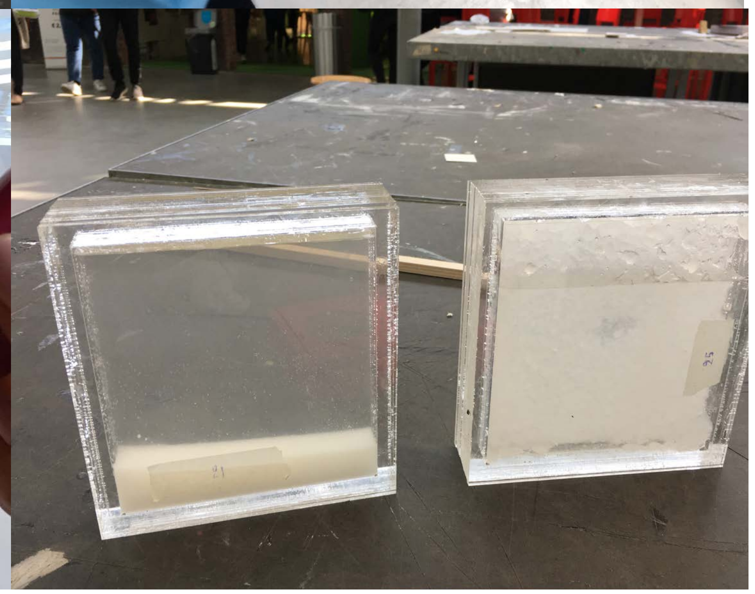


THE EXPERIMENT





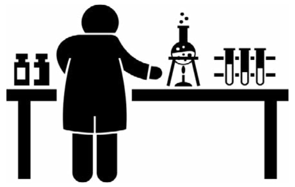




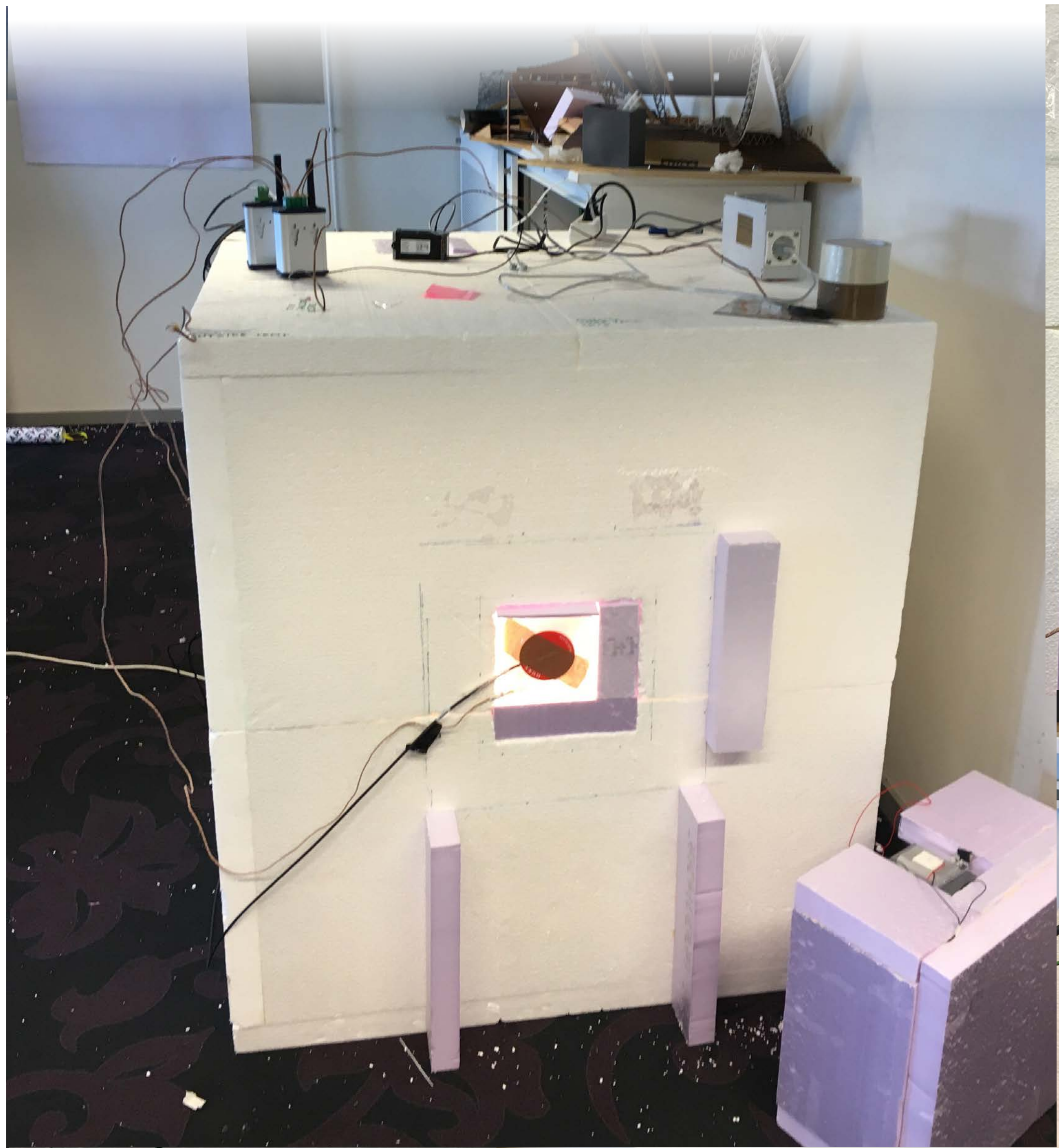
SP 21 / RUBITHERM	Column1
PROPERTIES	
Melting area °C	22-23
Congealing area °C	21-19
Heat storage capacity(kJ/kg)	180
Specific heat capacity (kJ/kg *K)	2
Density solid(kg/m^3)	1.5
Density liquid(kg/m^3)	1.4
Volume expansion(%)	3
Heat conductivity (W/ m*K)	0.6
Max. operation temperature °C	45
Heat stored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

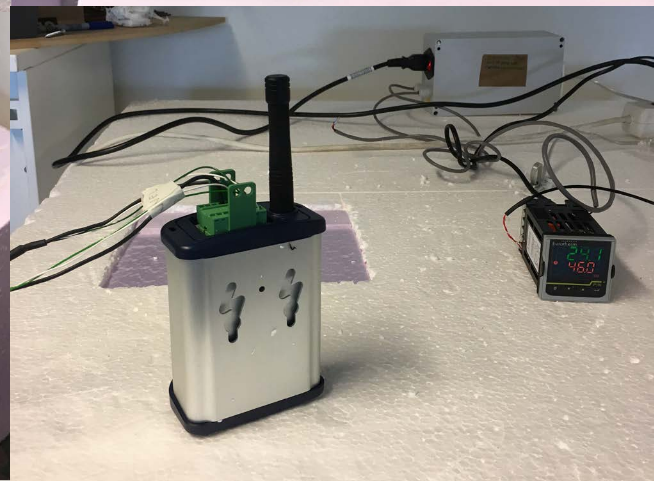
SP 31 / RUBITHERM	Column1
PROPERTIES	
Melting area °C	31-33
Congealing area °C	28-30
Heat storage capacity(kJ/kg)	210
Specific heat capacity (kJ/kg *K)	2
Density solid(kg/m^3)	1.35
Density liquid(kg/m^3)	1.3
Volume expansion(%)	3
Heat conductivity (W/ m*K)	0.8
Max. operation temperature °C	45
Heat stored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

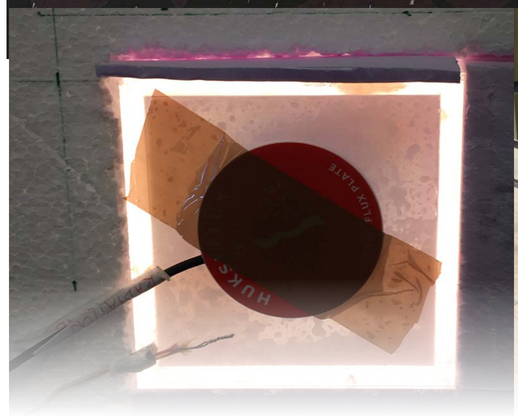


THE SET UP

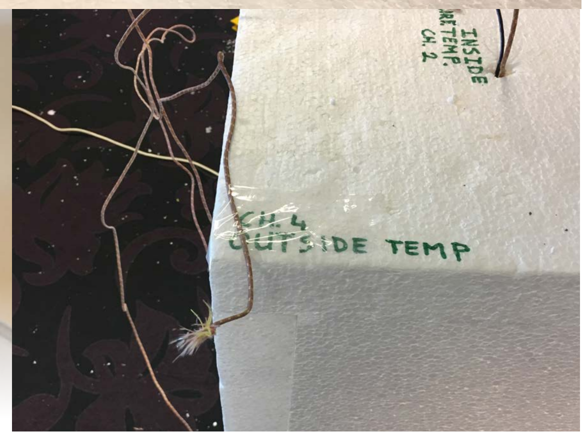


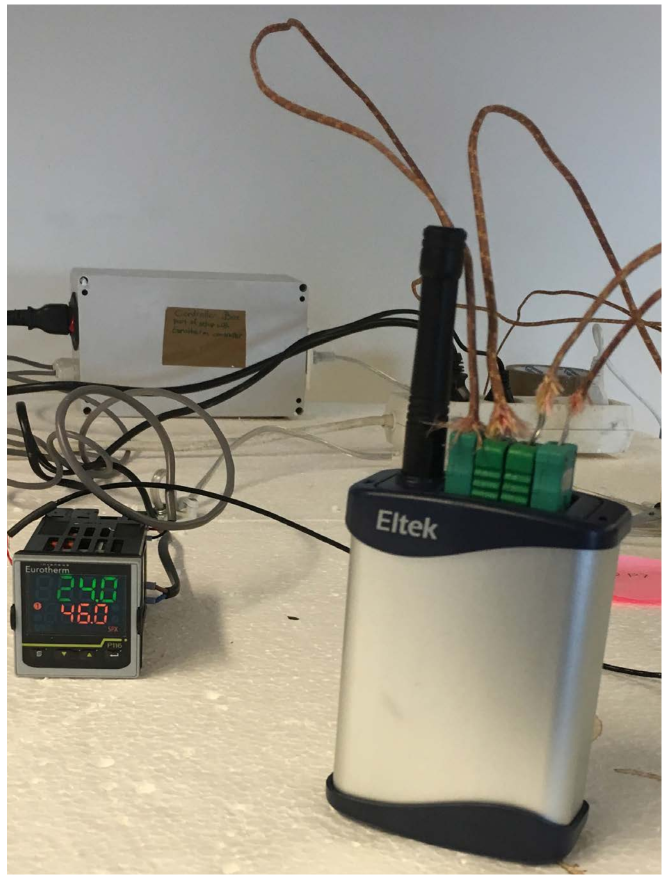

HUKSEFLUX
this side up
CE
HEAT FLUX PLATE





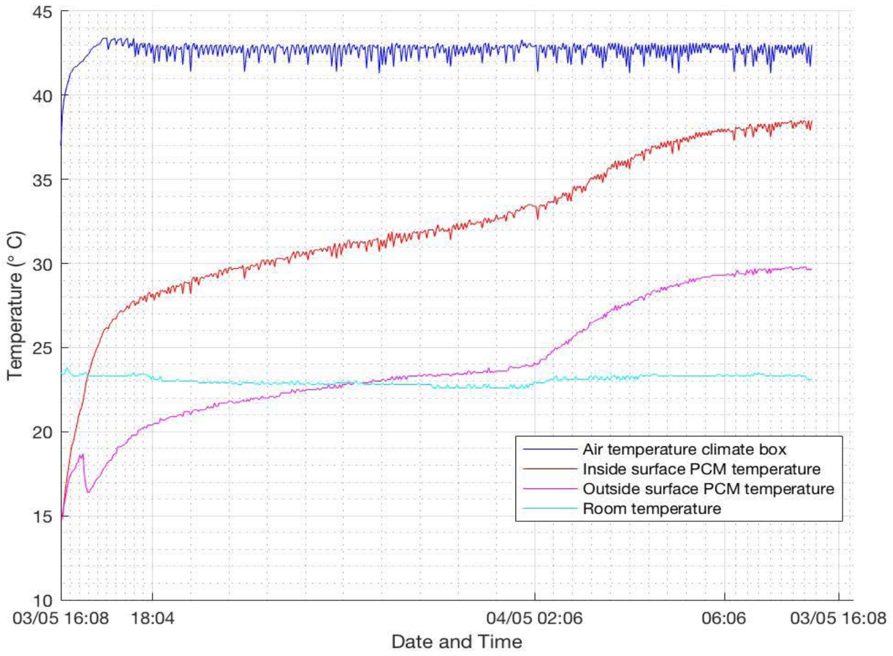

Controller Box
part of setup with
Eurotherm controller


INSIDE
CH. 2
CH. 4

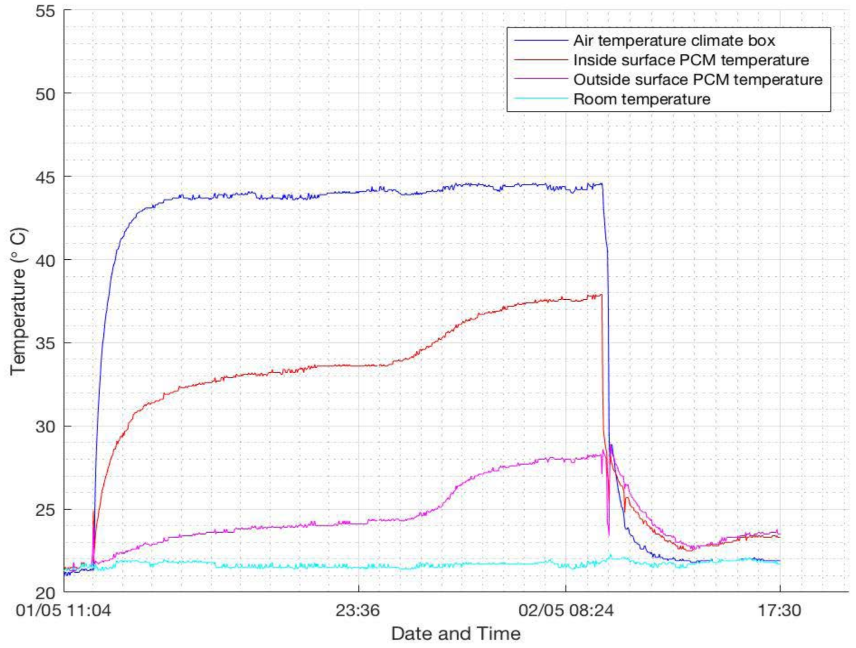

Eltek
24.0
46.0

TEMPERATURE MEASUREMENTS

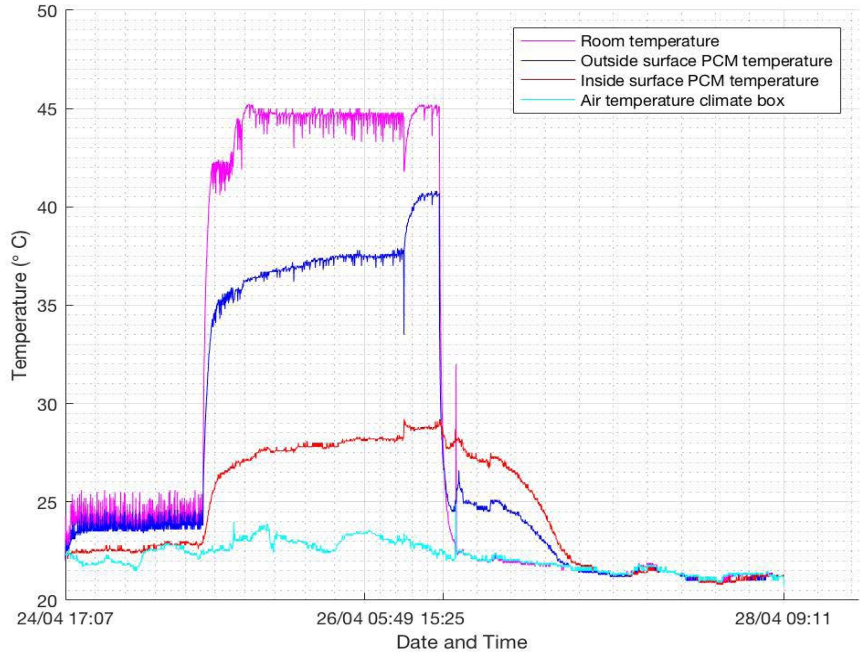
SAMPLE 1: PCM 21

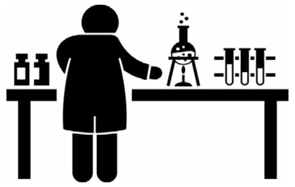


SAMPLE 2 : PCM 25



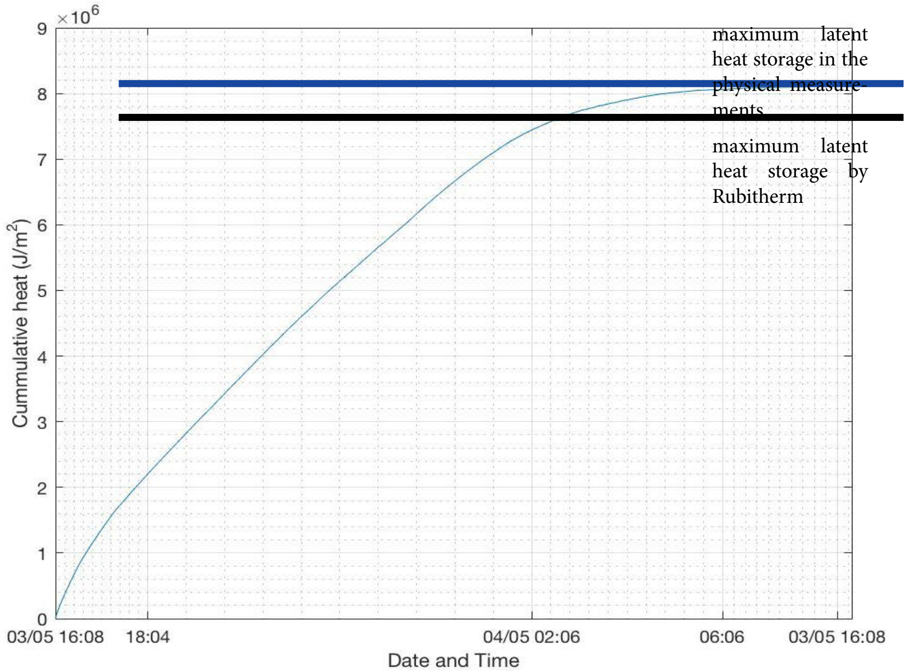
SAMPLE 3: PCM 31



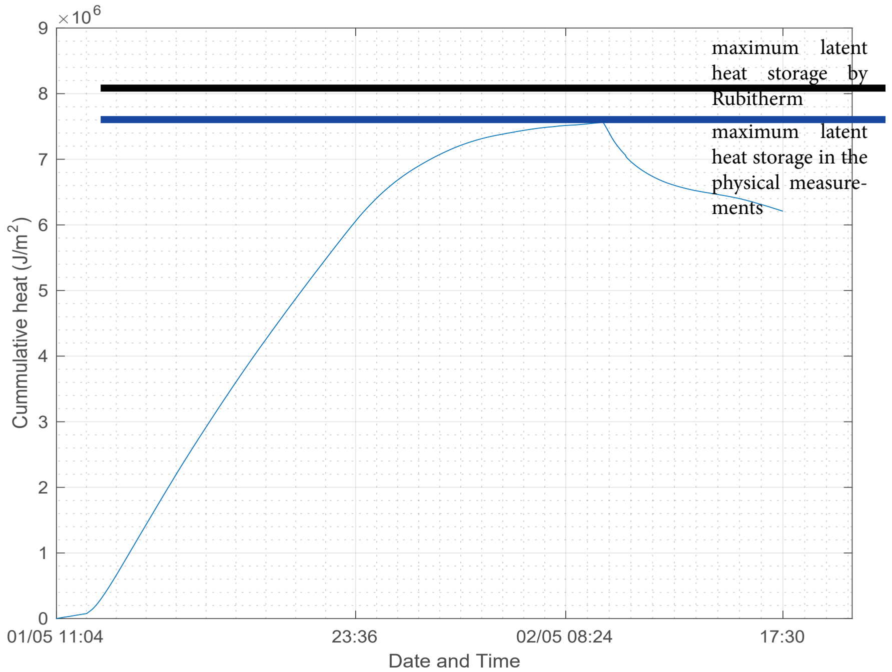


TOTAL HEAT STORED IN SAMPLES

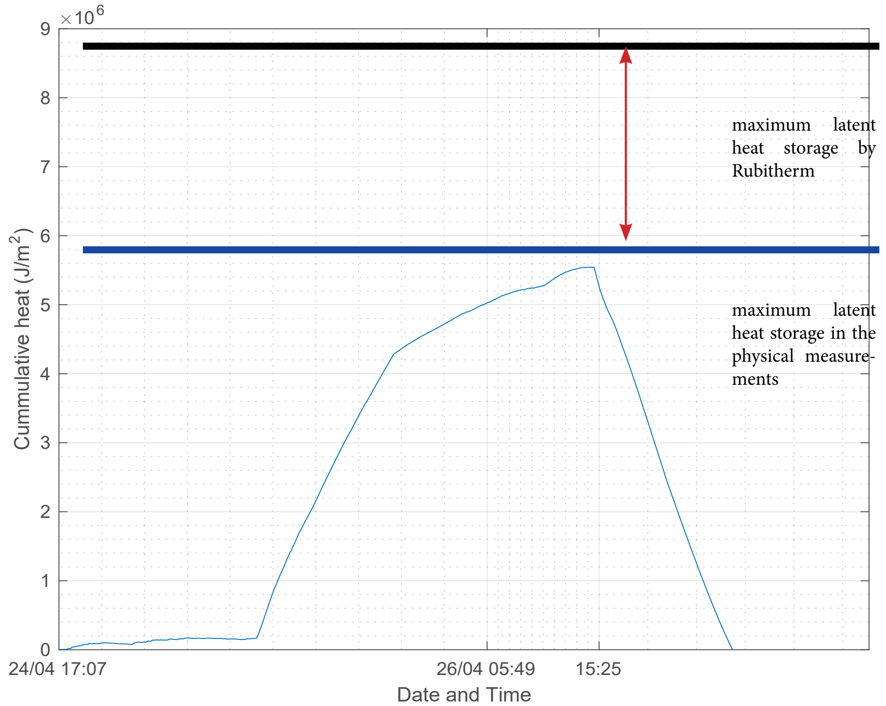
SAMPLE 1: PCM 21

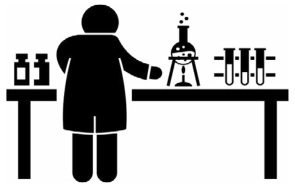


SAMPLE 2: PCM 25



SAMPLE 3: PCM 31

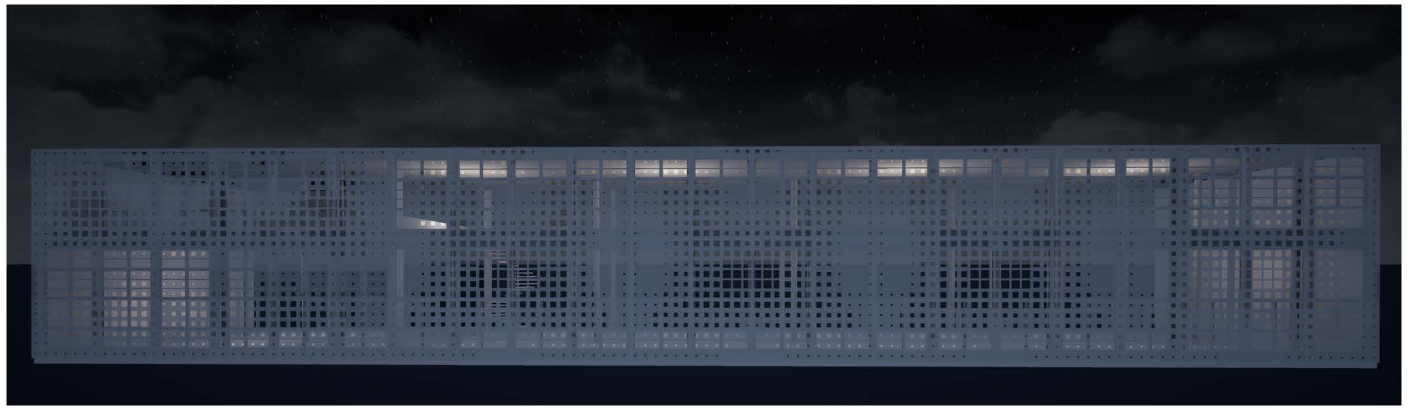




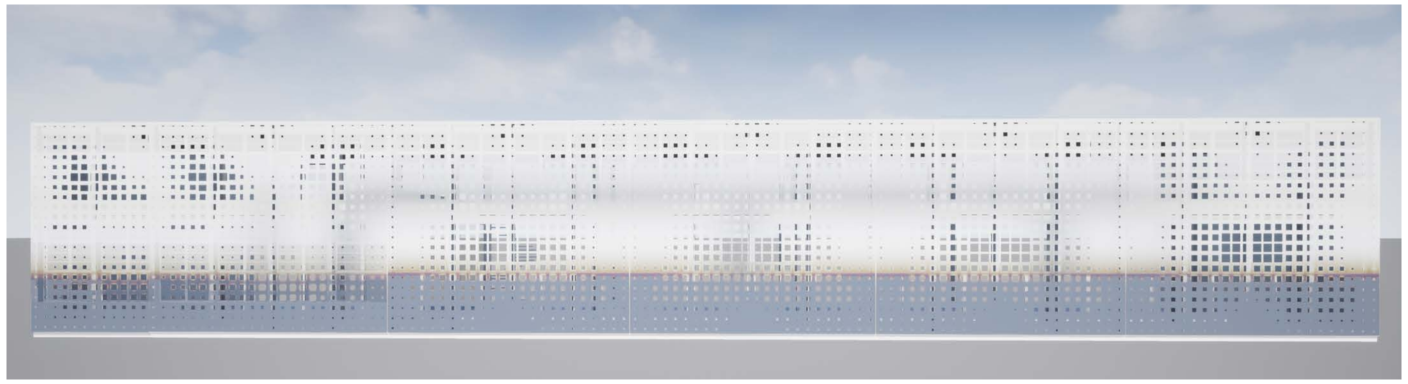
FACADE PERSPECTIVES

SUMMER DAY

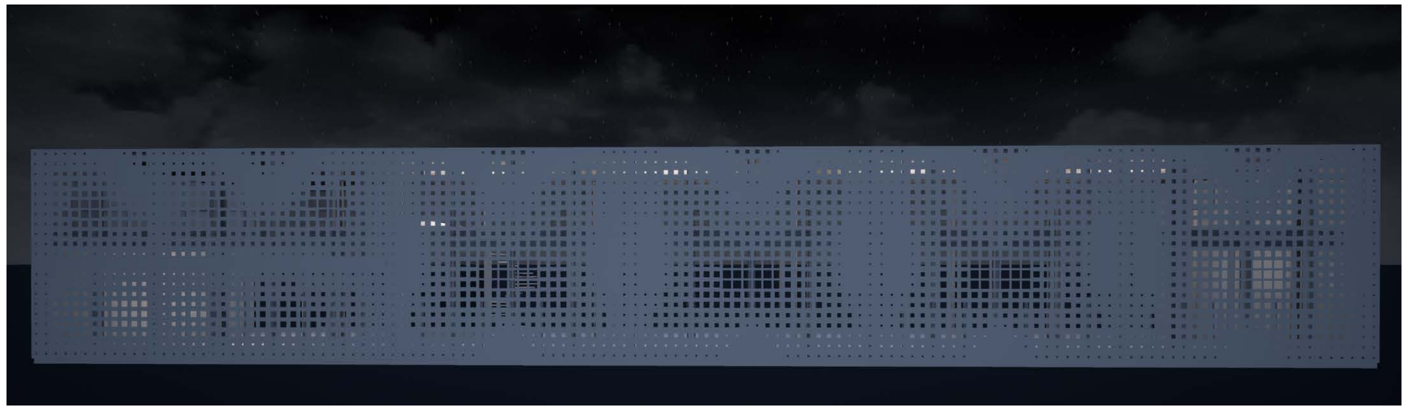
SUMMER NIGHT



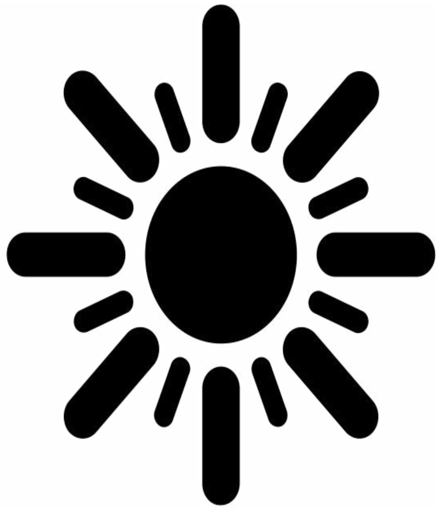
WINTER DAY



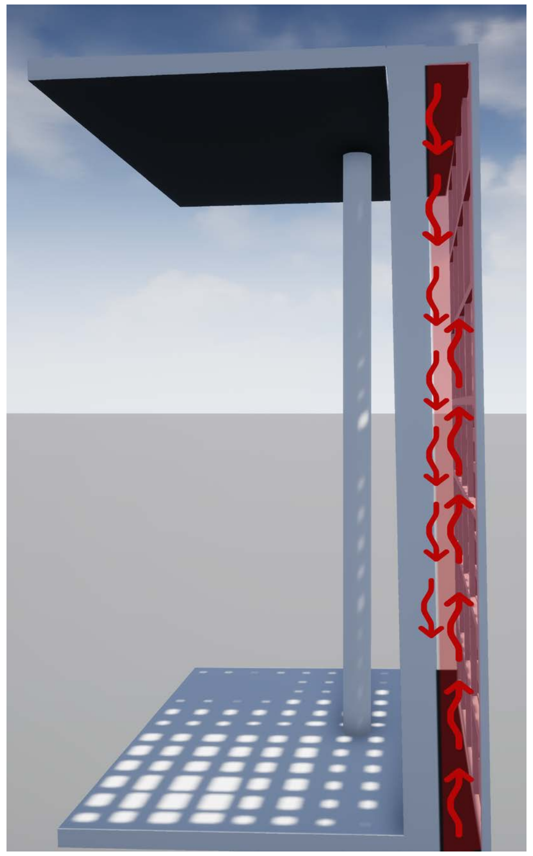
WINTER NIGHT

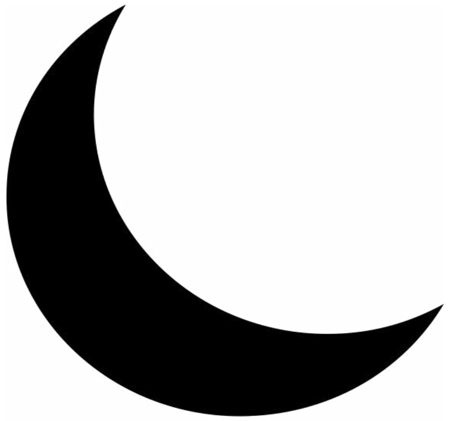


THE PERFORMANCE

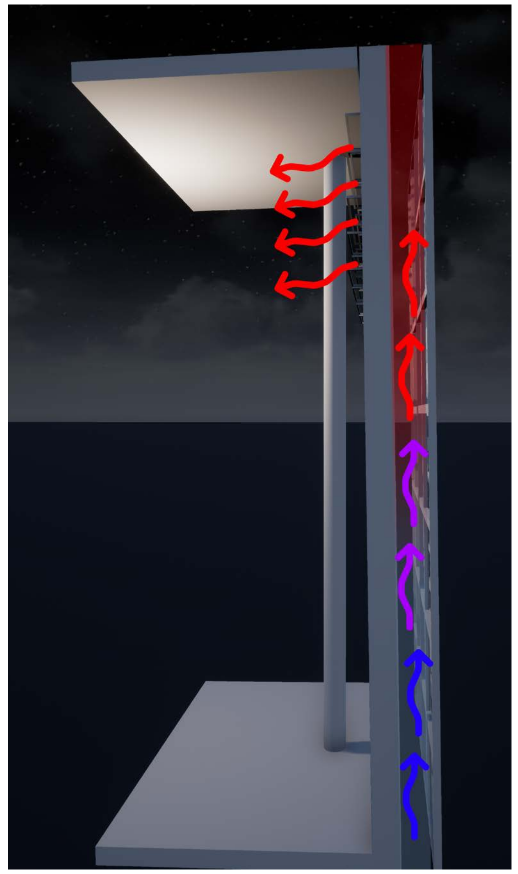


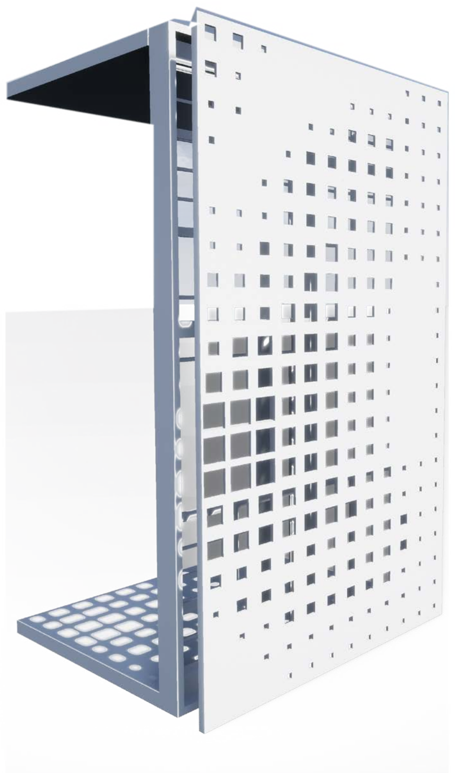
WINTER | DAY

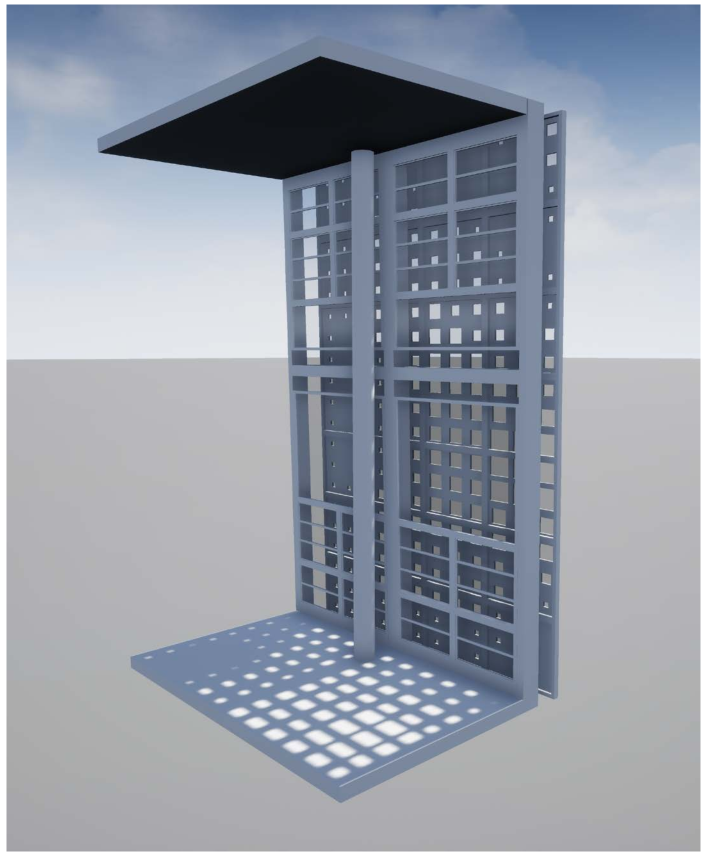


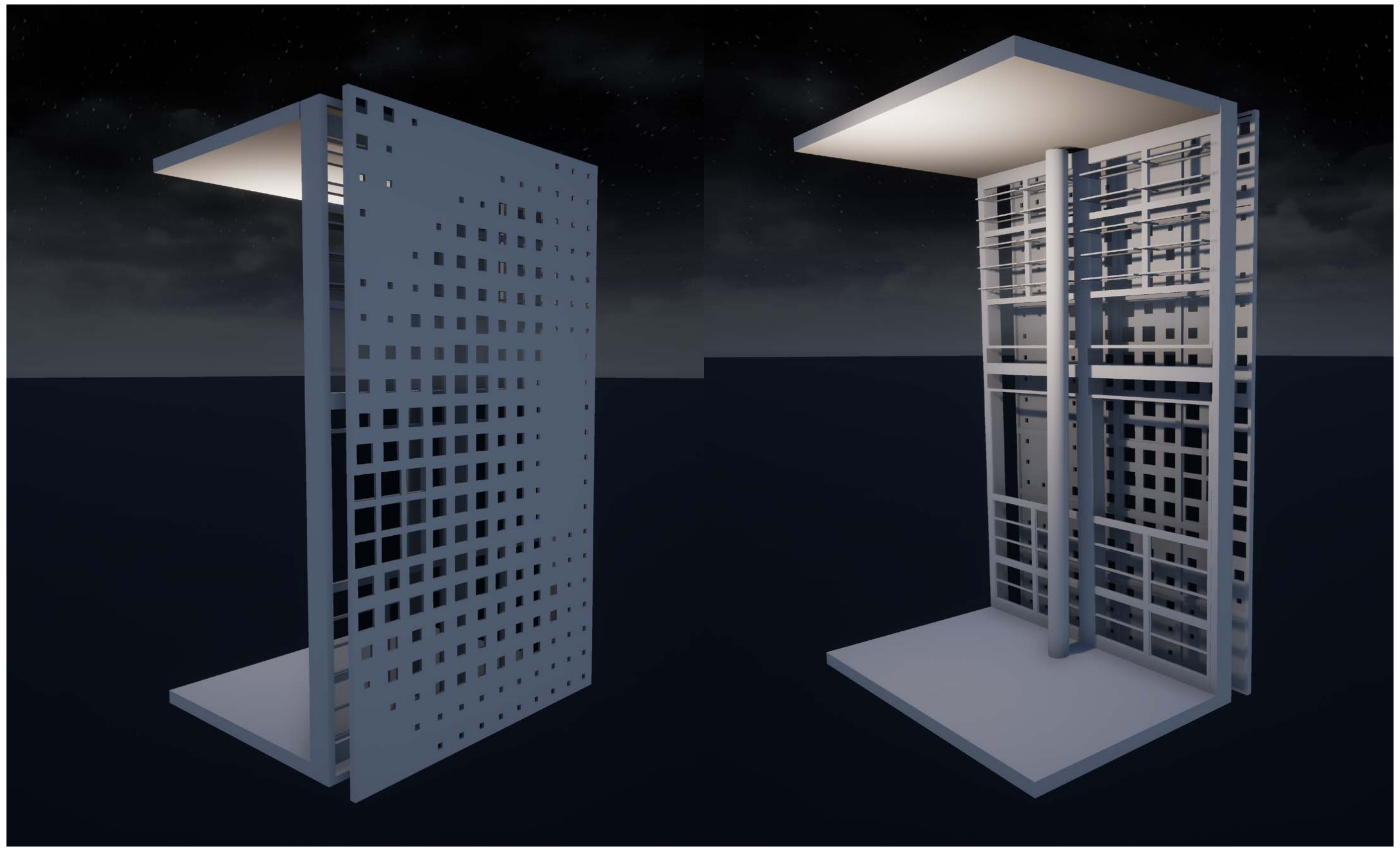


WINTER | NIGHT

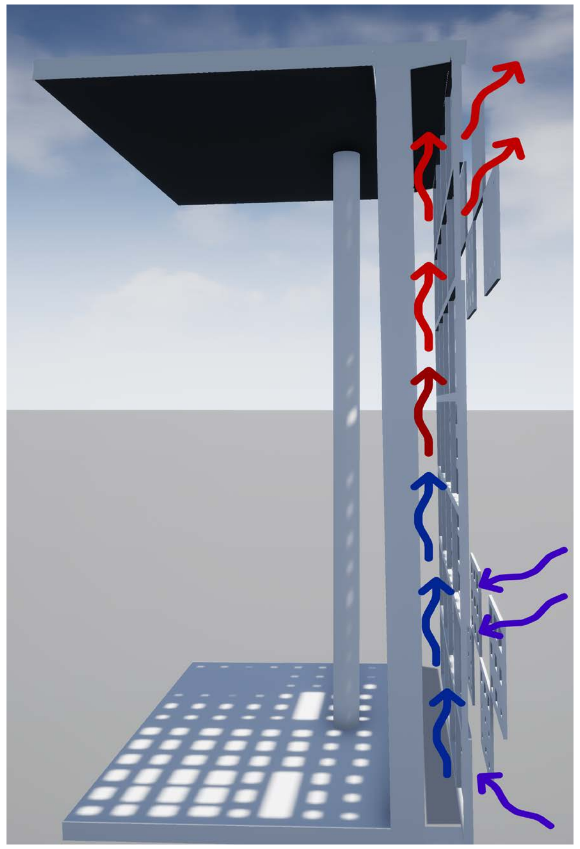




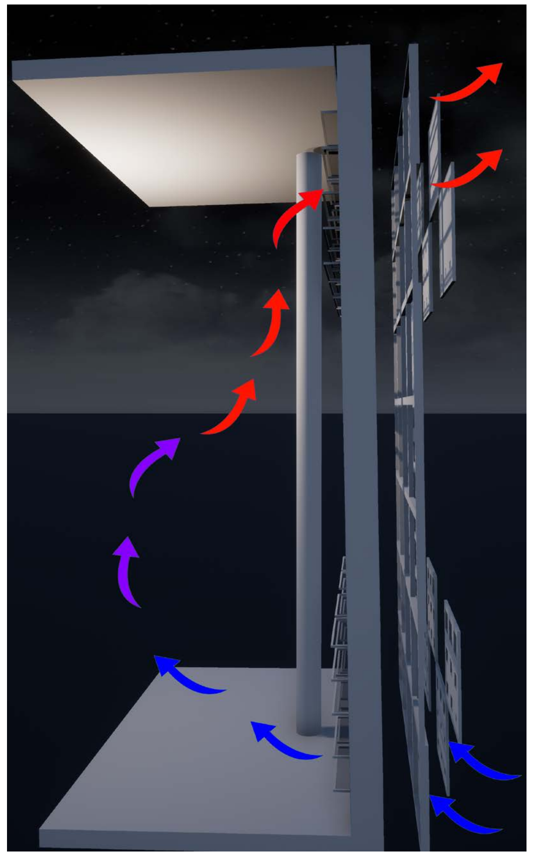


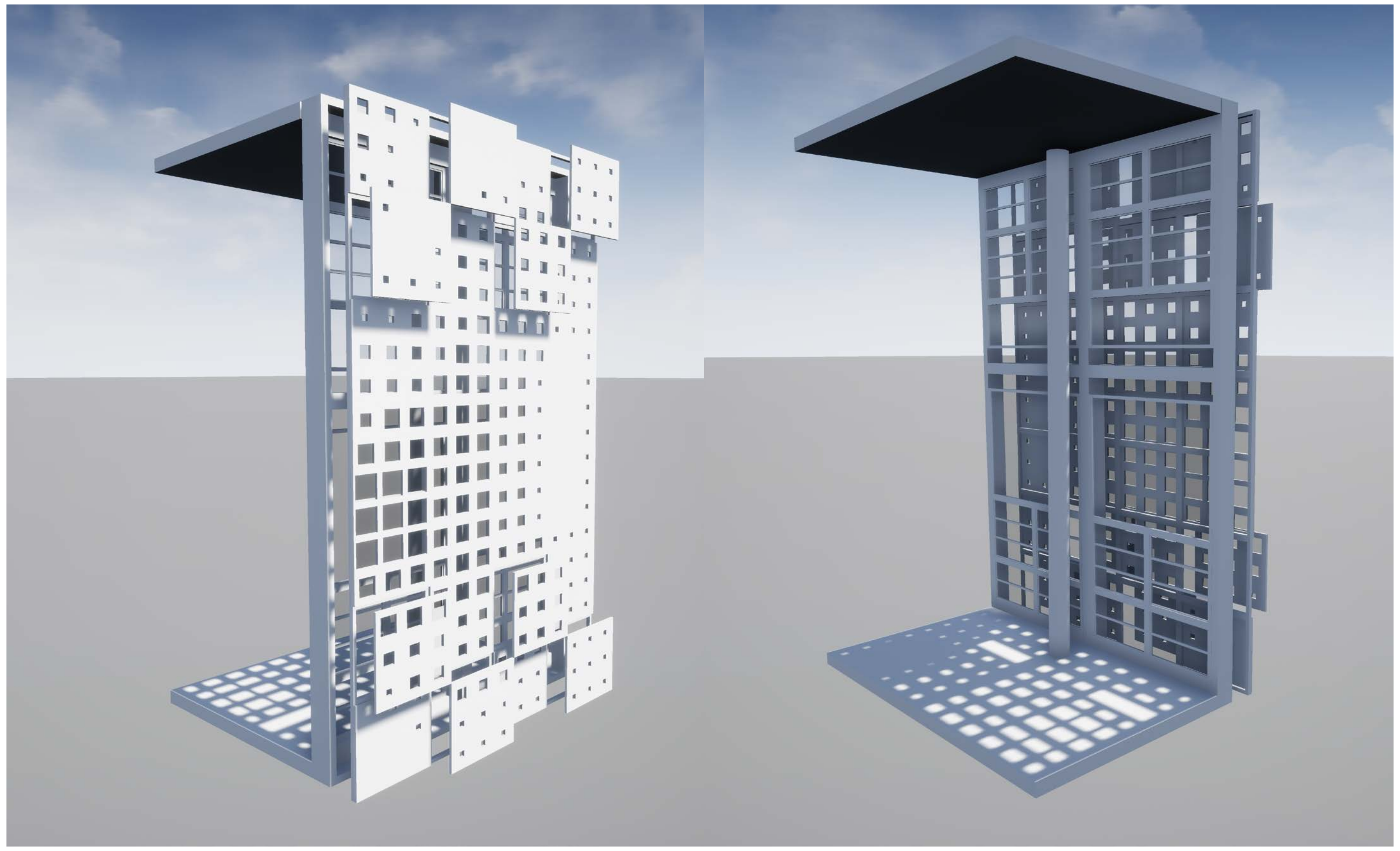


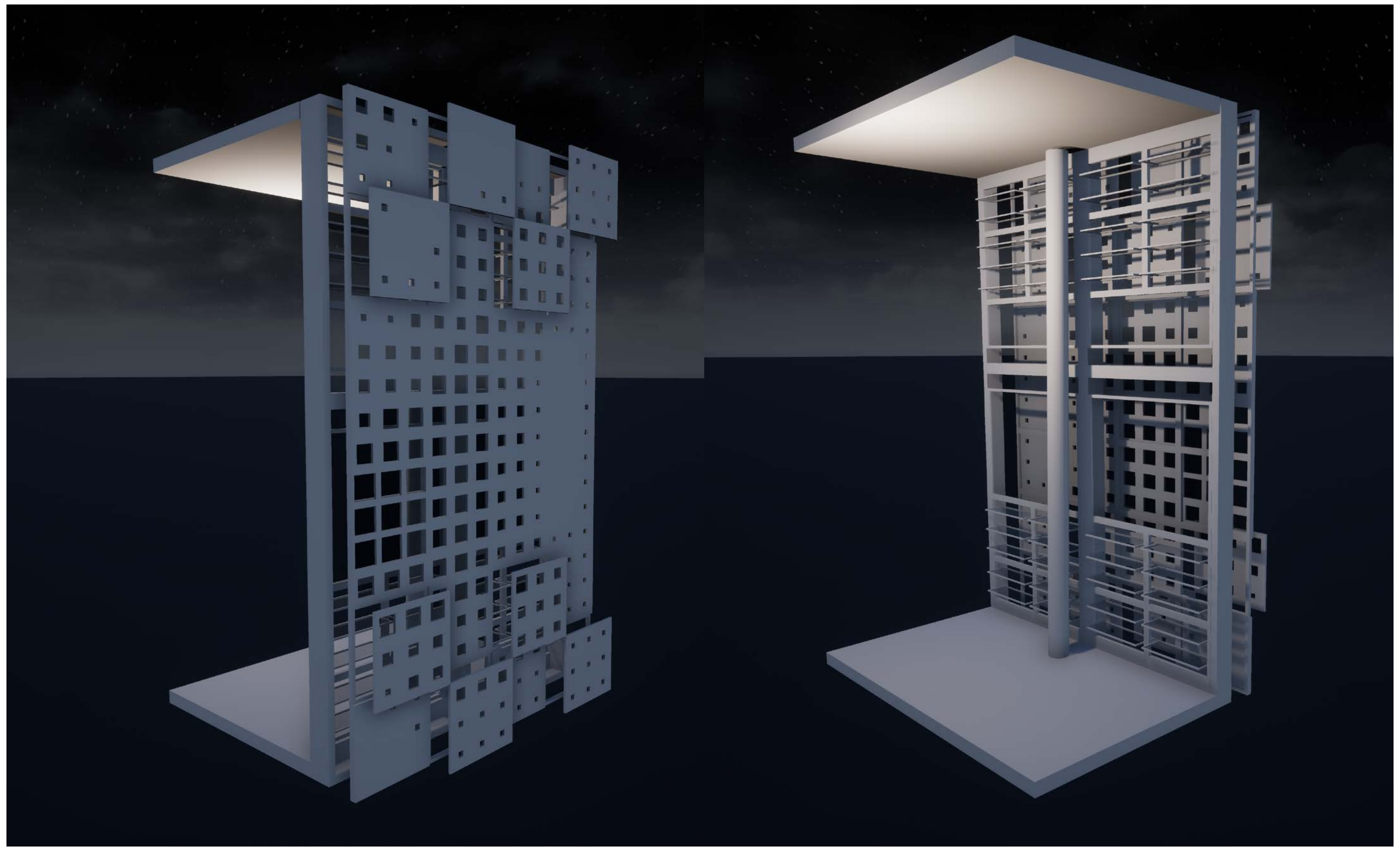
SUMMER|DAY



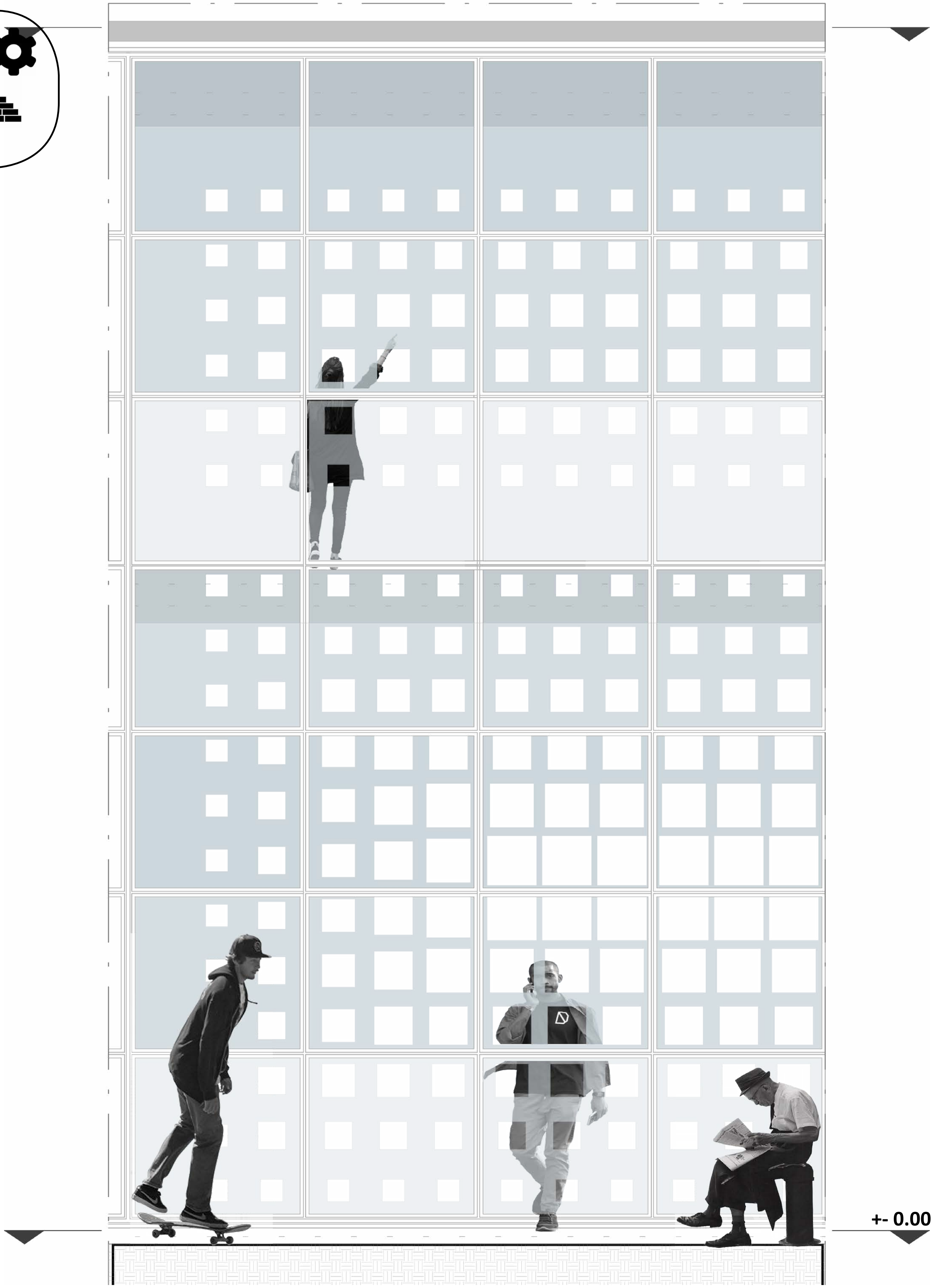
SUMMER|NIGHT







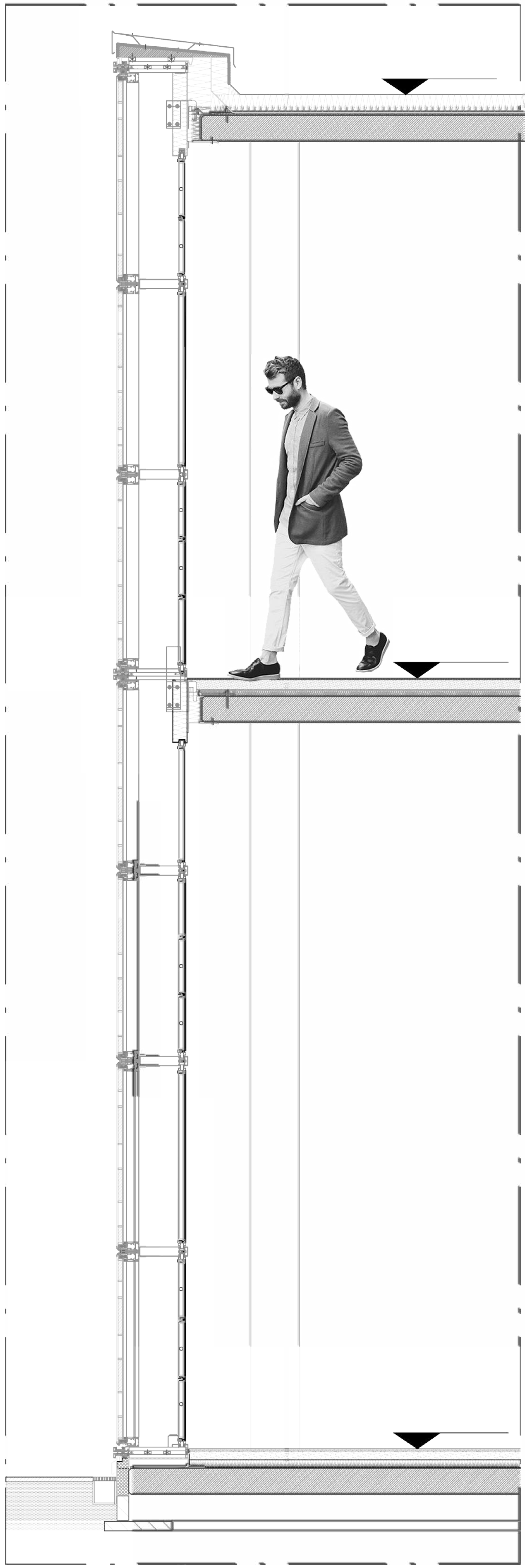
THE DESIGN

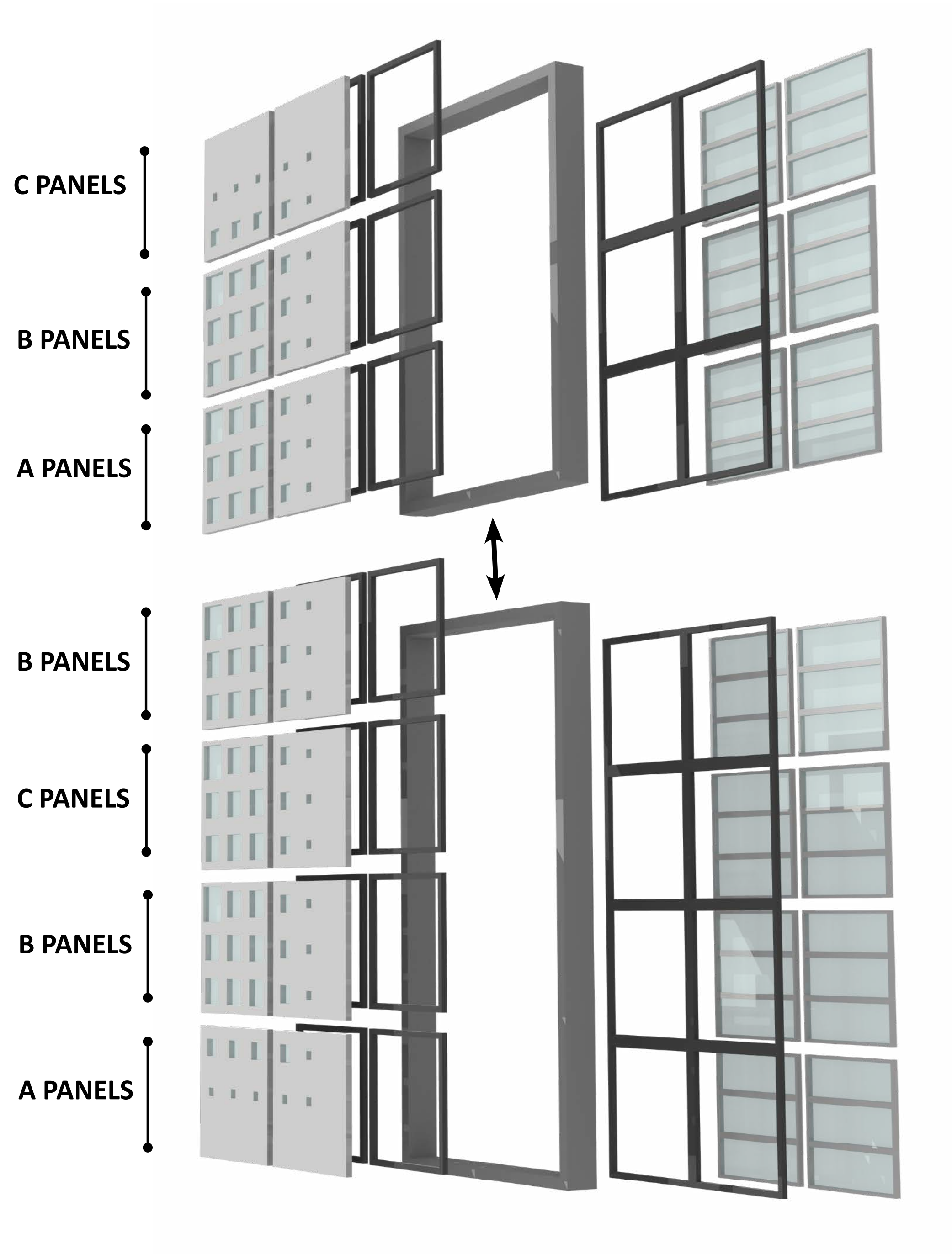


ELEVATION| SCALE: 1:50

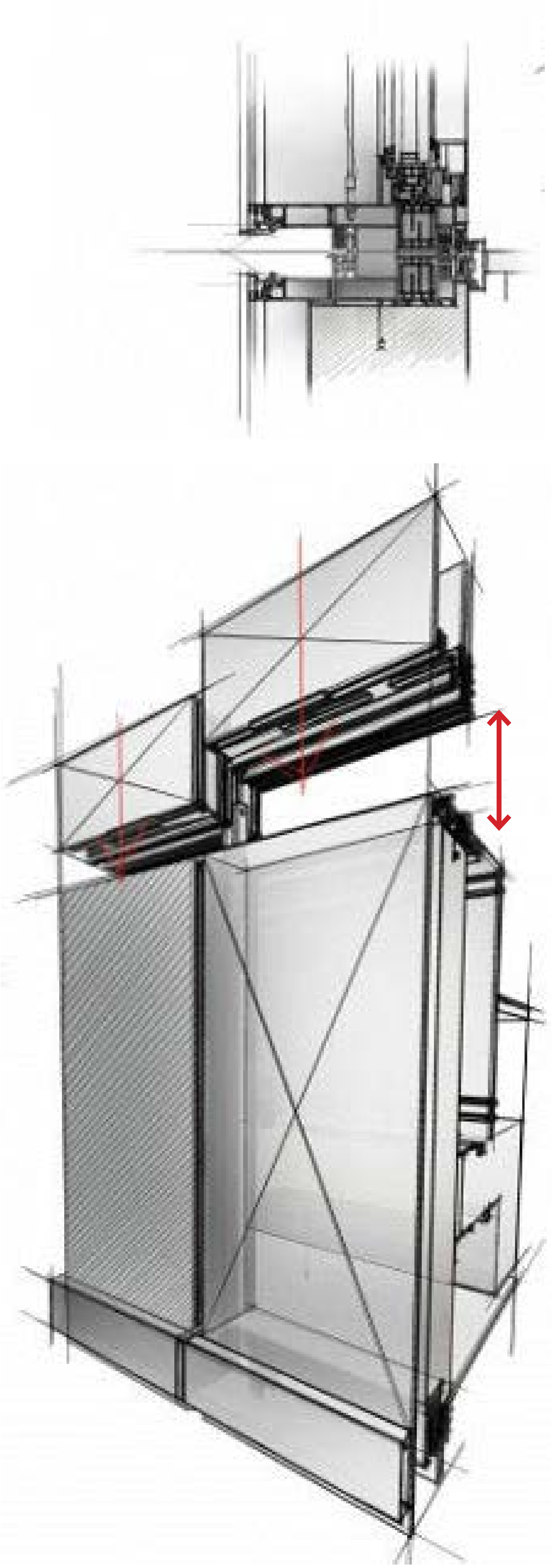
INNER ELEVATION| SCALE: 1:50

FACADE COMPONENTS

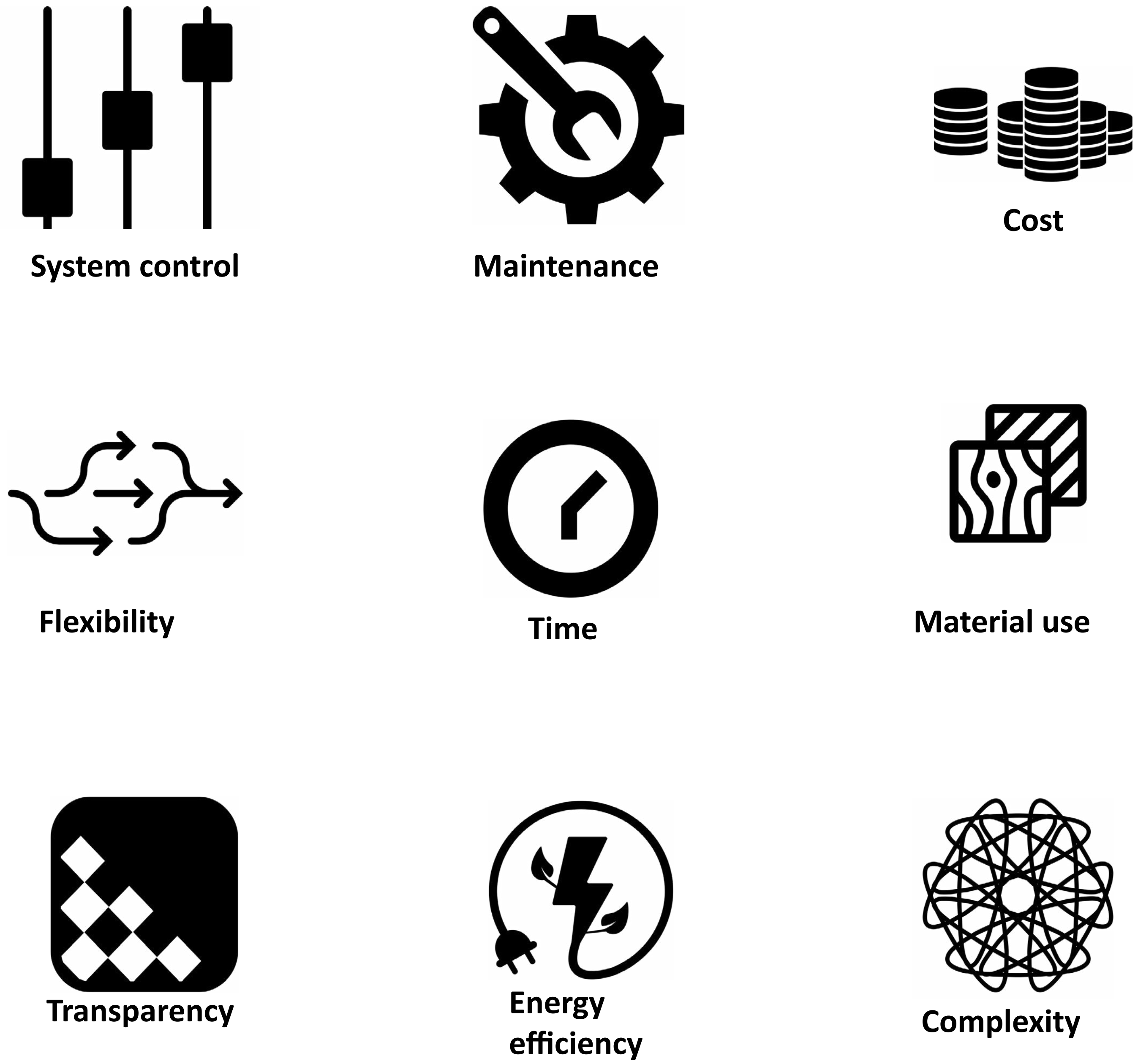




UNITIZED FACADE SYSTEM



FACADE ASPECTS



DESIGNER’S MANUAL

STEP 1

THE CHOICE OF PCM TYPE | FACADE LEVEL

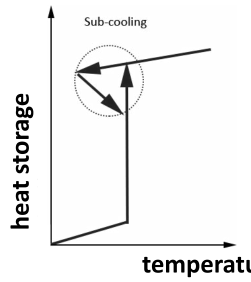
PARAFFINS OR SALT HYDRATES ?

Paraffins

- cost effective
- chemical stable
- flammable
- melting temperature range 20 -112 °C
- large volume alteration in the phase change
- prone to leakage

Salt hydrates

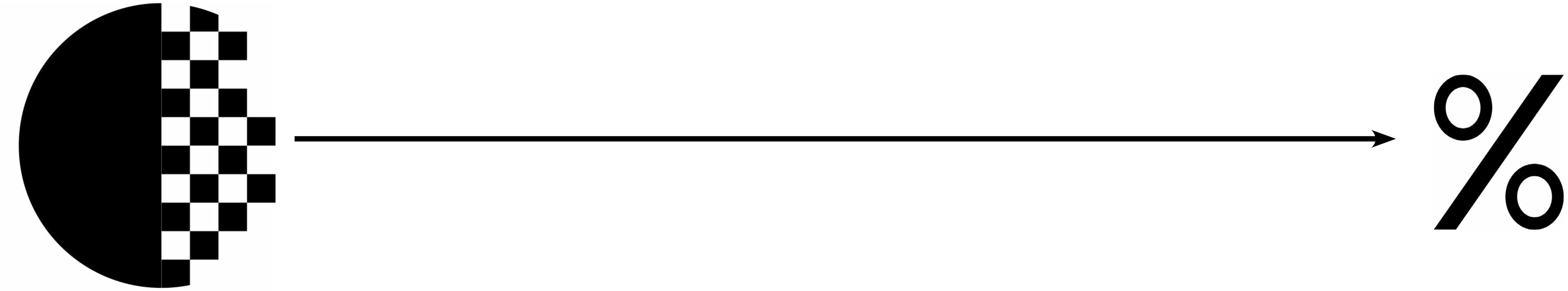
- cost effective
- thermal instability
- non- flammable
- melting temperature range 0-95 °C
- small volume alteration in the phase change
- prone to supercooling



ANSWER → SALT HYDRATES

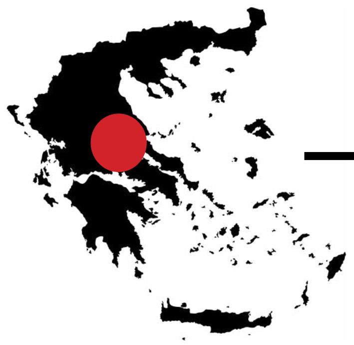
STEP 2

PCM TO GLAZING RATIO



GLAZING
PCM

A) ATHENS | MEDITERRANEAN CLIMATE



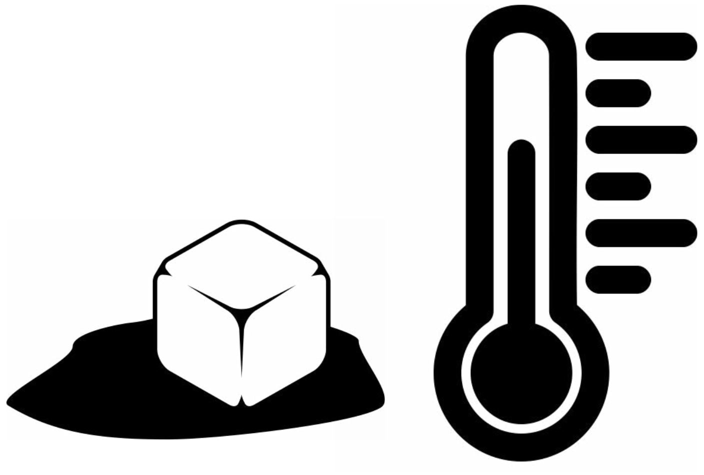
20% GLAZING
80% PCM

B) AMSTERDAM | TEMPERATE CLIMATE

30-40% GLAZING
70-60% PCM

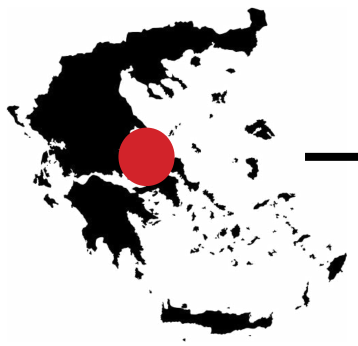
STEP 3

MELTING TEMPERATURE



^{0}C

A) ATHENS | MEDITERRANEAN CLIMATE



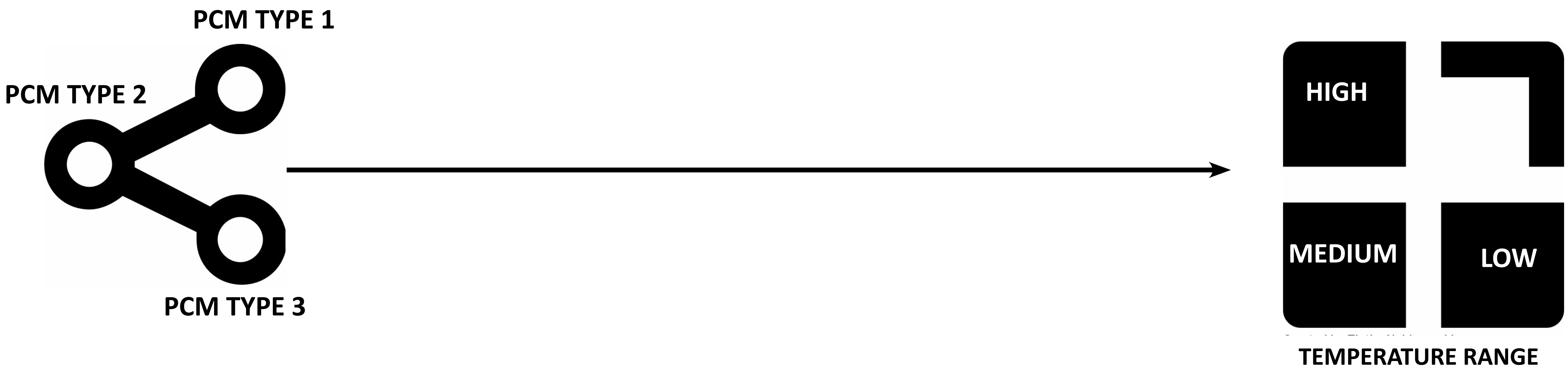
SP21 (21^{0}C)
SP25 (25^{0}C)

B) AMSTERDAM | TEMPERATE CLIMATE

SP21 (21^{0}C)

STEP 4

PCM COMBINATIONS

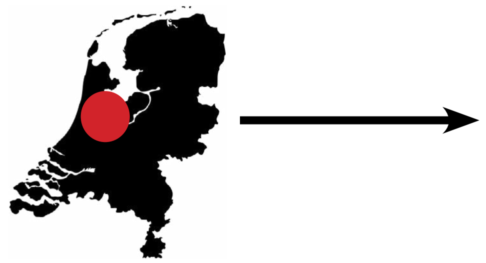


A) ATHENS | MEDITERRANEAN CLIMATE

SP21 - SP25 - SP29

SP21 - SP25 - SP31

B) AMSTERDAM | TEMPERATE CLIMATE

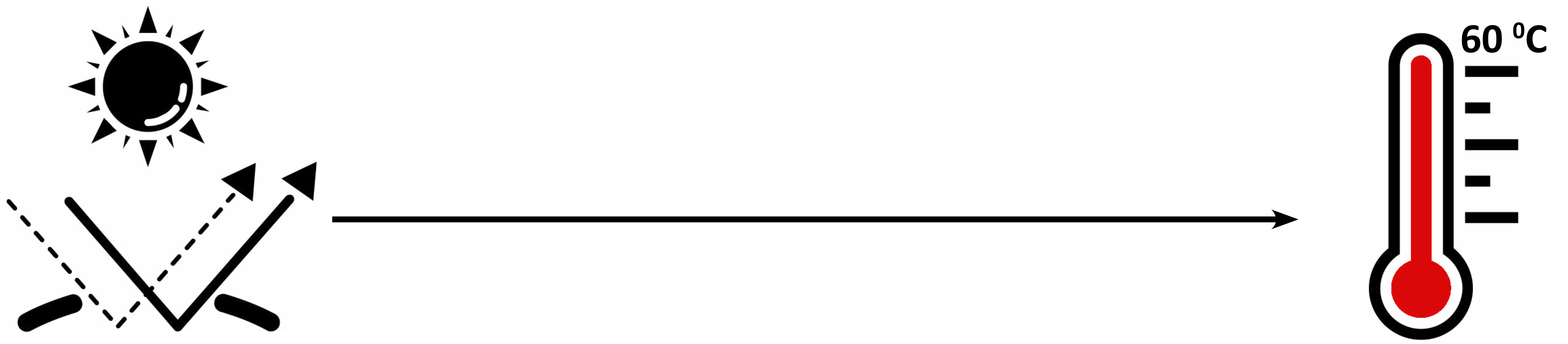


SP11 - SP21 - SP25

SP11 - SP21 - SP29

STEP 6

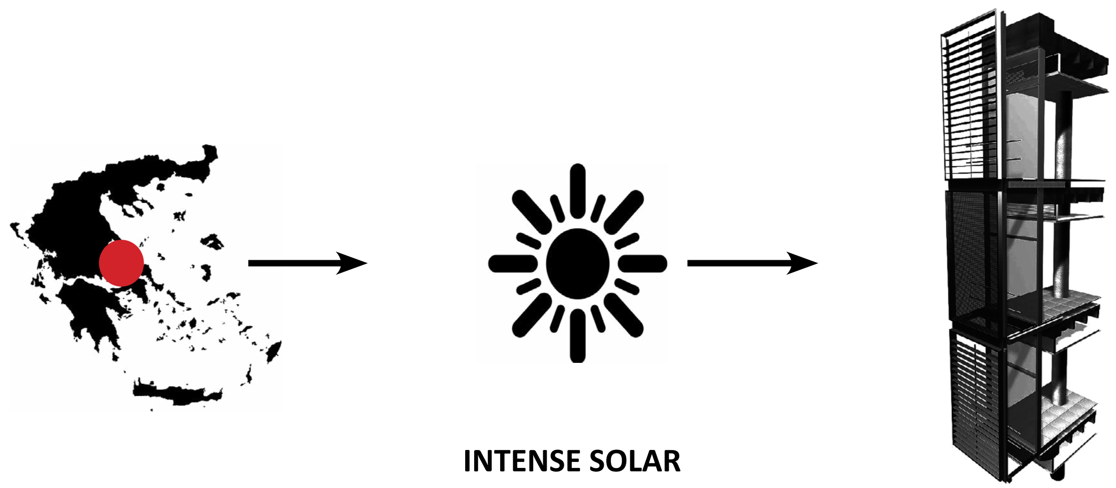
PCM PROTECTION



SUN PROTECTION

MAXIMUM OPERATIVE TEMPERATURE

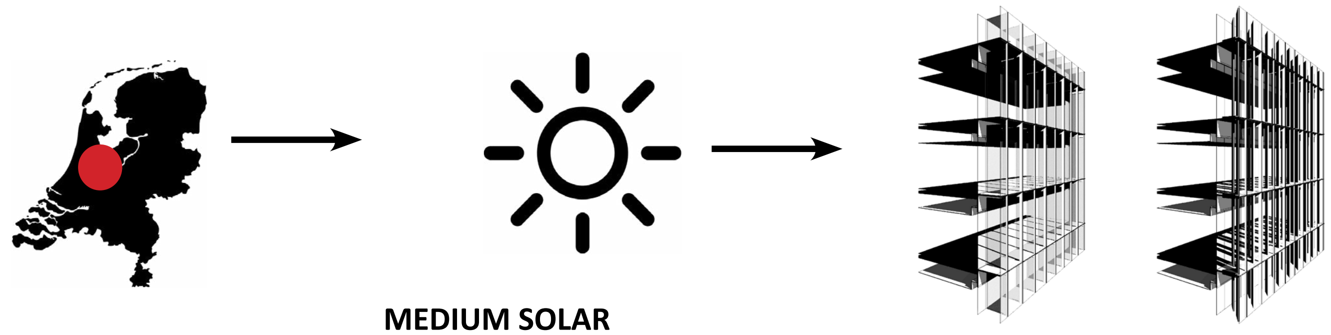
A) ATHENS | MEDITERRANEAN CLIMATE



INTENSE SOLAR IRRADIATION

INTEGRATED SHADING SYSTEM

B) AMSTERDAM | TEMPERATE CLIMATE

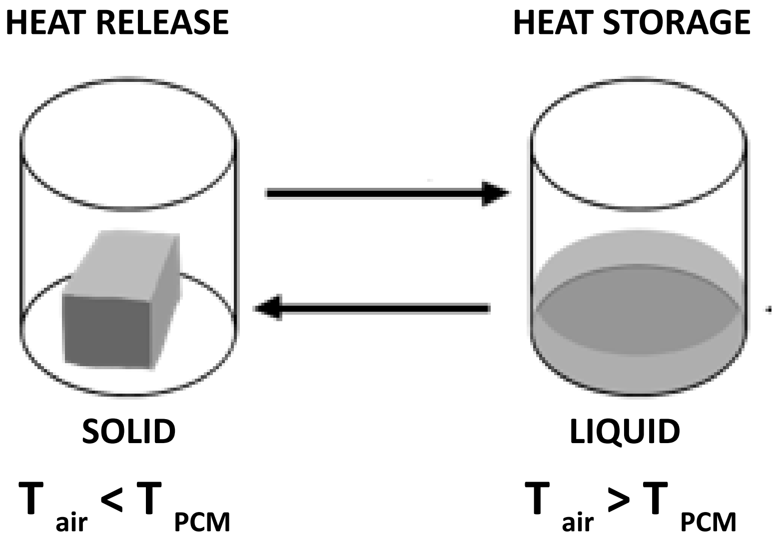


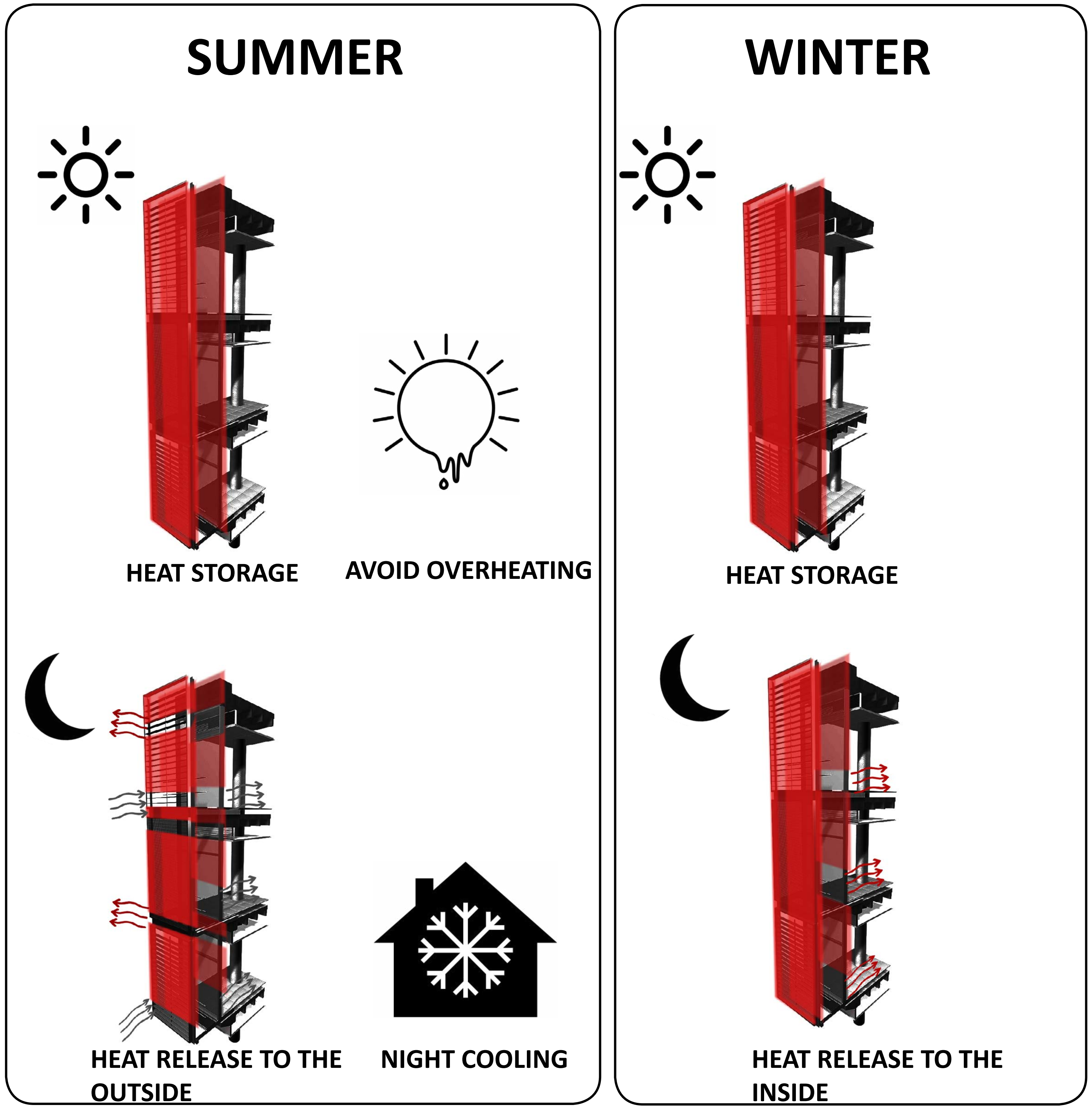
MEDIUM SOLAR IRRADIATION

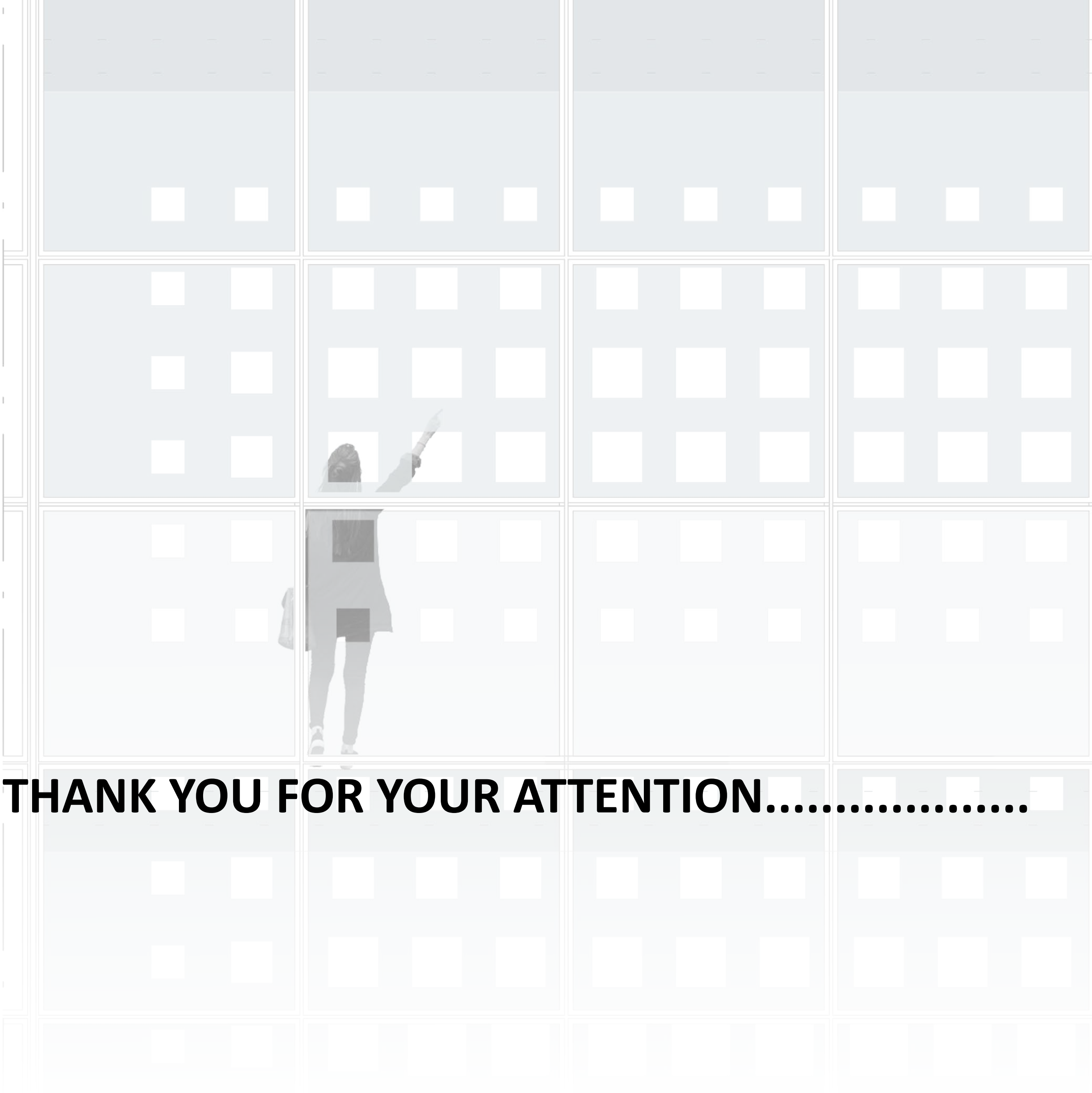
ADAPTIVE SHADING SYSTEM

STEP 7

RESPONSIVENESS







THANK YOU FOR YOUR ATTENTION………………..