Solar Shape

Morphing Memory

Kinetic Envelope

Integration of thermo-responsive Shape Memory Alloys in an autoreactive facade system to reduce the building's impact on the Urban Heat Island effect in the Mediterranean climate (case study: Athens, Greece)

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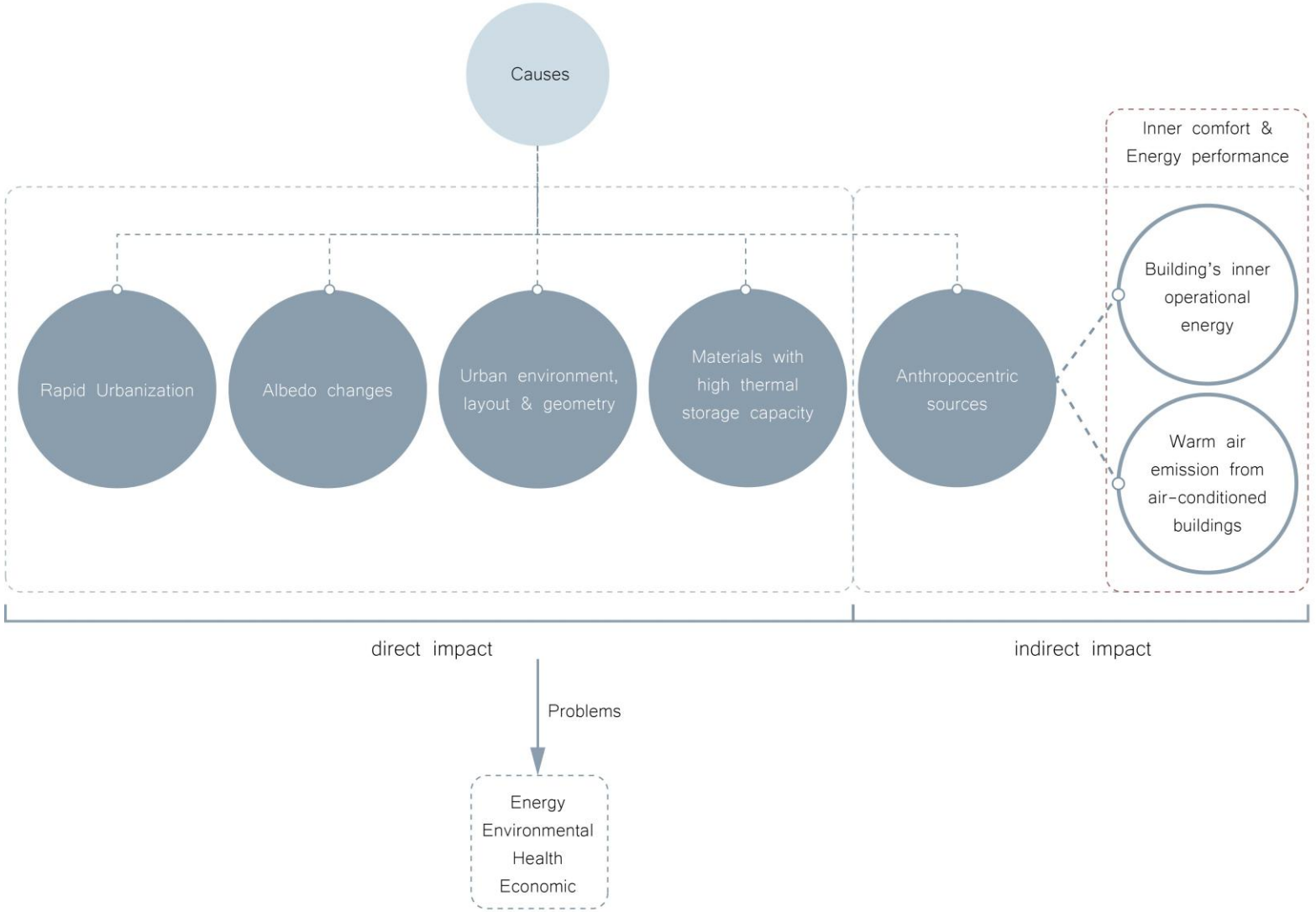
Track: Building Technology

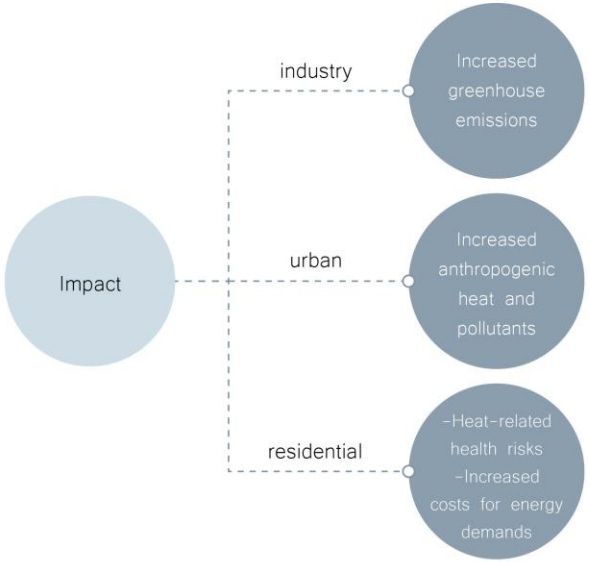
P5 Presentation - 21.06.2021

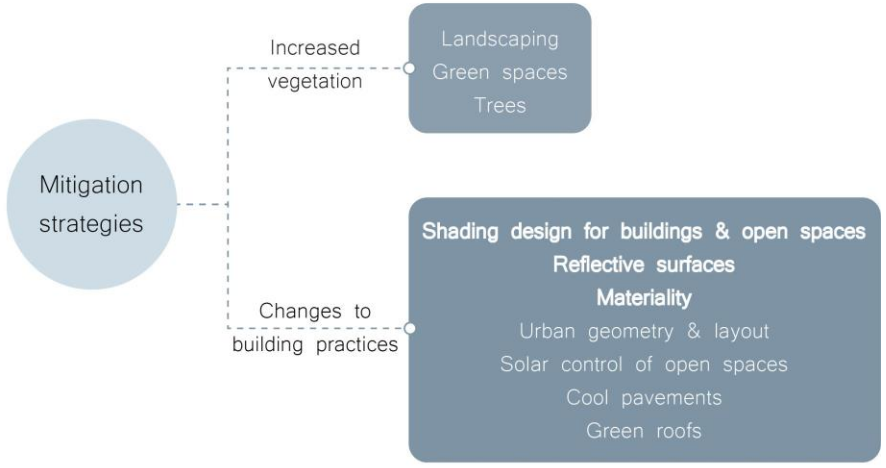
Research Question

"How can **thermo-responsive Shape Memory Materials** be integrated in an **autoreactive facade system** to reduce the building's impact on the **Urban Heat Island effect** in the **Mediterranean climate**, with a focus on the case study of Athens, Greece?"

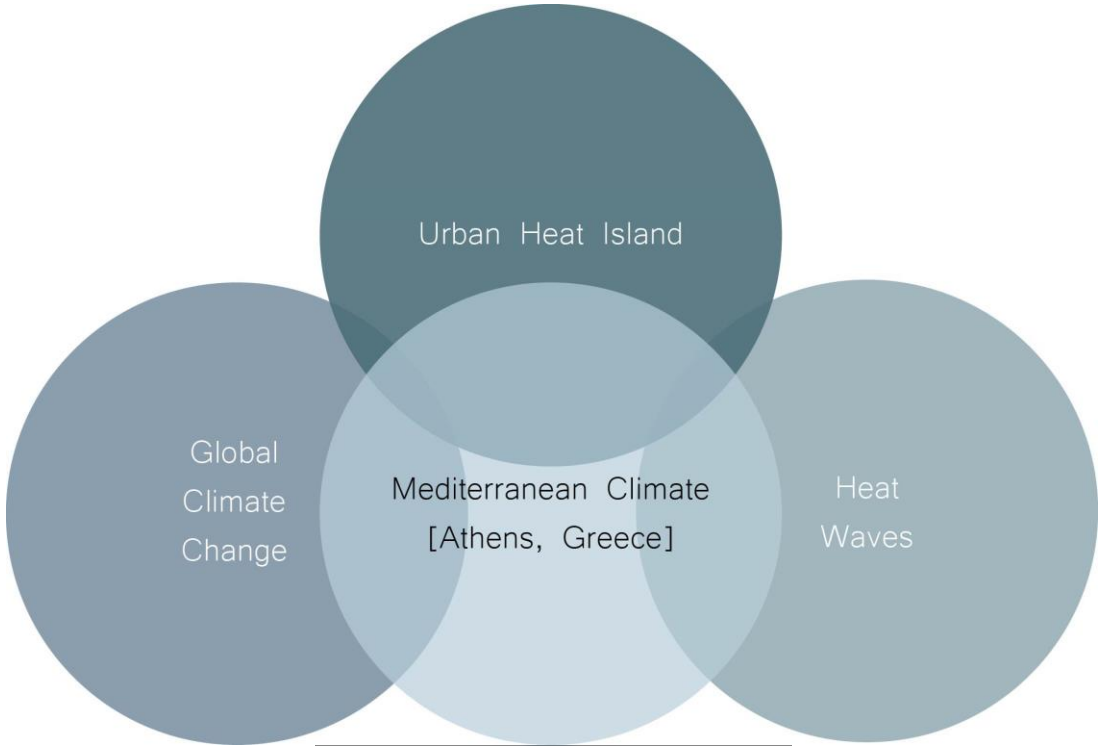
Problem Statement – Urban Heat Island (UHI) effect





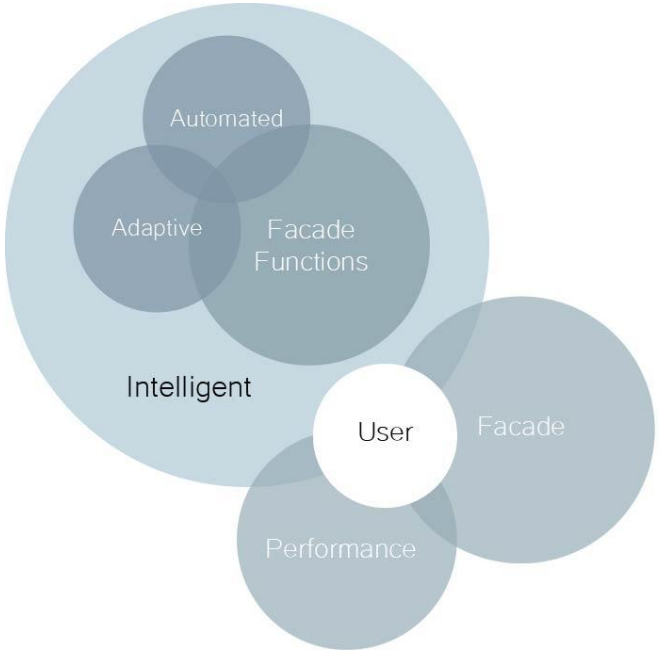


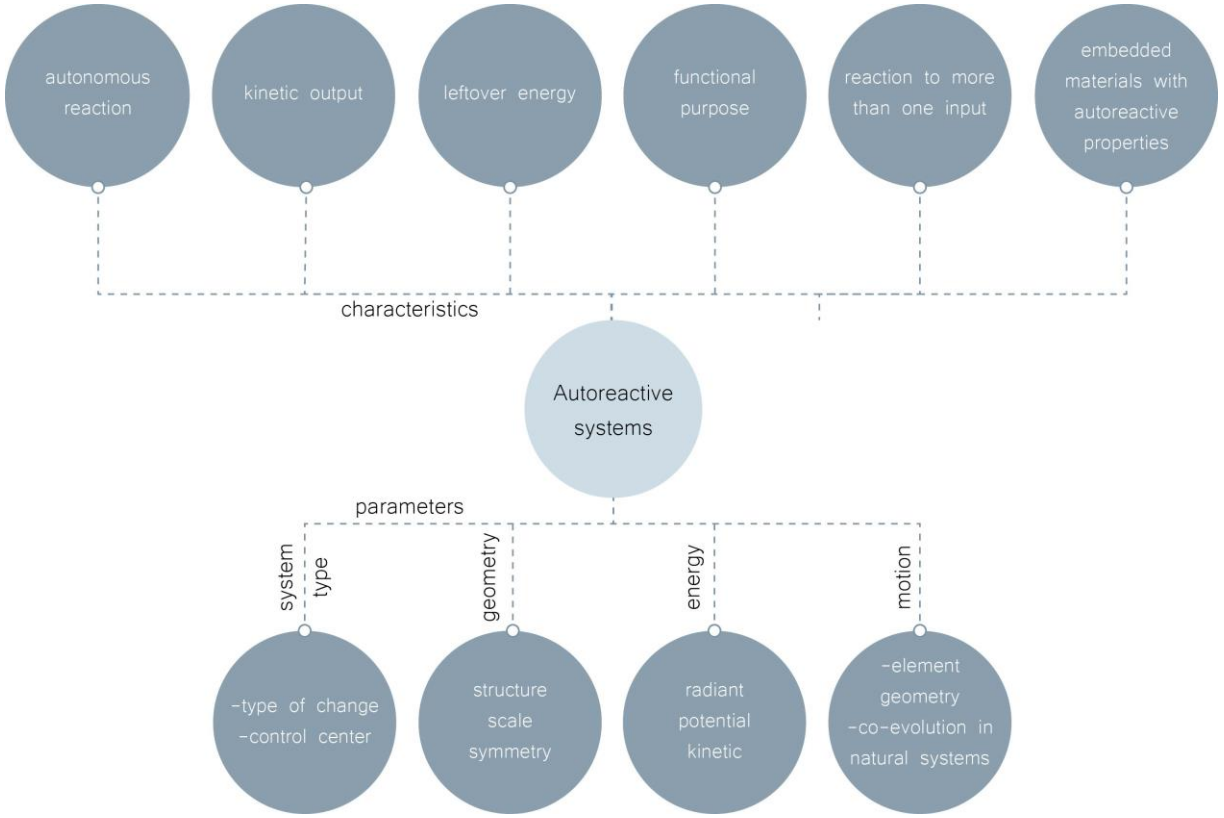
Climatic context – Mediterranean climate (Athens case study)



Dynamic adaptive façades – Autoreactive systems

- Real-time climatic responsiveness
  - dynamic anisotropy: a change in structure modulates the environmental flows according to the climatic conditions
- Able to:
  - adapt physical properties in a reversible way as a response to boundary conditions at different times of the day
  - manage energy flows by altering the properties of fixed devices or by controlling moving parts
  - achieve the three performance requirements: environmental impact neutralization, energy saving and occupant's satisfaction

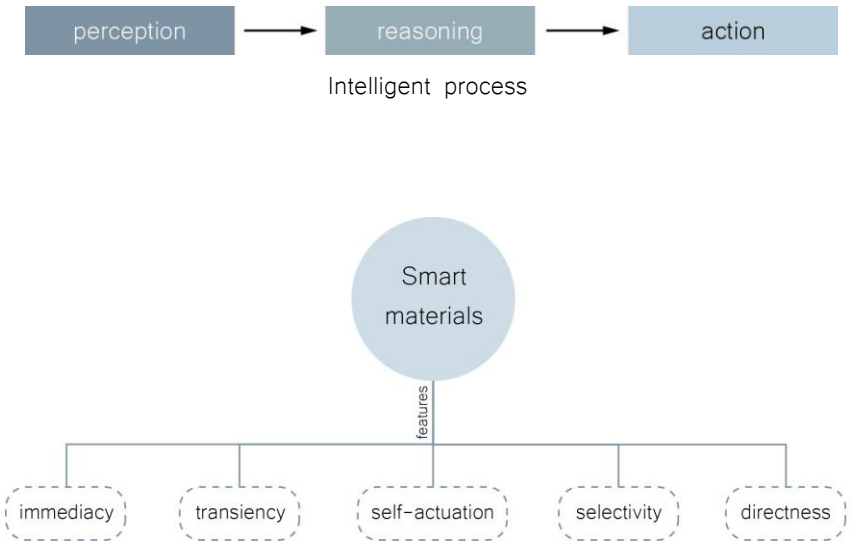




Autoreactive materials – Thermo-responsive Shape Memory Materials

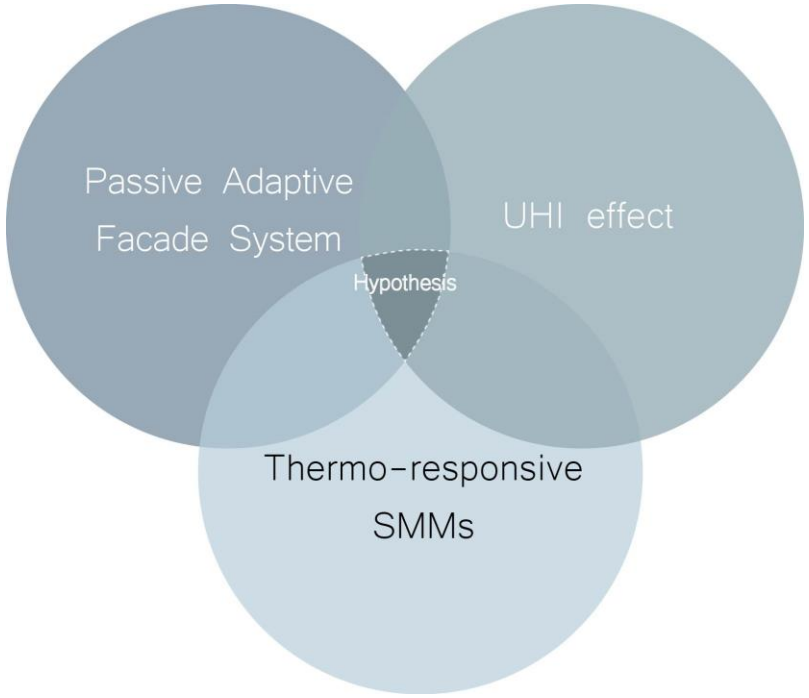
- **High integration** and **reduced complexity** of mechanical parts
- **"material as the machine":** combination of sensing, actuation and mechanical functions
- **Passive, low-energy** actuation systems
- **Designed materials** with properties that can be changed in a controlled way

- Able to:
  - **respond to environmental changes** at the most optimum conditions
  - **adapt their own functions** according to the changes
  - **revert to their original states** once the stimulus is removed



“SMM façade integration – UHI effect” hypothesis

“*whether*, *how* and *to what extent* the implementation of SMMs in an integrated passive adaptive solar morphing system can contribute to the reduction of the building’s impact on the UHI effect in an energy-efficient and autoreactive way”



Bio-inspired design approach - Nature's response strategies and principles for climatic adaptiveness

- **Autoreactive systems:**

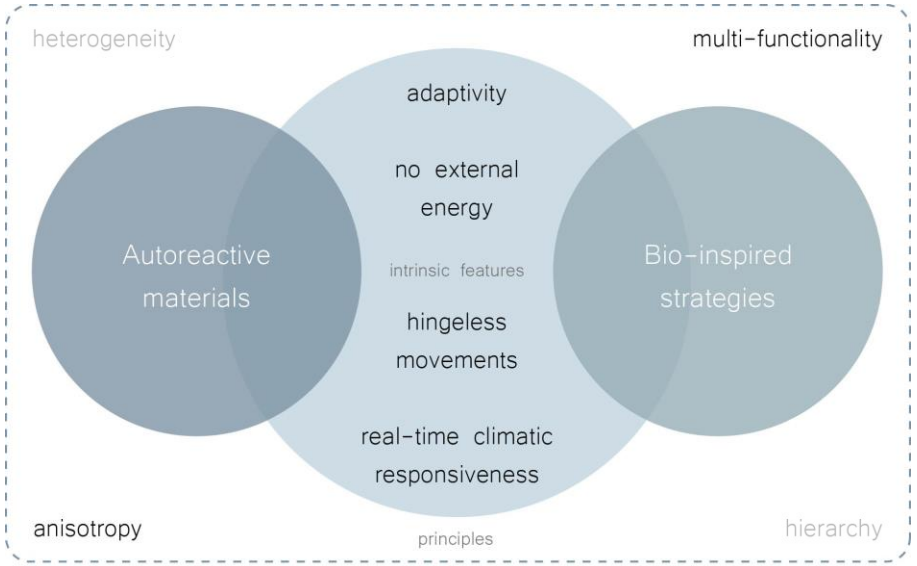
  material systems with intelligence and life features integrated in the microstructure to reduce mass and energy with adaptive functionality

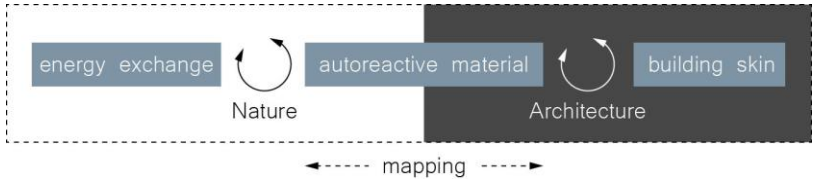
→ **minor complexity, low weight, high functional density, economic efficiency**

- **Biological systems:**

  design and development of natural organisms in an integrated process: multiple component functions

→ **efficiency, functionality, precision, self-repair, durability, adaptability**





Façade Design Integration

Autoreactive System

“a system using latent energy from its surrounding environment to achieve physical change through the use of adaptive materials undergoing dynamic change in response to an external change of conditions”

+

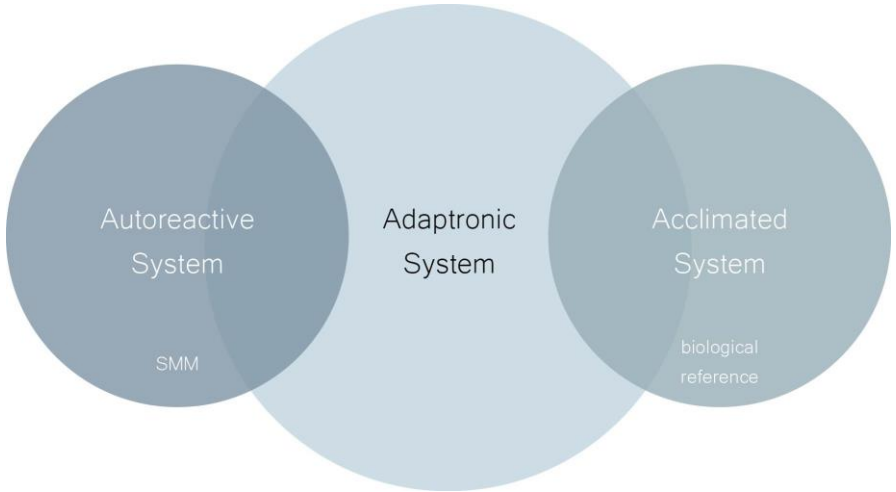
Acclimated System

“a process in an individual organism adjusting to a gradual change in its environment through its morphological, behavioral, physical changes“

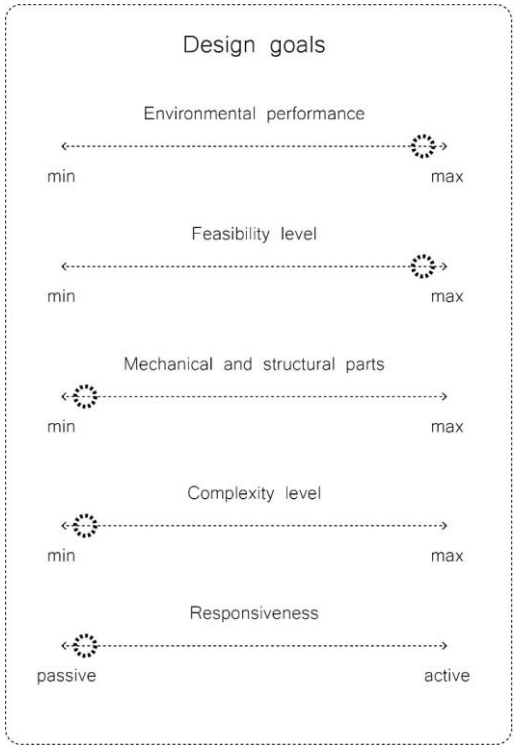
↓

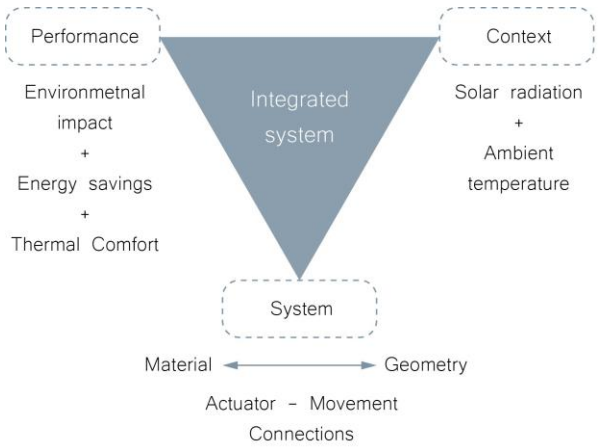
Adaptronic System

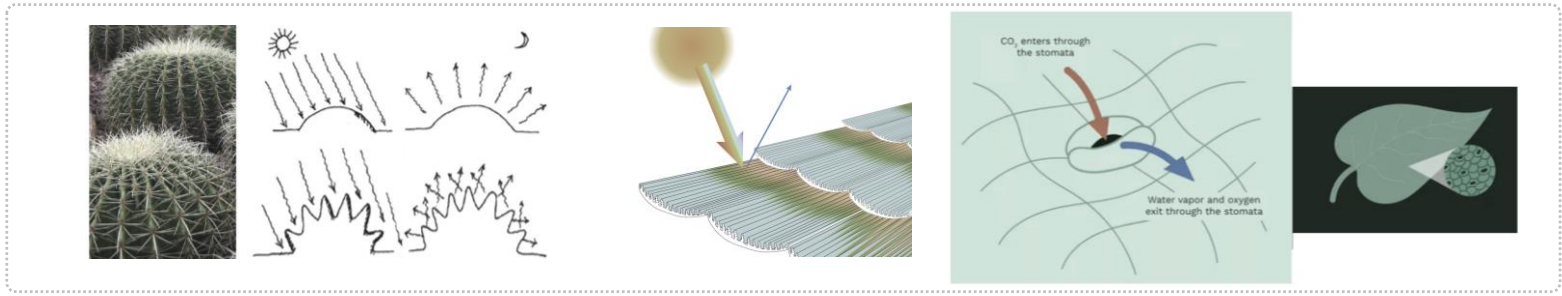
"the integration of actuators, sensors and controls with a material or structural component“



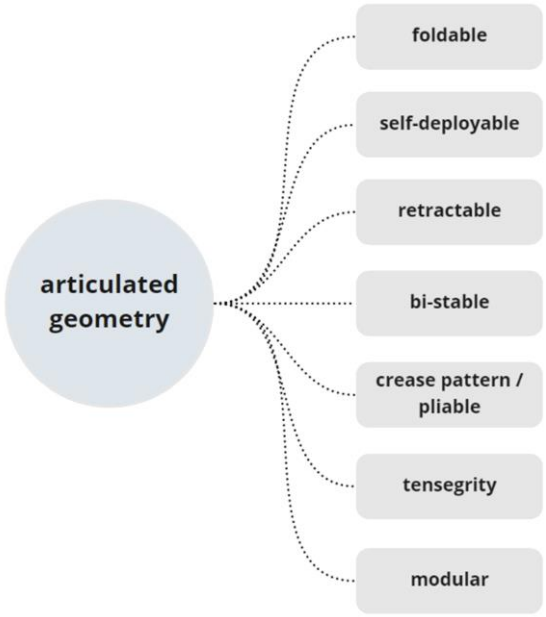
Goals & Concept



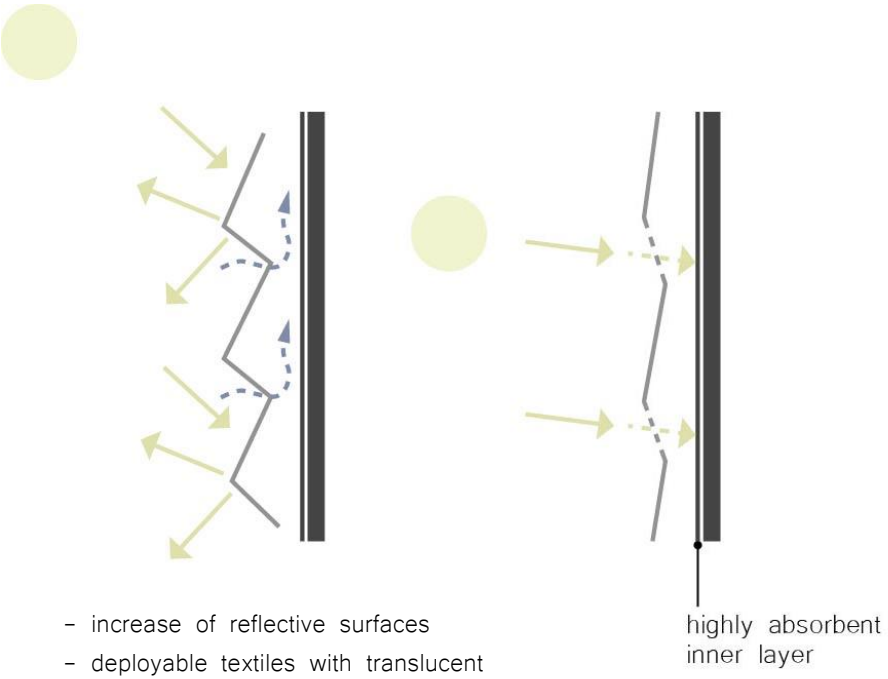




Mechanism Bio-inspiration



Possible geometry features

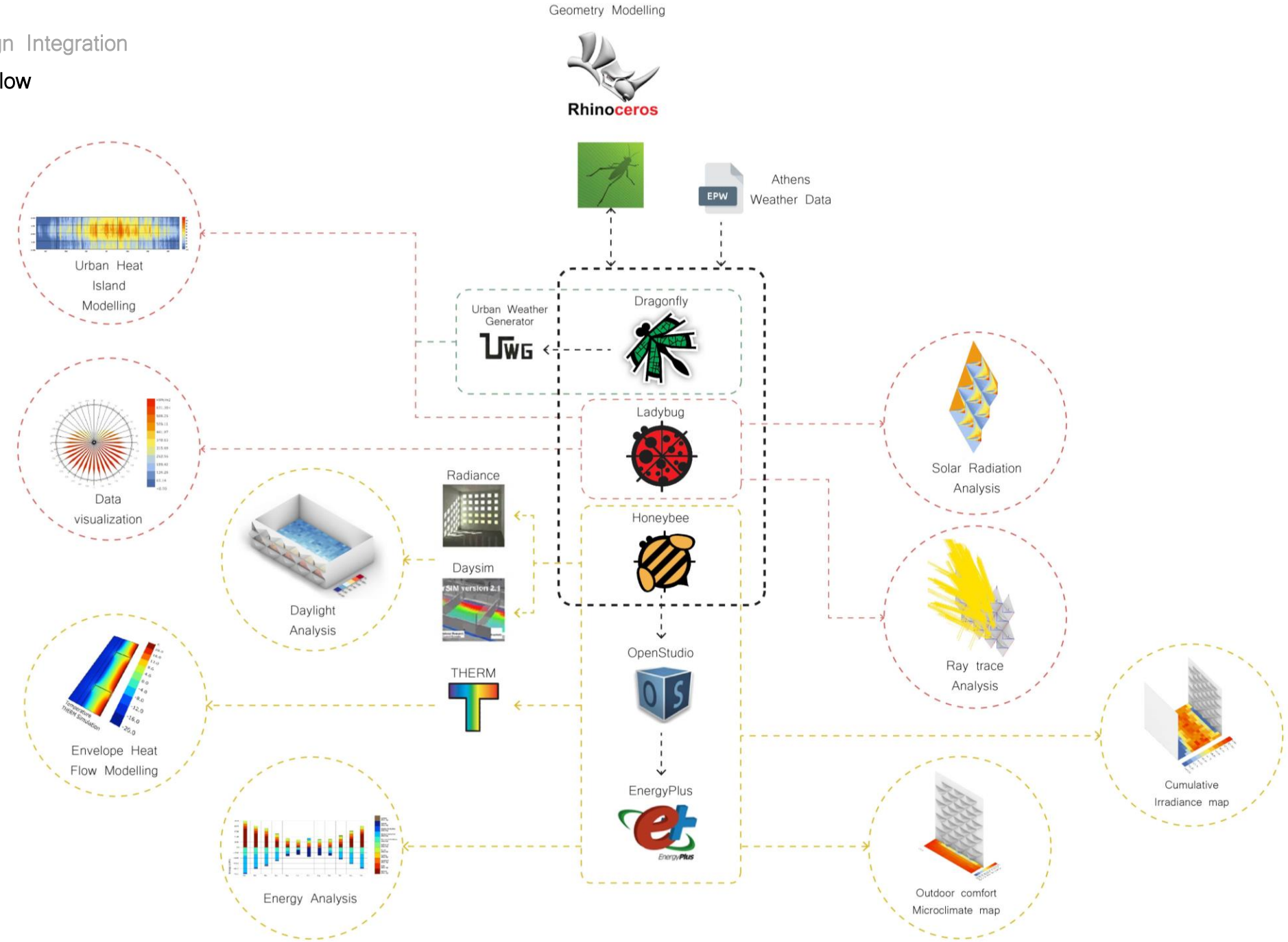


- increase of reflective surfaces
- deployable textiles with translucent and ventilated surfaces

highly absorbent inner layer

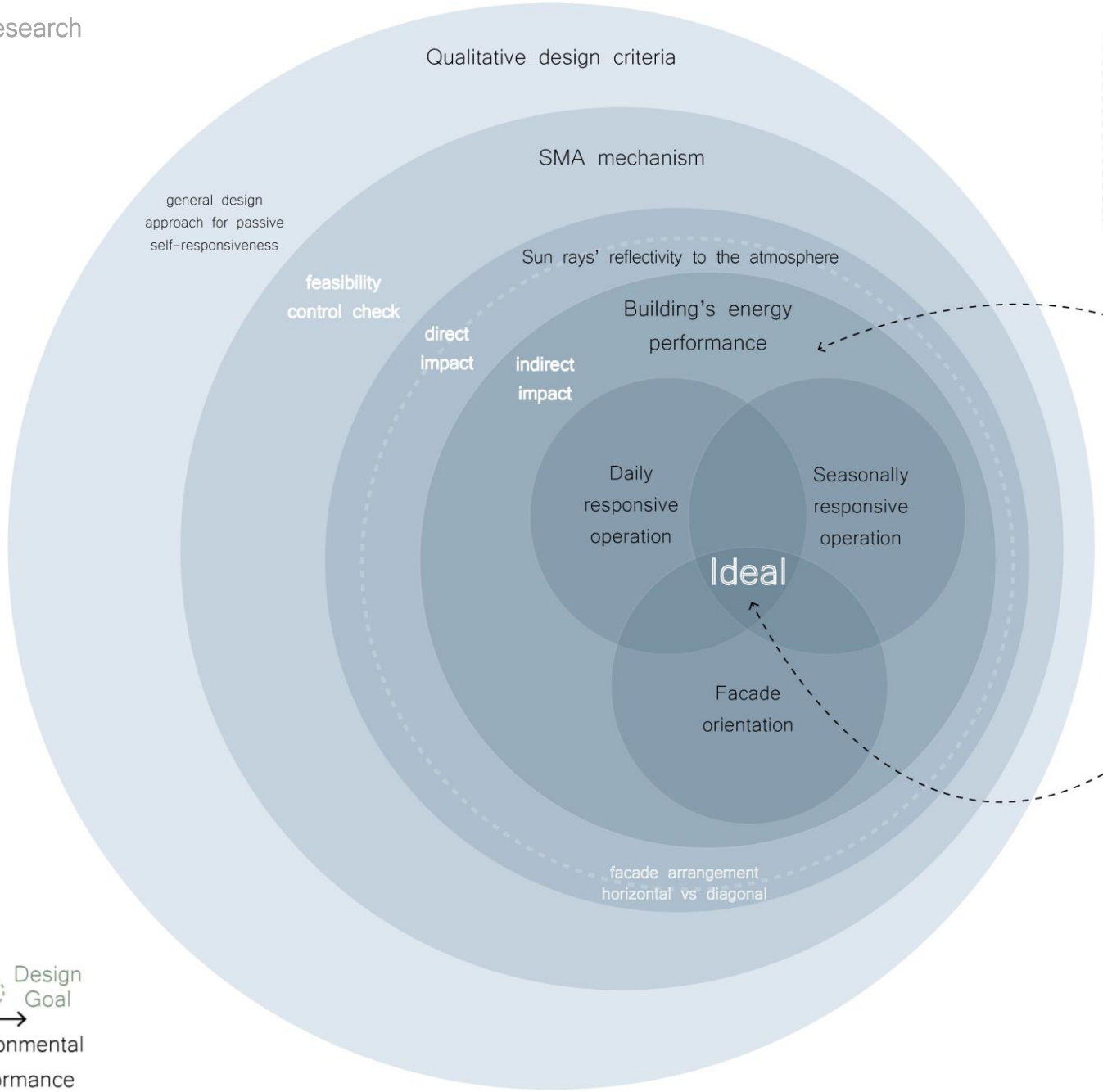
Façade performance principle

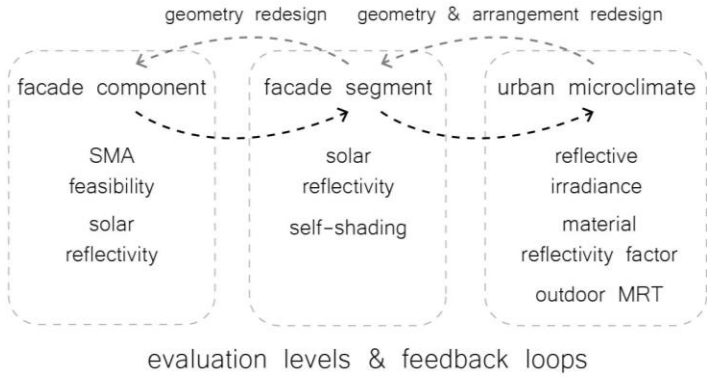
Design Workflow



Informed design by research

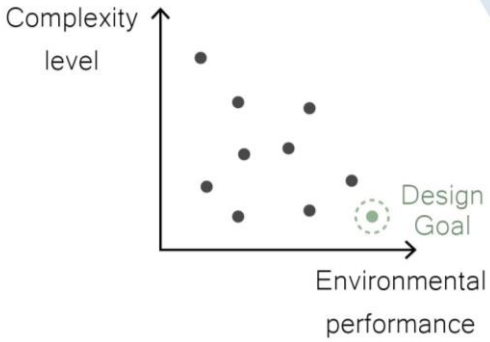
Layers of evaluation



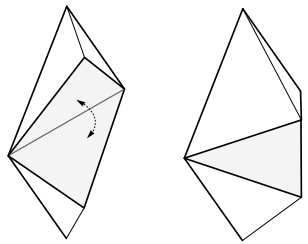


Minimum performance requirement

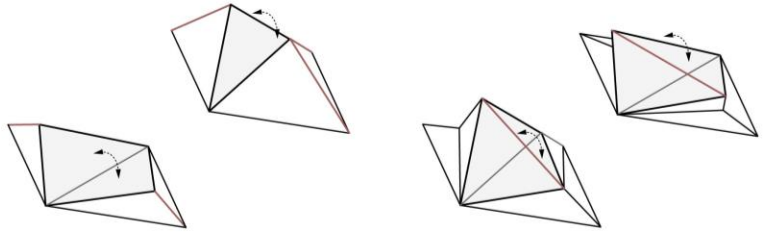
Complexity level-environmental performance ratio?



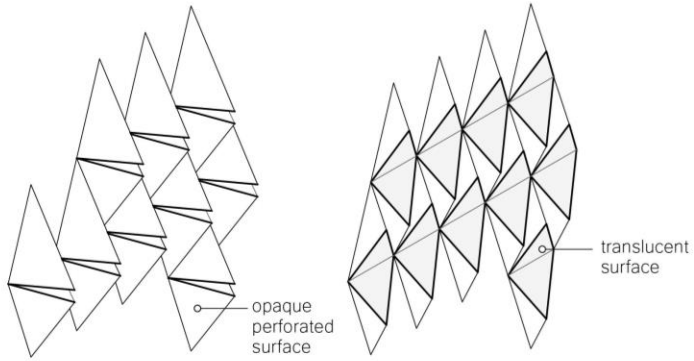
Geometry design concept



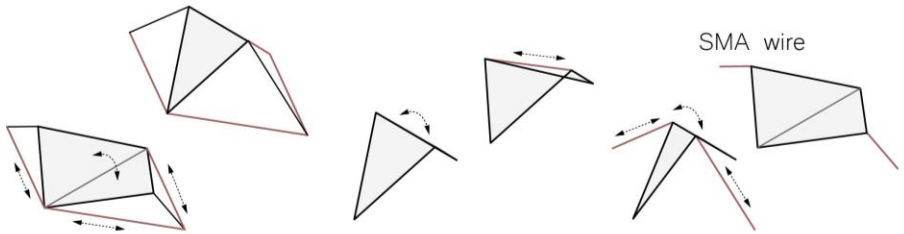
geometry initial design concept



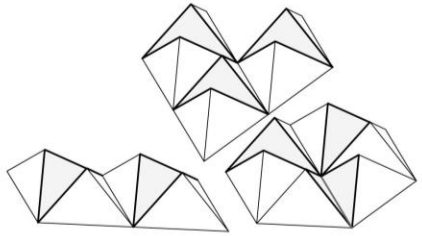
component mechanism alternatives



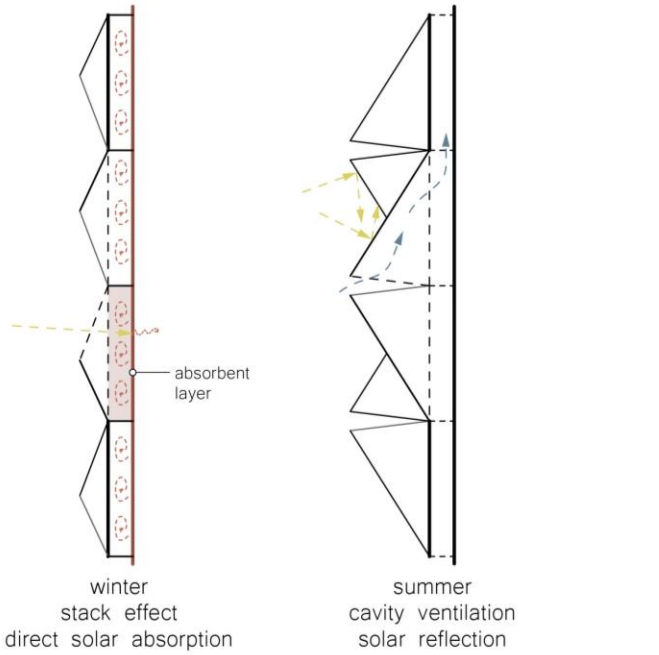
facade segment example



SMA wire actuation movement alternatives

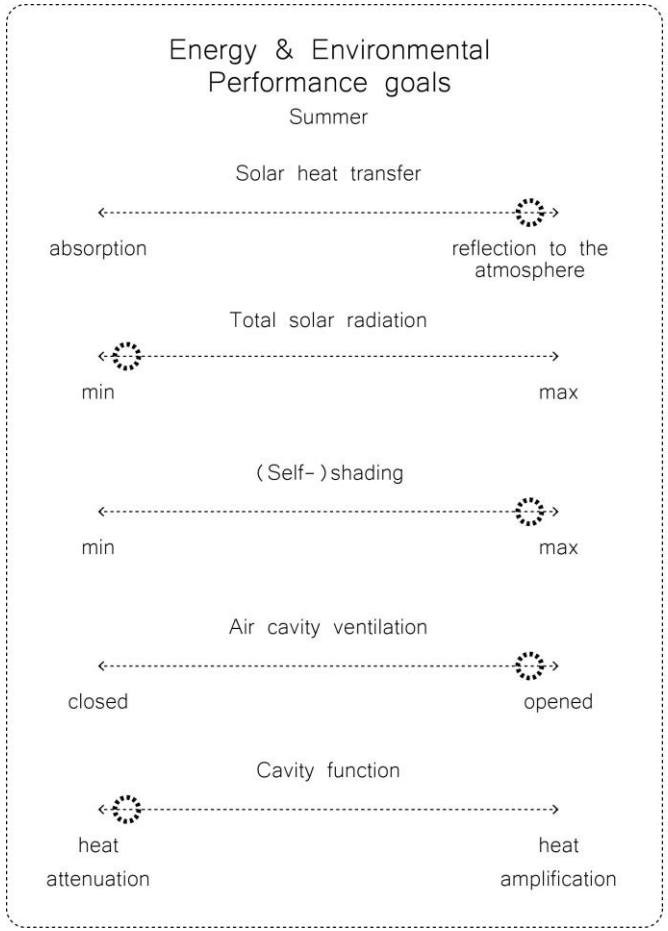


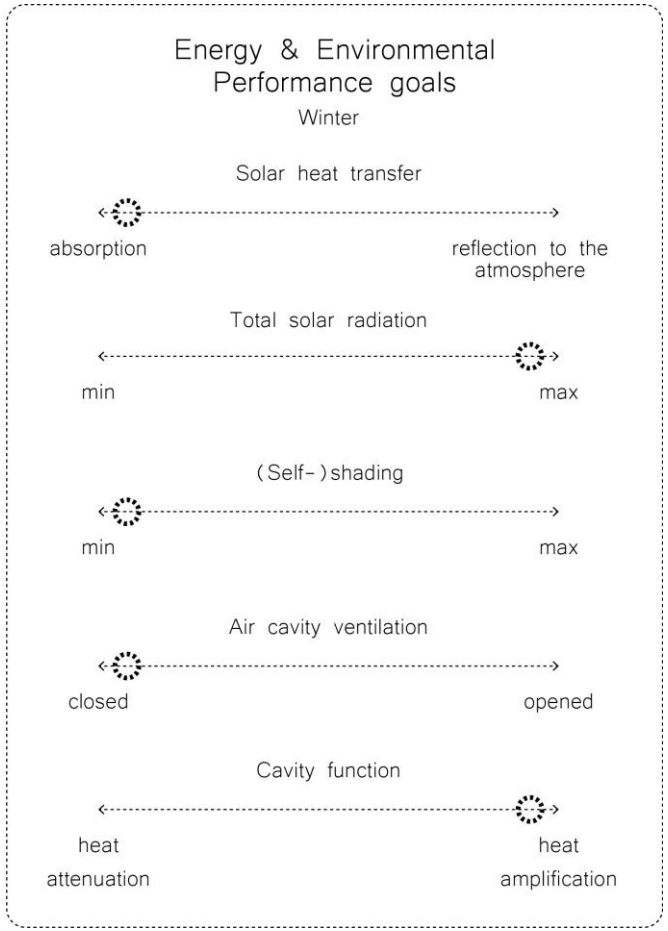
component orientation combinations



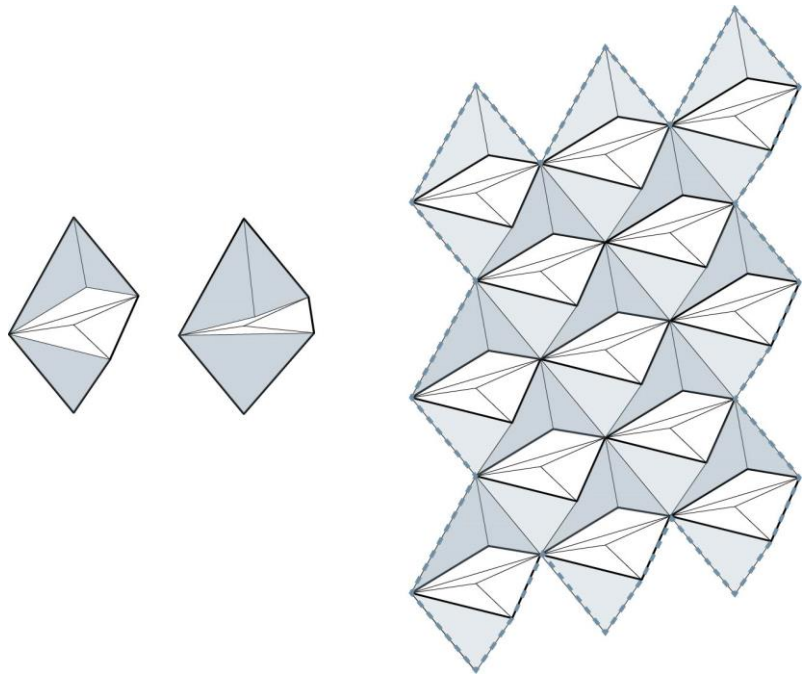
facade function in open and closed position

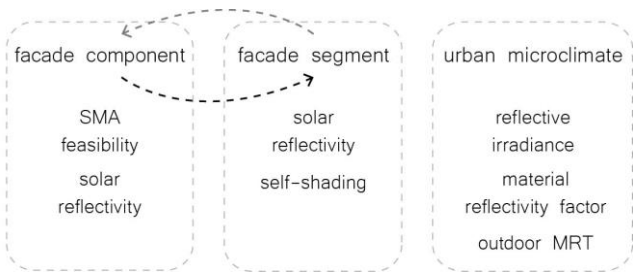
Energy & Environmental Performance goals



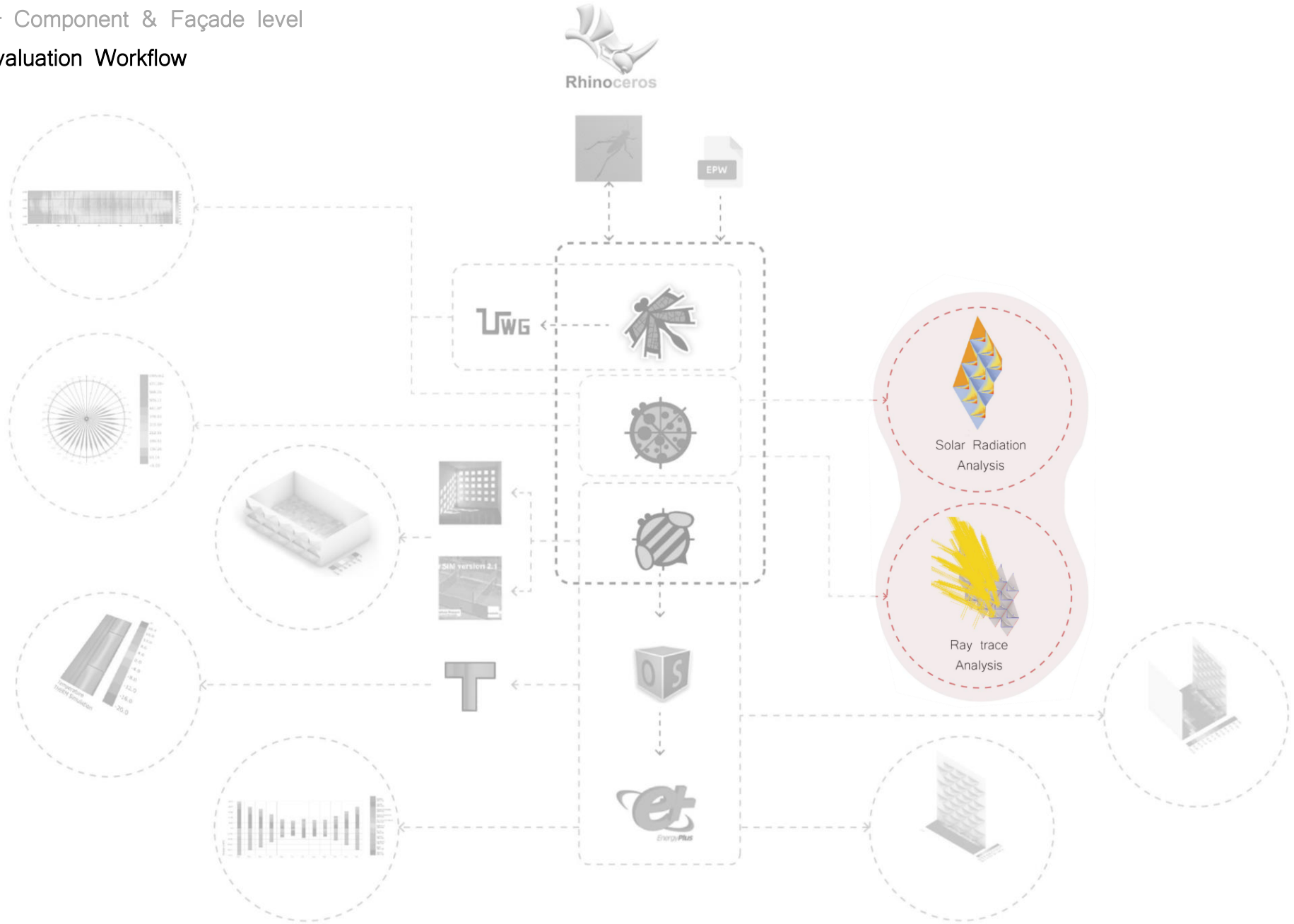


Direct Impact – Component & Façade level

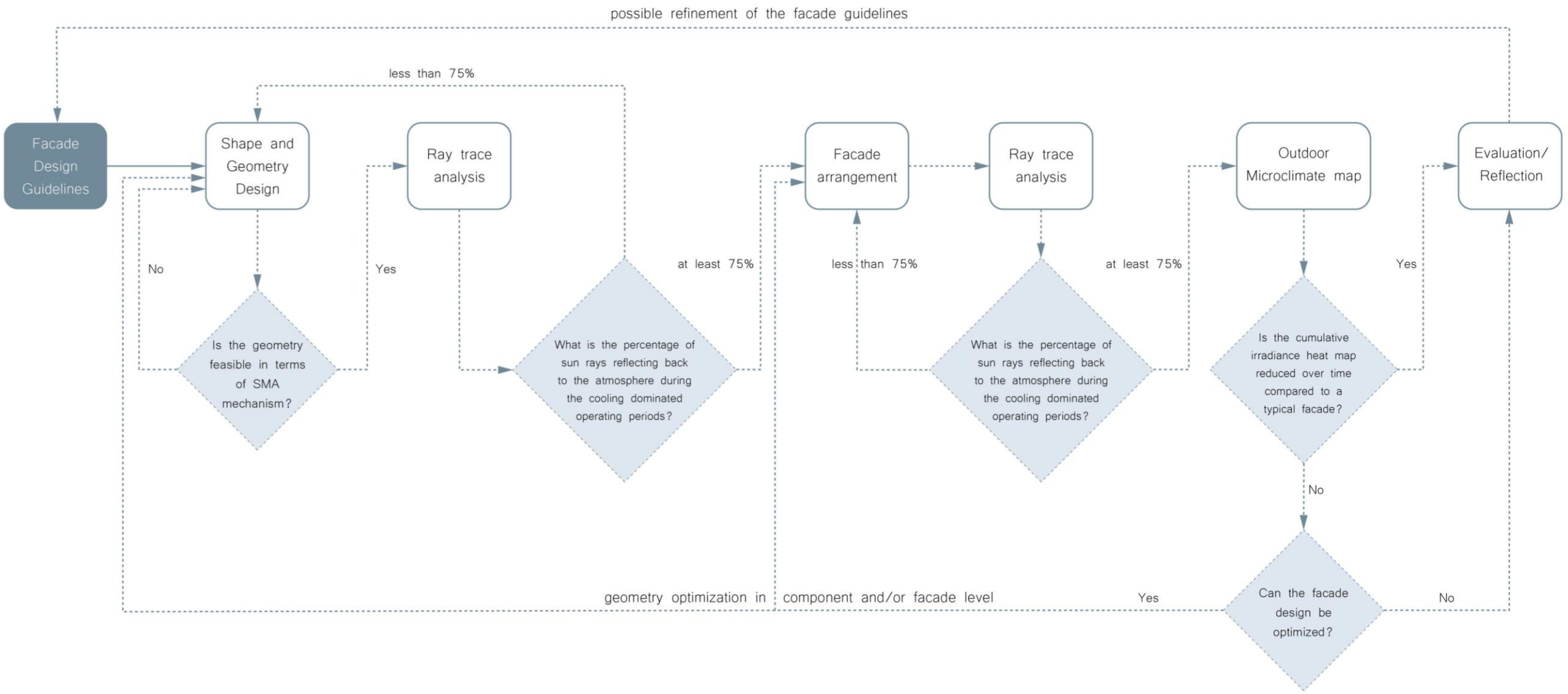




Performance Evaluation Workflow

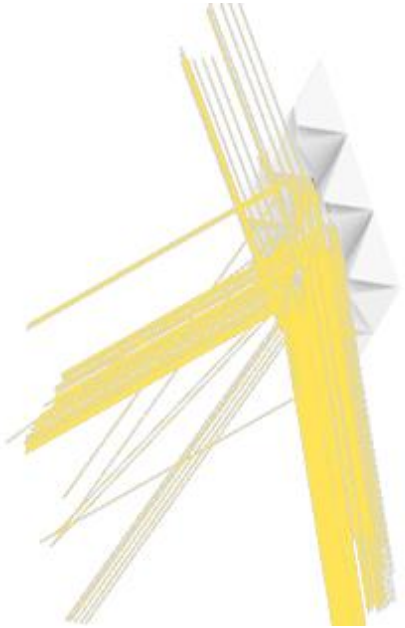


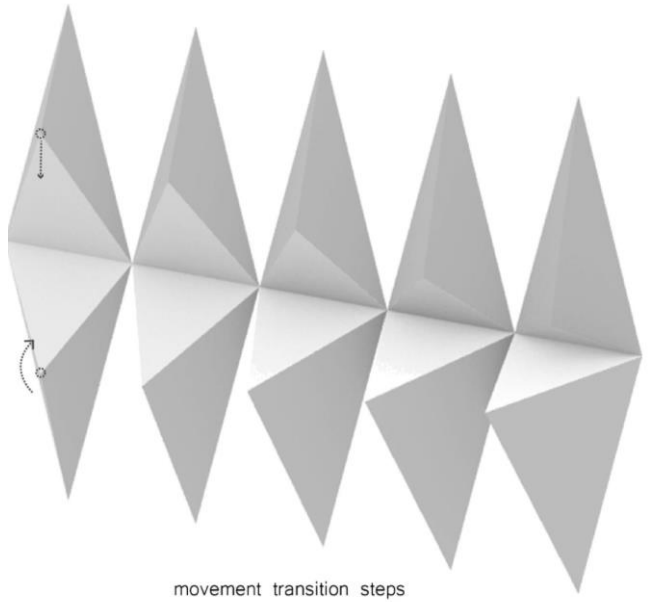
Performance Evaluation Workflow



Geometry refinement

Goal: to maximize the amount of sun rays reflected back to the atmosphere and not towards the urban environment



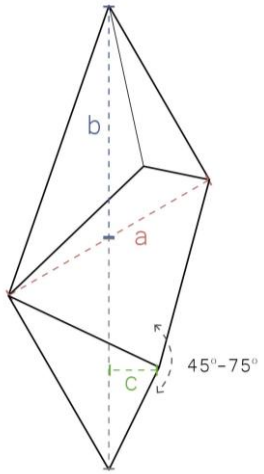


movement transition steps

reflected rays:
10% on June 21st 10-18hrs

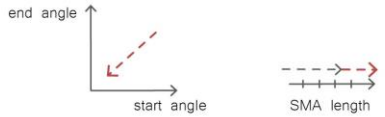
SMA feasibility evaluation study

Variables



Design guidelines

Strain ratio (limit: **3-5%**)
desired rotational degree range:
start: 45° **end: 75°**



! if SMA is too long, it is more likely to break (longevity and durability cycles are compromised) !

! if rotation range is too small, then the effect is not much different than an equivalent static façade component !

1/0.75
1/0.5

A

start angle / end angle	40°	45°	50°	55°
70°	x	x	**4.8%**	**3.5%**
75°	x	7%	6%	**4.8%** 1

1/1
1/0.5

B

start angle / end angle	40°	45°	50°	55°
70°	x	**4.6%**	**3.7%**	x
75°	6.3%	5.5%	**4.7%** 2	x

1/1.5
1/0.5

C

start angle / end angle	40°	45°	50°	55°
70°	x	x	**2.6%**	x
75°	**4.3%**	**3.8%**	**3.2%** 3	x

1/1.5
1/1

D

start angle / end angle	40°	45°	50°	55°
70°	x	x	5.4%	**4.1%**
75°	x	8%	6.8%	5.4%

1/2
1/1

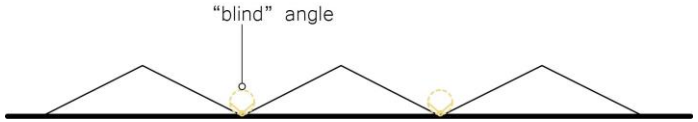
E

start angle / end angle	40°	45°	50°	55°
70°	x	**5%**	5.4%	**3.1%**
75°	x	6%	**5.1%**	**4.1%**

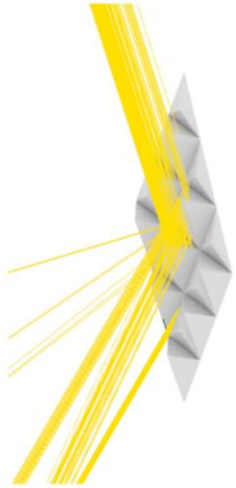
Sun ray trace analysis studies

Top views

Diagonal arrangement



Horizontal arrangement

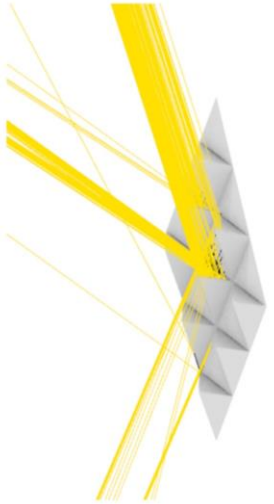


1a)

reflected rays:

60% on June 21st 12hrs

60% on June 21st 10-18hrs

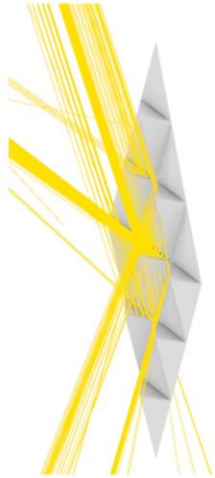


1b)

reflected rays:

85% on June 21st 12hrs

90% on June 21st 10-18hrs



2)

reflected rays:

75% on June 21st 12hrs

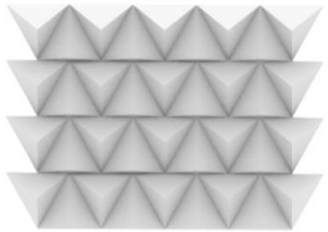
80% on June 21st 10-18hrs

3)

reflected rays:

60% on June 21st 12hrs

85% on June 21st 10-18hrs

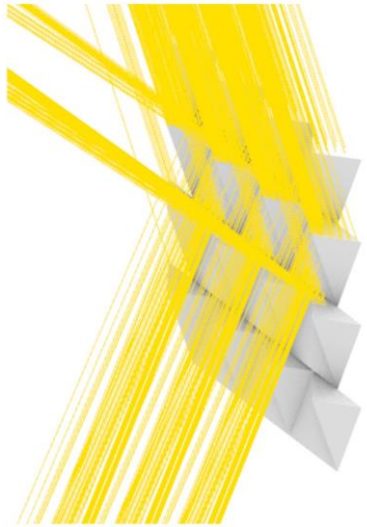


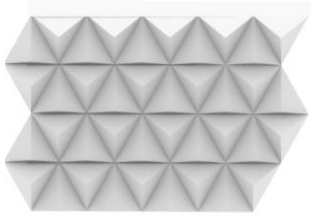
Horizontal arrangement

reflected rays:

75% on June 21st 12hrs

85% on June 21st 16hrs



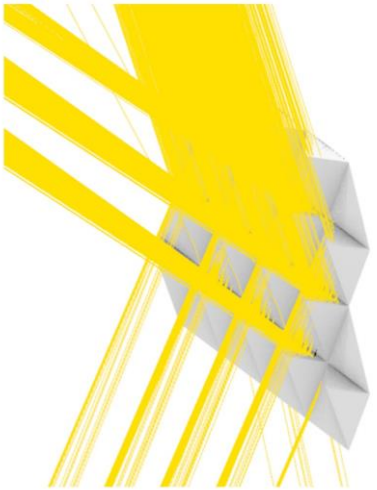


Diagonal arrangement

reflected rays:

85% on June 21st 12hrs

70% on June 21st 16hrs

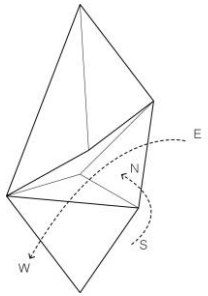


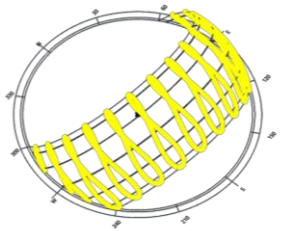
Dynamic response operation basis

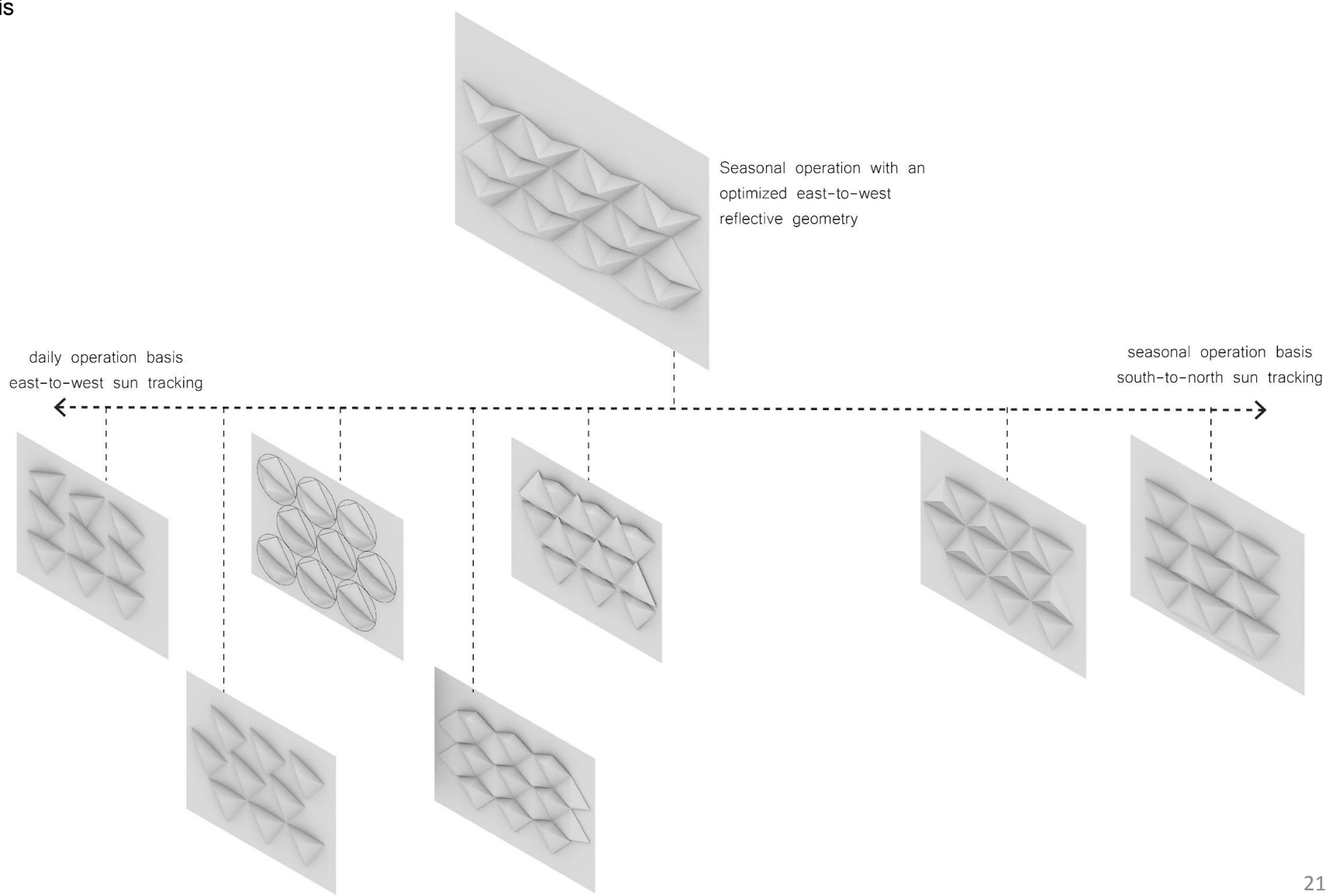
Scenario:
South-facing façade

Evaluation focus:
Façade component & arrangement

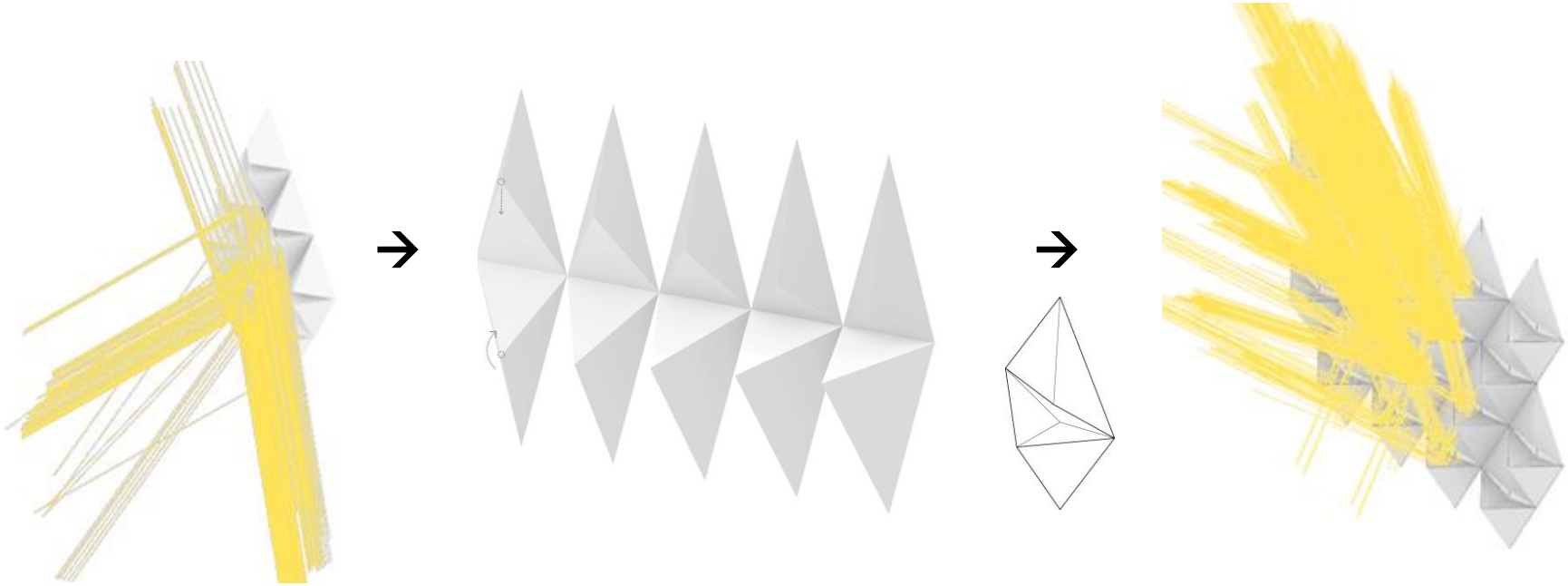
Evaluation criteria:
SMA feasibility
Sun ray trace analysis







Geometry design optimization stages



1/0.5, 1/0.5 proportions

Top pyramid 10° rotation from z axis

Diagonal arrangement

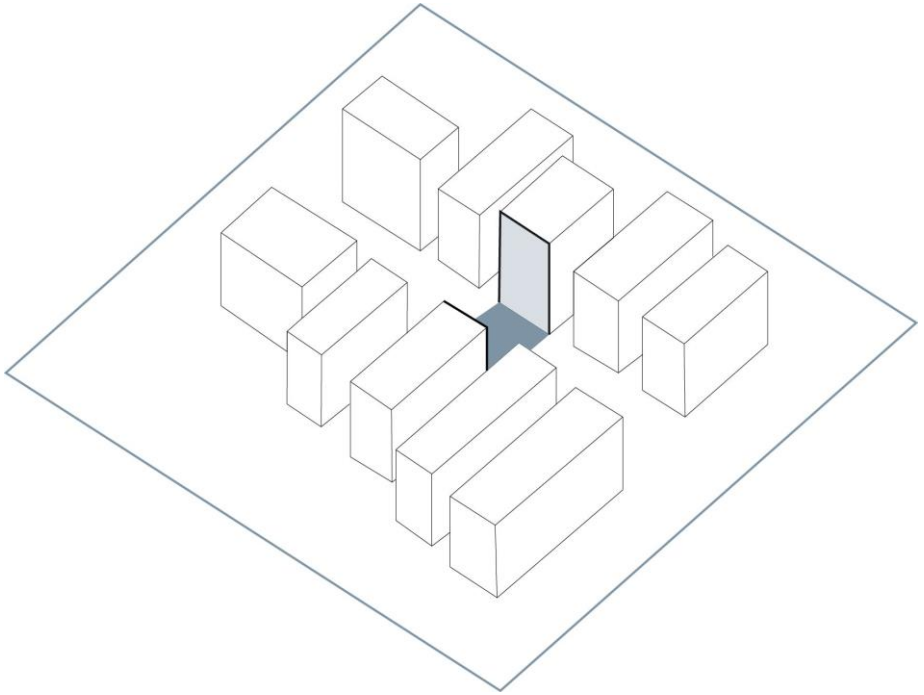
Bottom pyramid with a folding line inwards

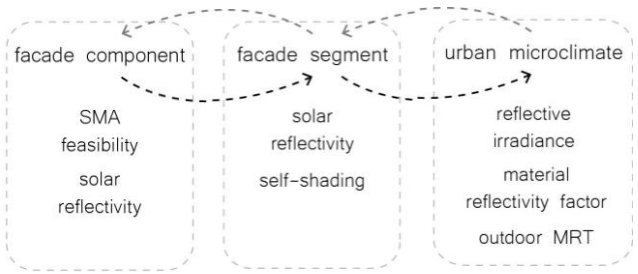
Reflected rays:

95% on June 21st 12hrs

80% on June 21st 10-16hrs

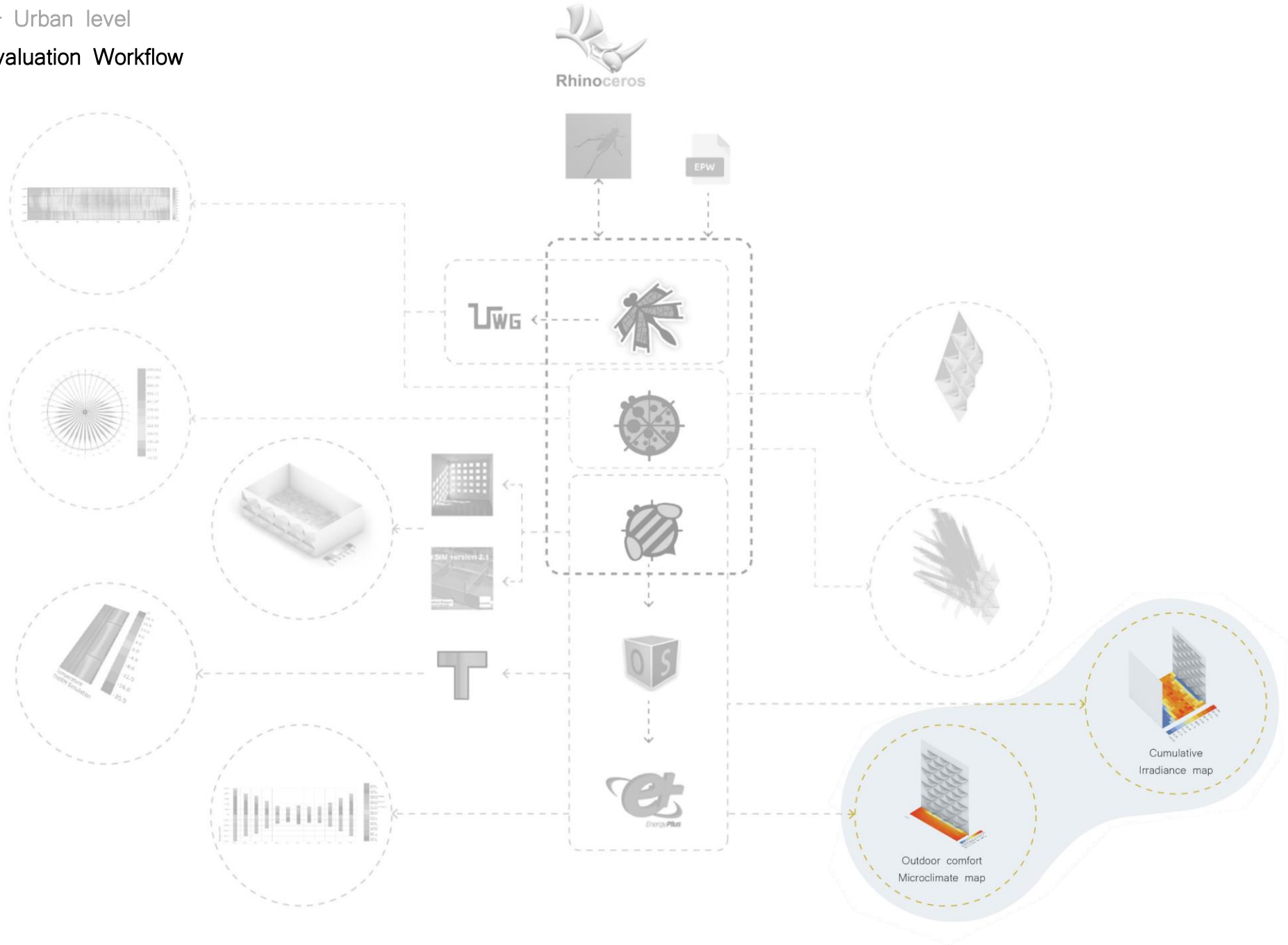
Direct Impact – Urban level



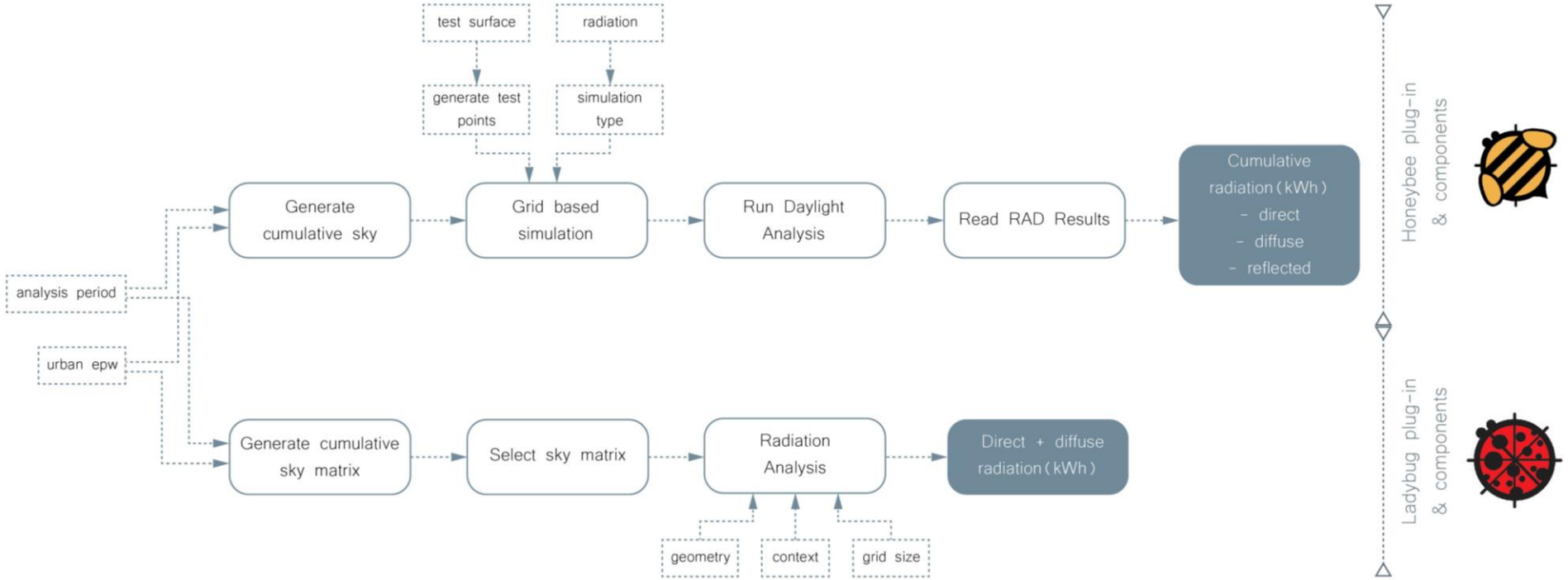


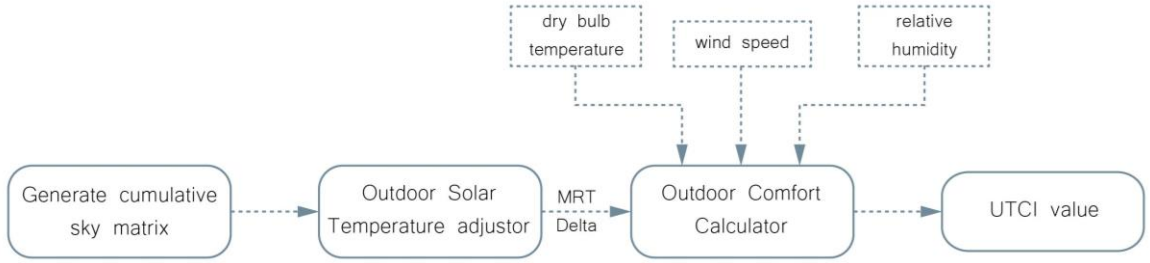
Direct Impact – Urban level

Performance Evaluation Workflow



Performance Evaluation Workflow



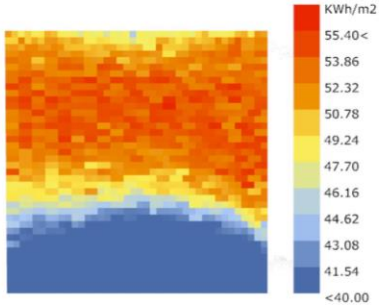
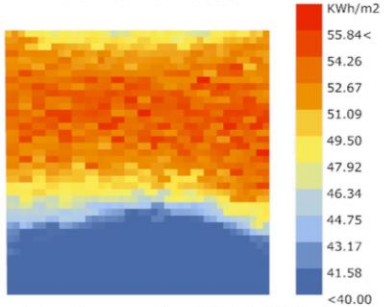
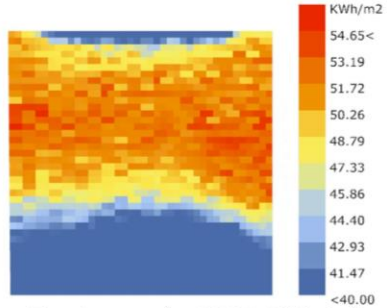
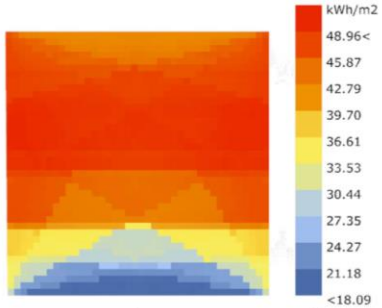
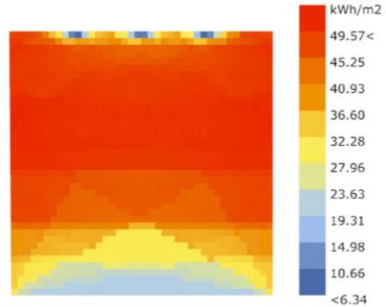
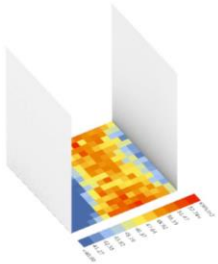
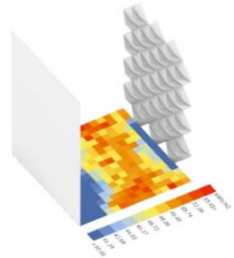


Microclimate heat maps

Reflected radiation

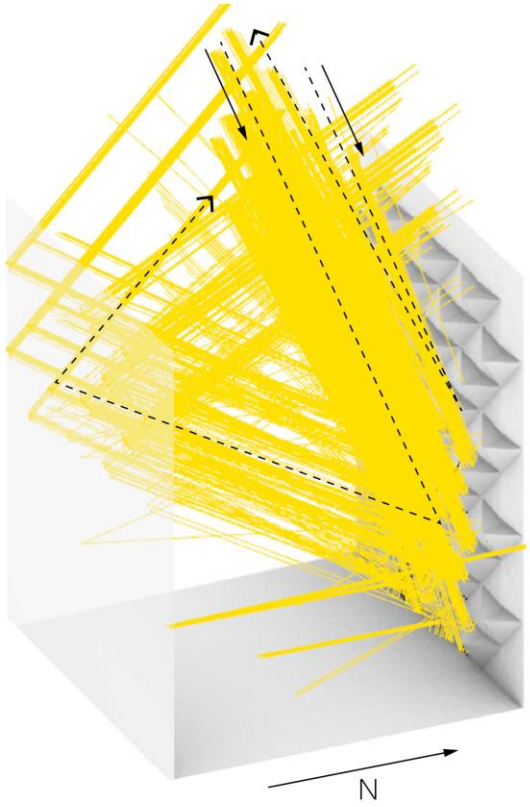
- South-facing opaque façade
- Typical Athens urban canyon
- Analysis period: Hottest week

- **4%** reduction of total radiation
- **40%** reduction of the reflected radiation from the facade and the surrounding surfaces

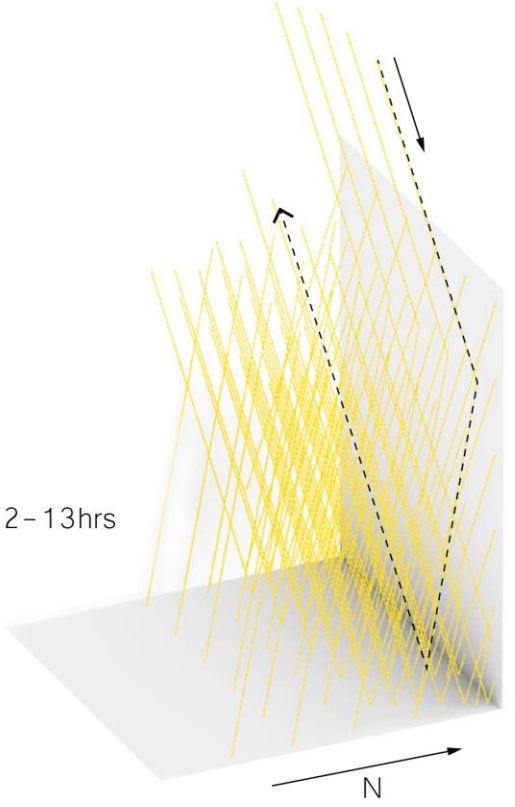
Facade type	Standard facade		Facade design
Glazing ratio / Radiation values	0% fully opaque	85% curtain wall	
	Top view grid results		
Cumulative radiation (1) (direct, diffuse and reflected)	 Total per m^2: 1129 kWh/m^2	 Total per m^2: 1131 kWh/m^2	 Total per m^2: 1088 kWh/m^2
Direct and diffuse radiation (2)	 Total per m^2: 1018 kWh/m^2		 Total per m^2: 1019 kWh/m^2
Reflected radiation (1)-(2)	Total per m^2: **113 kWh/m^2**		Total per m^2: **69 kWh/m^2**
Axo view grid results			

Comparative sun ray trace analyses

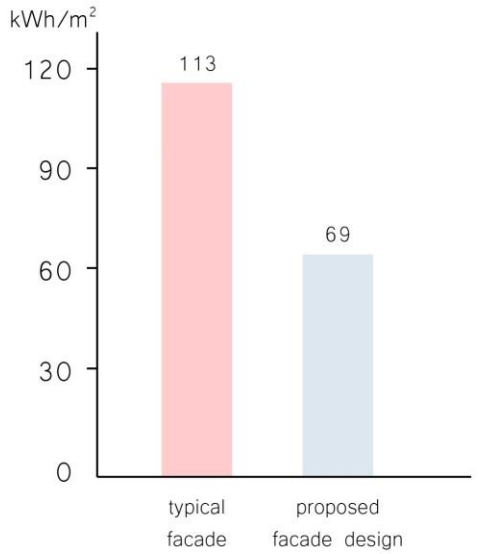
June 21st 12-13hrs



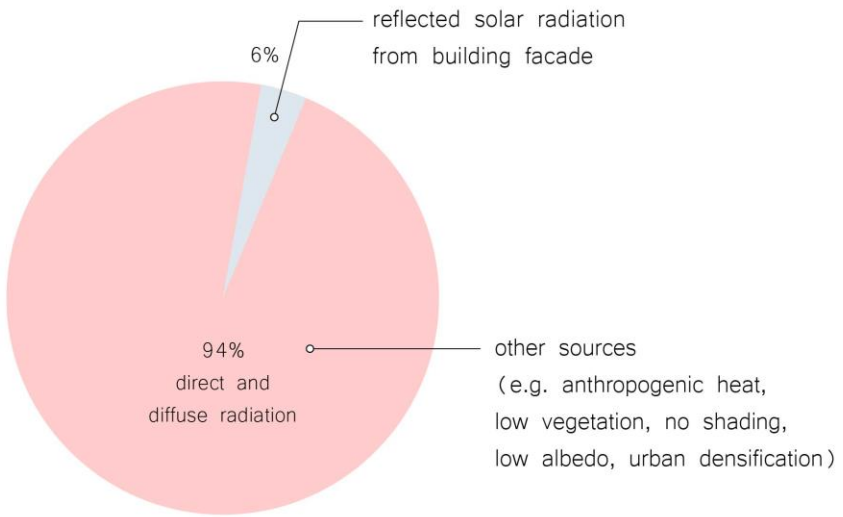
June 21st 12-13hrs



Conclusions

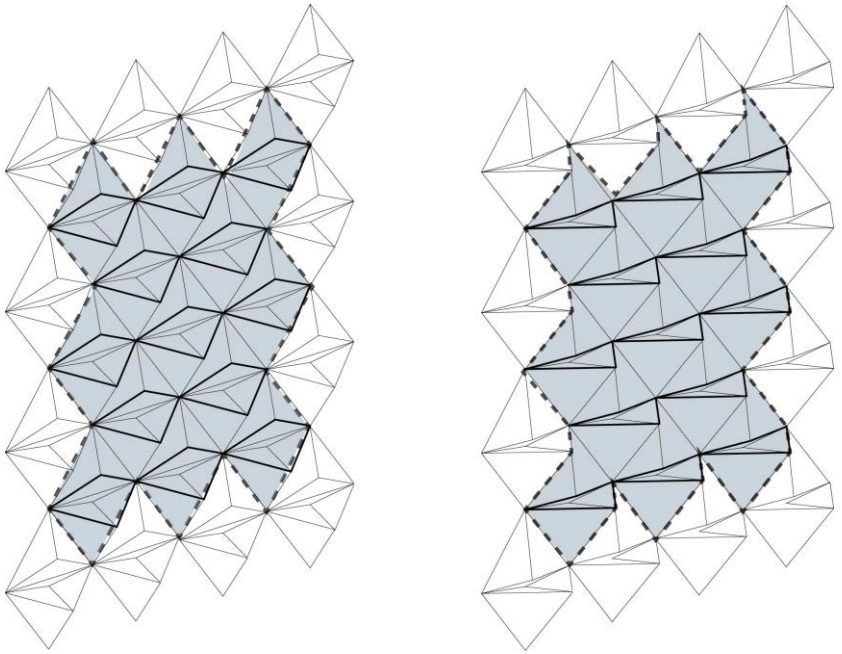


building's direct UHI impact footptint based on the reflective radiation to the street level

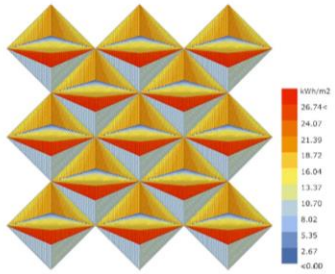
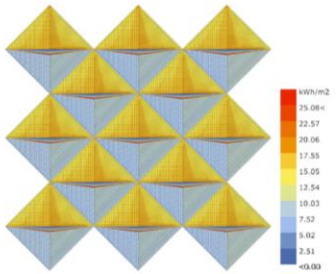
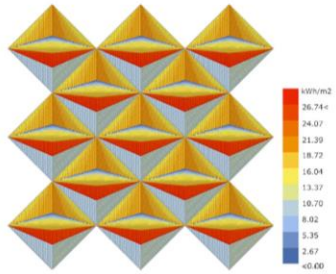
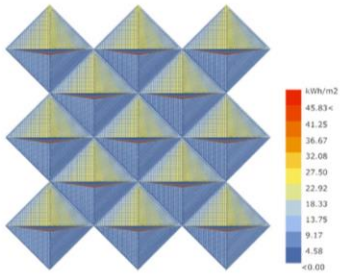
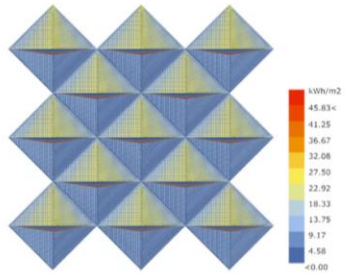
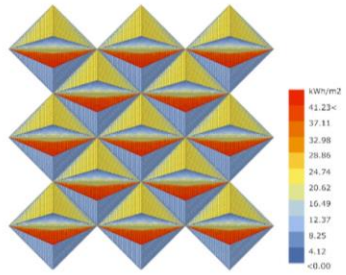
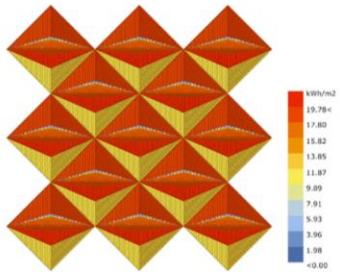
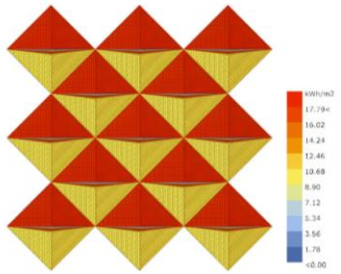
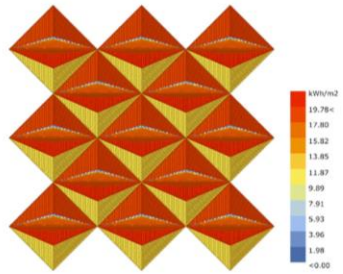


cumulative solar radiation distribution in the urban microclimate

Direct & Indirect Impact – Façade Surface level



Solar radiation analyses

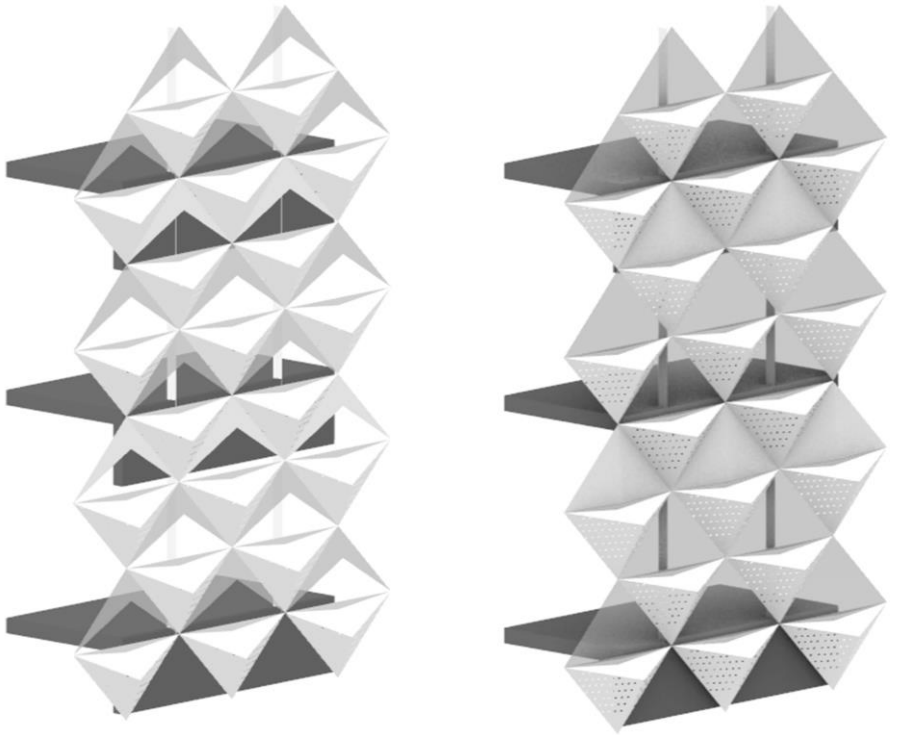
Analysis period \ Facade type	Dynamic facade	Static facade (closed)	Static facade (open)
Typical Spring Week (05-11/04) (start of dynamic facade activation)	 Total radiation: 441.5 kWh	 Total radiation: 429 kWh	 Total radiation: 441.5 kWh
Extremely Hot Week (03-09/08) (peak of dynamic facade movement)	 Total radiation: 503.6 kWh	 Total radiation: 503.6 kWh	 Total radiation: 519.5 kWh
Typical Winter Week (15-21/12) (end of dynamic facade movement)	 Total radiation: 474 kWh	 Total radiation: 452.7 kWh	 Total radiation: 474 kWh

test facade segment

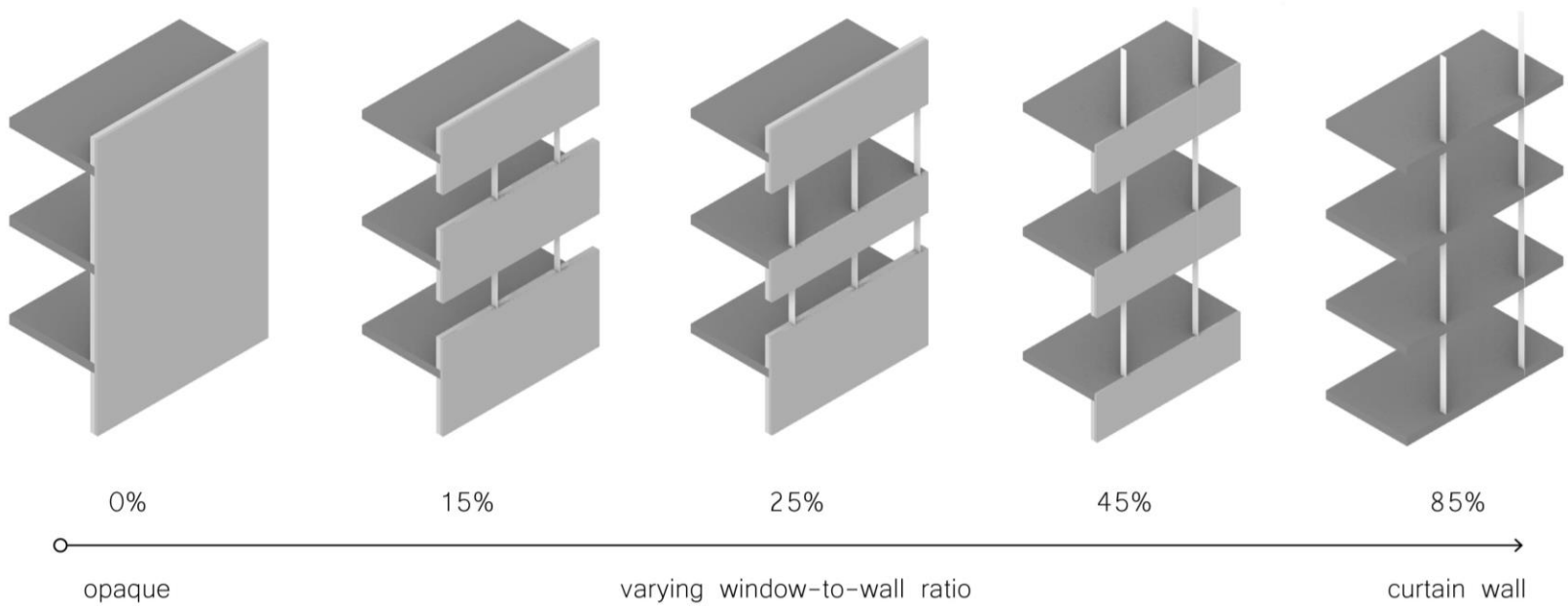
open position

closed position

Façade application



Inner facade's window-to-wall ratio range



Case study

Scenario:

- Athens city center urban canyon
- Retrofit intervention
- Typical south-facing office building
    - 6-7 floors with a 45-85% glazing ratio
    - Built between 1960-1980

Building type characteristics:

- Low building energy performance (outdated building components)
→ increased cooling demands
→ increased heat released from air-conditioning units
→ **increased indirect UHI impact**

- Construction materials: concrete (thermal mass) and glazed surfaces (reflective)
→ **increased direct UHI impact**

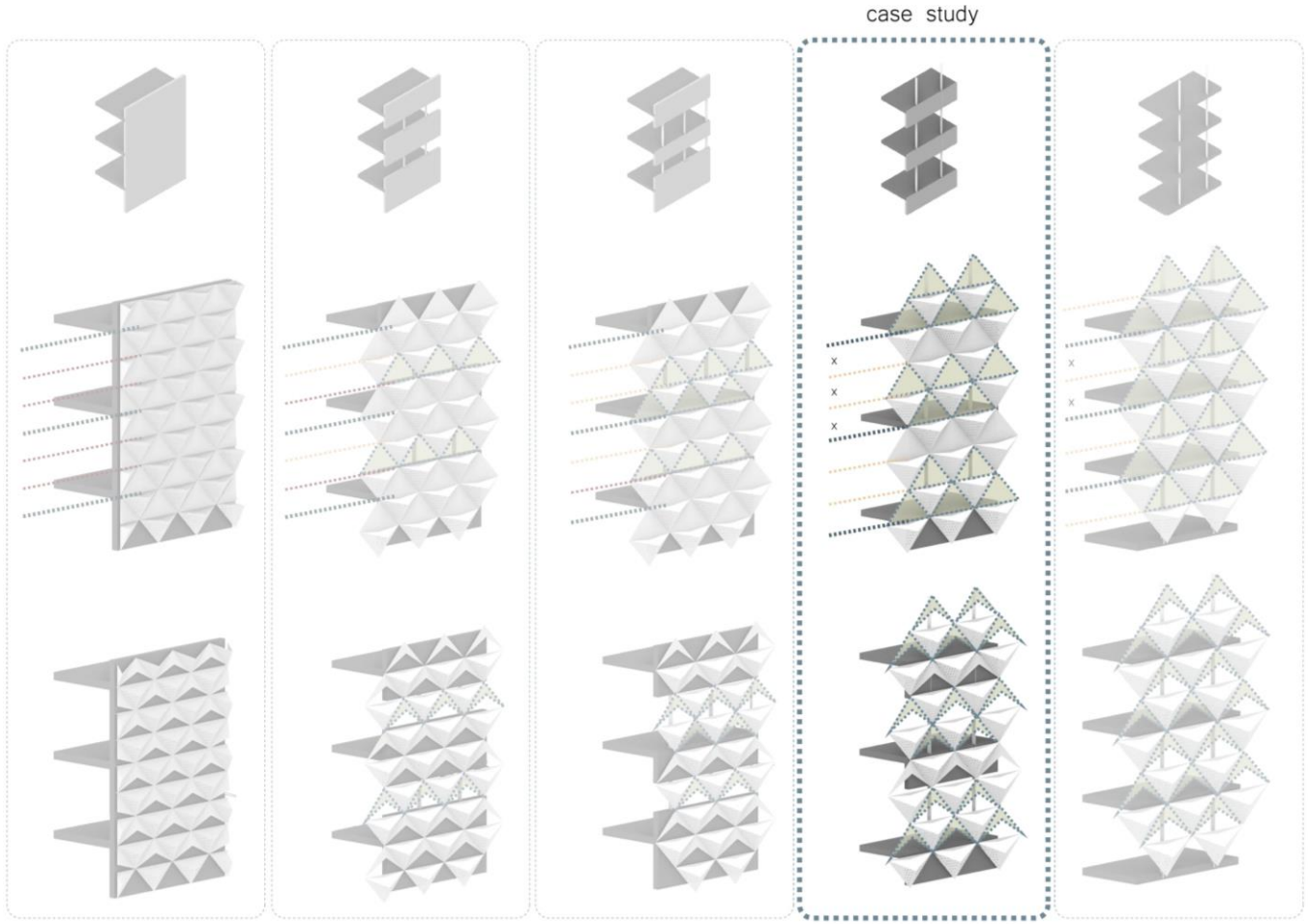
Retrofit strategy: window replacement and outer facade skin (overcladding)

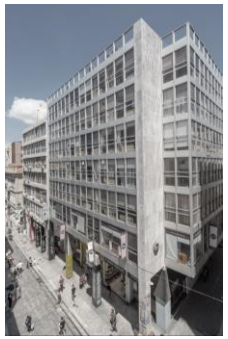
Passive design based on [Geometry + Materiality + Dynamic movement]

direct impact — direct + indirect impact

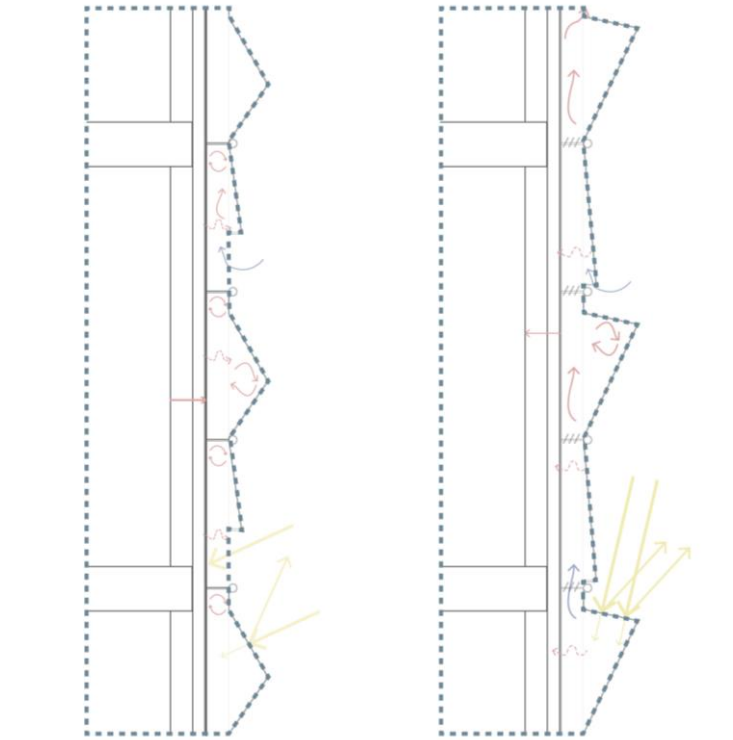
Goals:
- low tech
- low energy
- low cost & maintenance

→ lower UHI impact
→ higher energy & environmental performance

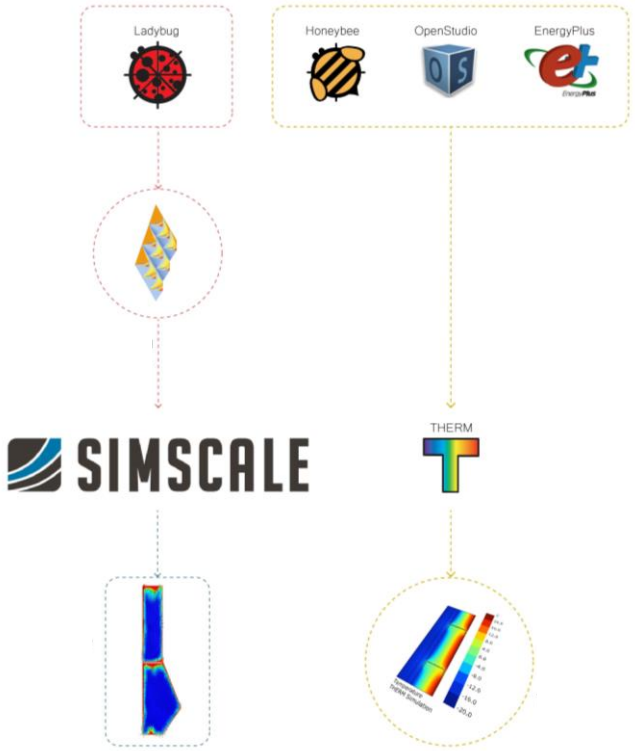


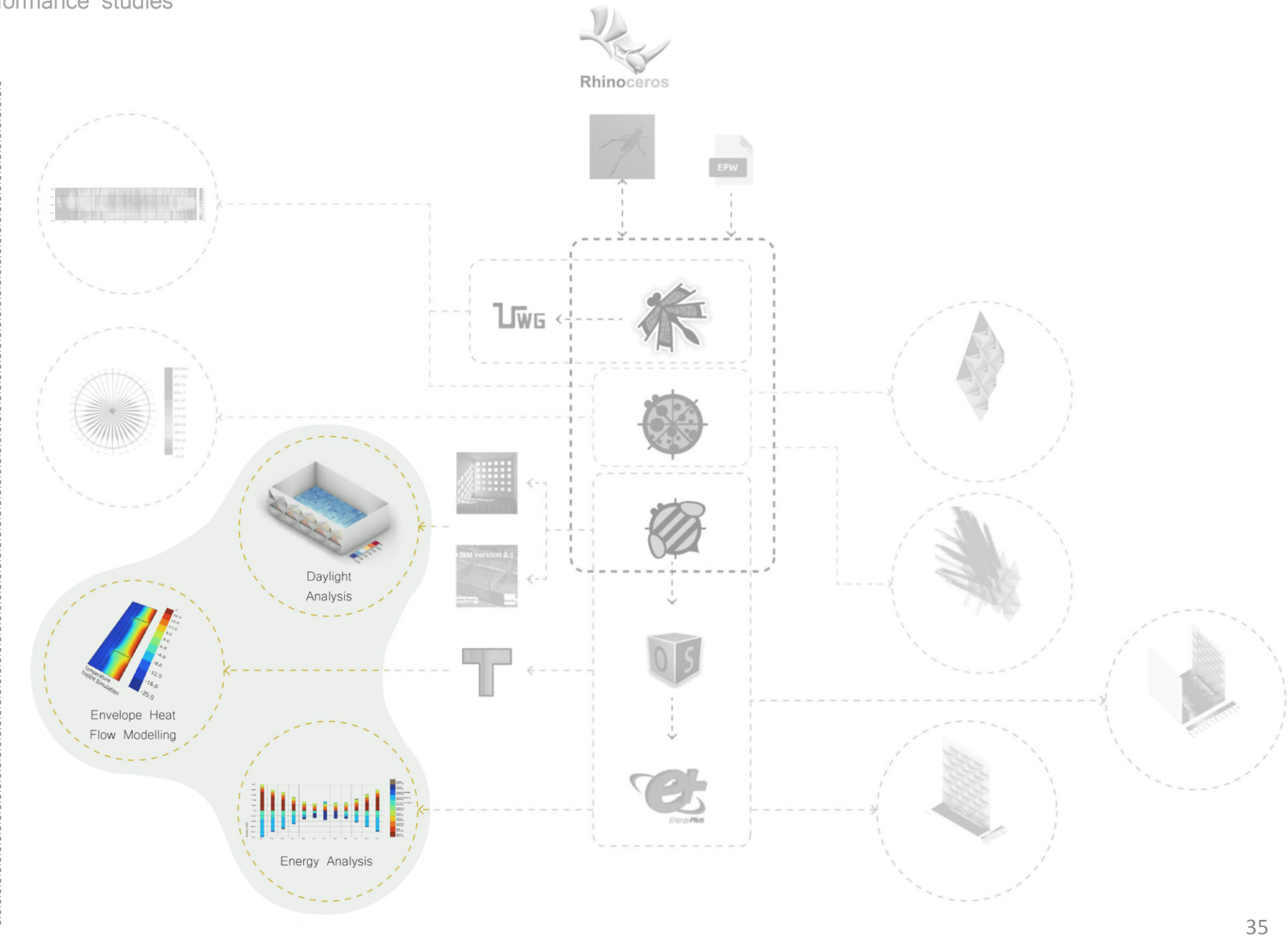


Indirect Impact – Building's interior level

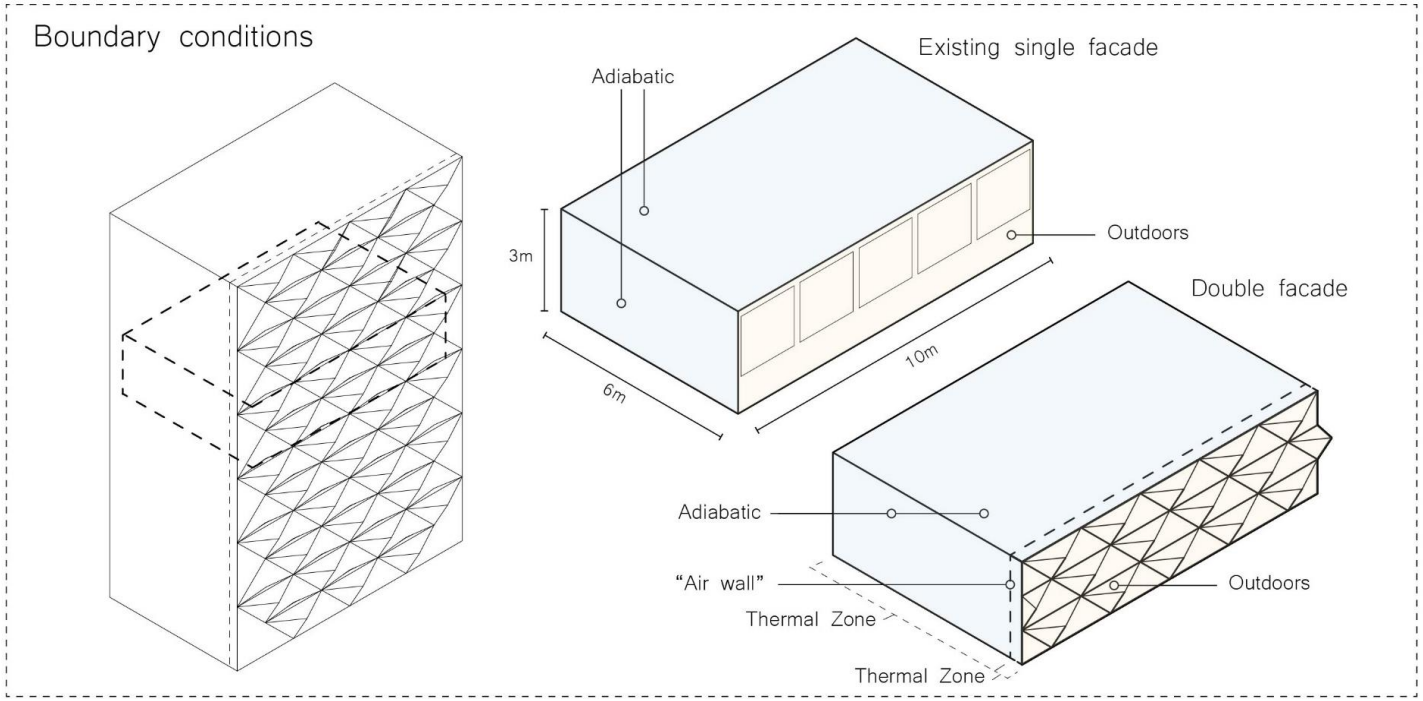


Performance Evaluation Workflow



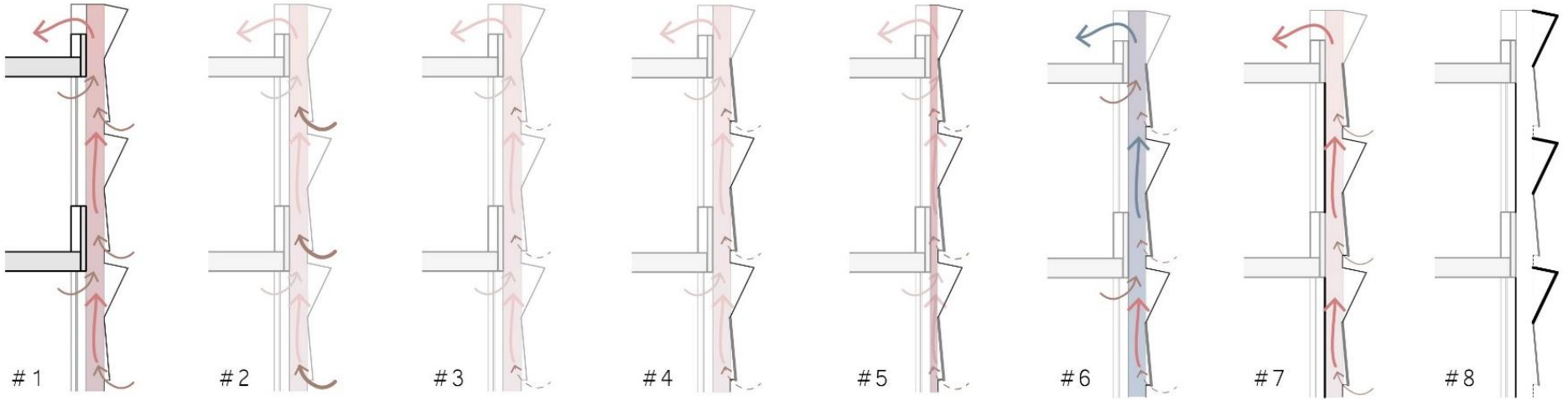


Cooling demands estimation studies - Energy Use Intensity (EUI)



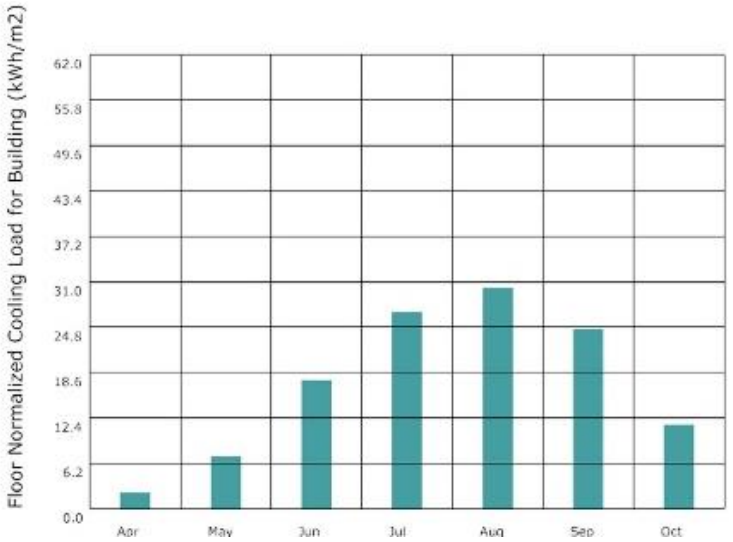
Cooling demands estimation studies - Energy Use Intensity (EUI)

Case	Test variables			
#	Operable effective area (w / w/o air exchange between the cavity and the interior)	Night-time ventilation	SHGC value (translucent part)	Cavity width
1	0.4m² (w air exchange)	-	0.93	400mm
2	1m² (w air exchange)	-	0.93	400mm
3	0 (slightly ventilated) (w air exchange)	-	0.93	400mm
4	0 (slightly ventilated) (w air exchange)	-	0.6	400mm
5	0 (slightly ventilated) (w air exchange)	-	0.6	150mm
6	0.4m² (w scheduled air exchange)	yes	0.6	400mm
7	0.4m² (no natural ventilation) (w/o direct air exchange)	-	0.6	400mm
8	w/o air exchange, no double skin function or natural ventilation (no cavity thermal zone), exterior facade skin only as sun-shading			

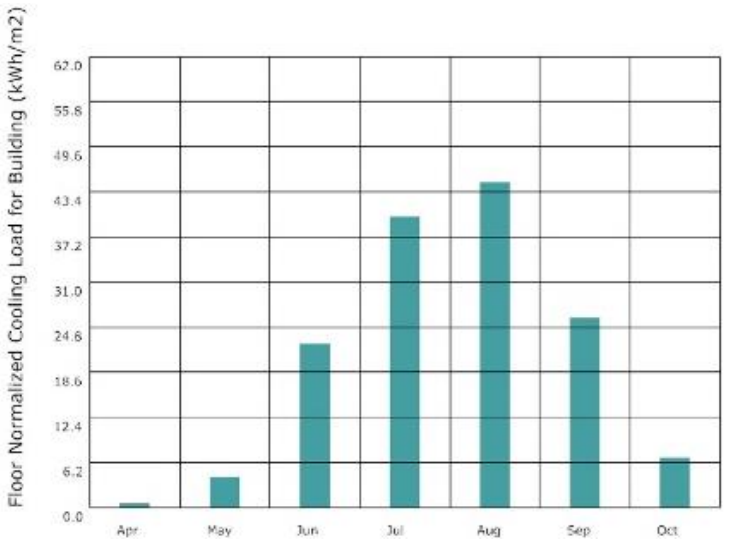


Cooling demands estimation studies - Energy Use Intensity (EUI)

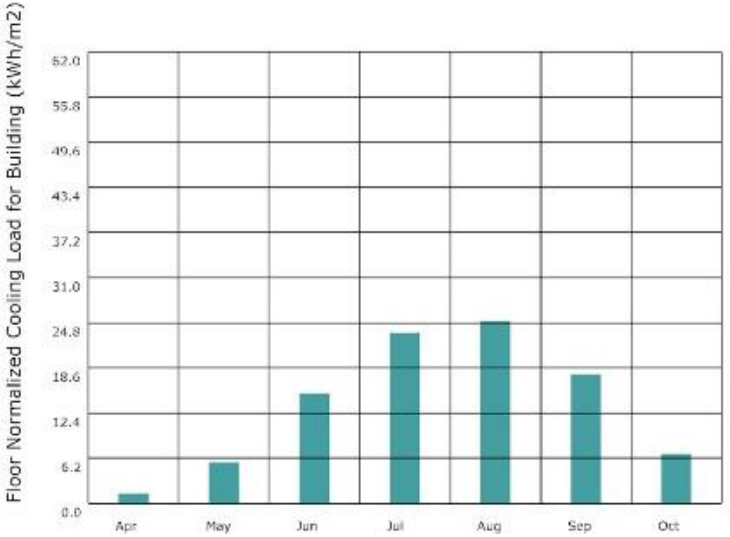
Case	Cooling loads per m^2 (Energy Use Intensity)	Difference in %
Existing single facade	**120 kWh/m^2**	
#1	145.1 kWh/m^2	+21%
#2	188.7 kWh/m^2	+57%
#3	113.5 kWh/m^2	-5.4%
#4	104.4 kWh/m^2	-13%
#5	109.7 kWh/m^2	-8.5%
#6	102.3 kWh/m^2	-15%
#7	104.4 kWh/m^2	-13%
#8	95 kWh/m^2	-21%



Existing single facade



Case#2 (w natural ventilation)

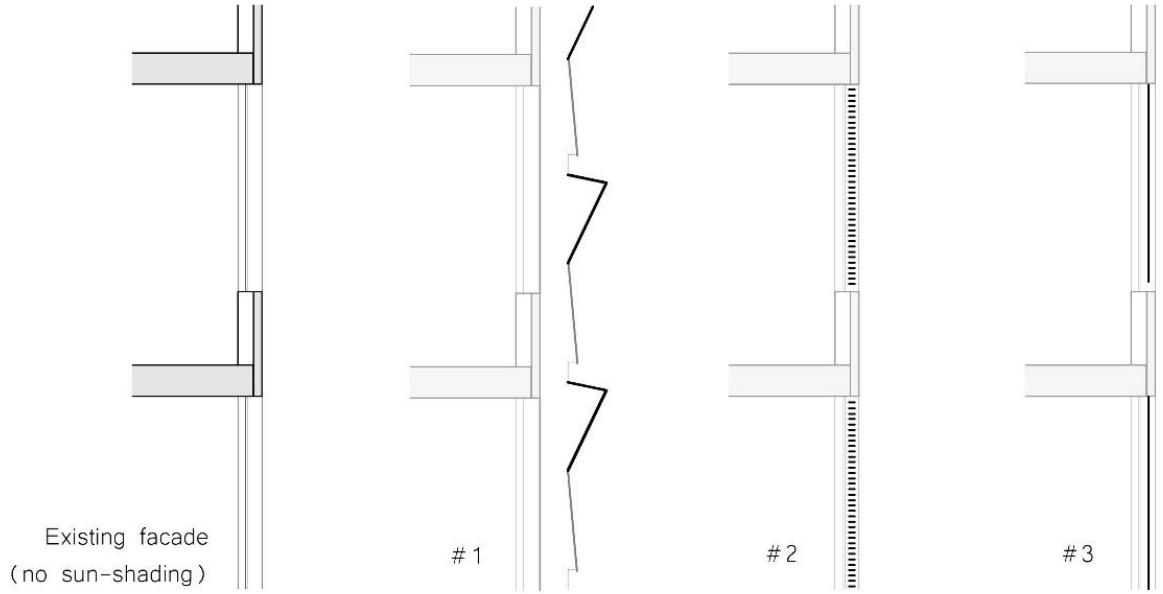


Case#8 (only sun-shading)

Cooling demands estimation studies - Energy Use Intensity (EUI)

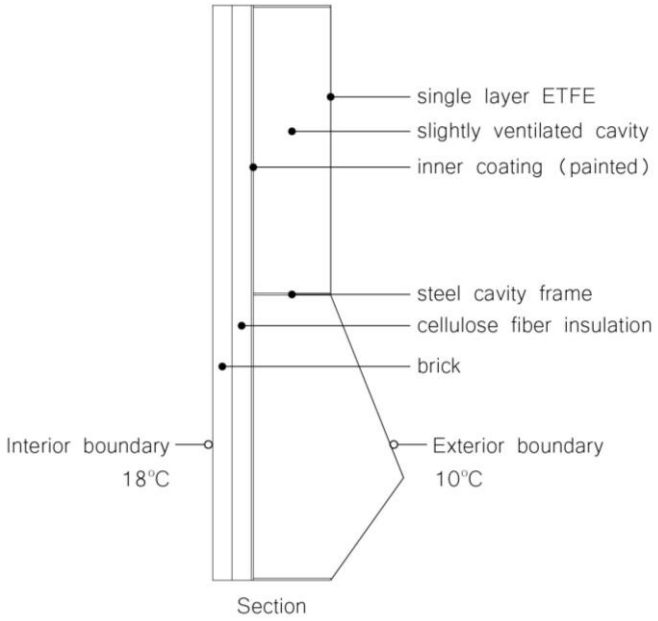
Case	Shading type scenario	Cooling loads per m^2 (Energy Use Intensity)	Difference in %
#	Existing single facade with no sun-shading	**120 kWh/m^2**	
1	Proposed facade skin design only as sun-shading	95 kWh/m^2	-21%
2	Typical exterior horizontal venetian blinds*	92 kWh/m^2	-23%
3	Exterior fabric roller shade/perforated metal screen*	89.5 kWh/m^2	-25%

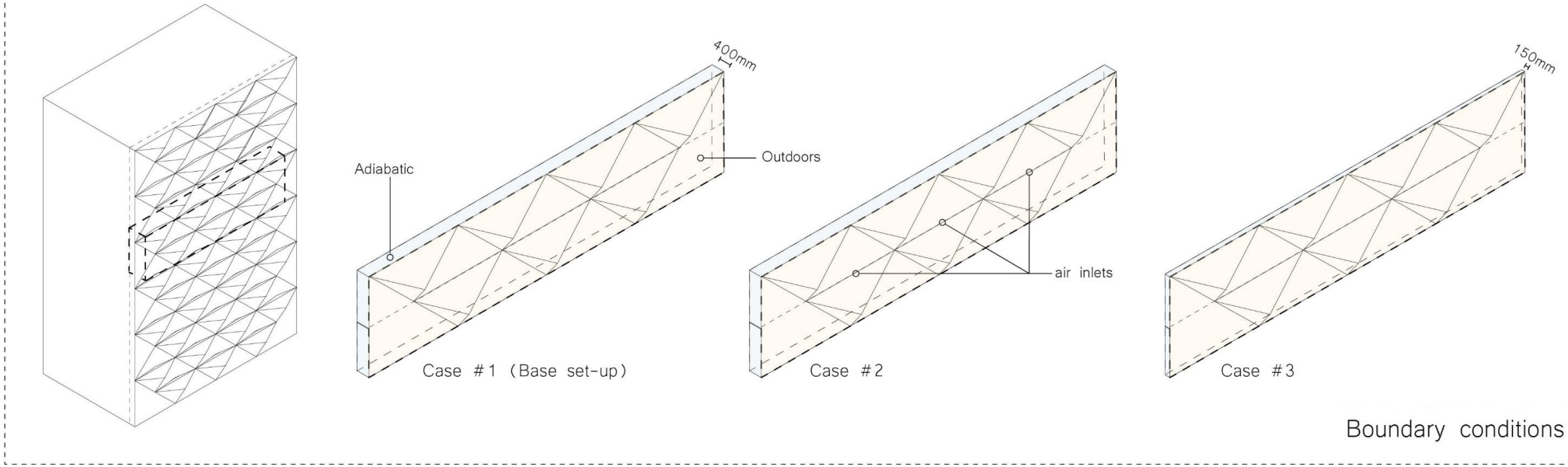
*Shading is on, if the outside air temperature exceeds the Cooling Setpoint of 24°C and if the horizontal solar radiation exceeds the SetPoint of 400 W/m^2



Convective heat transfer CFD simulations

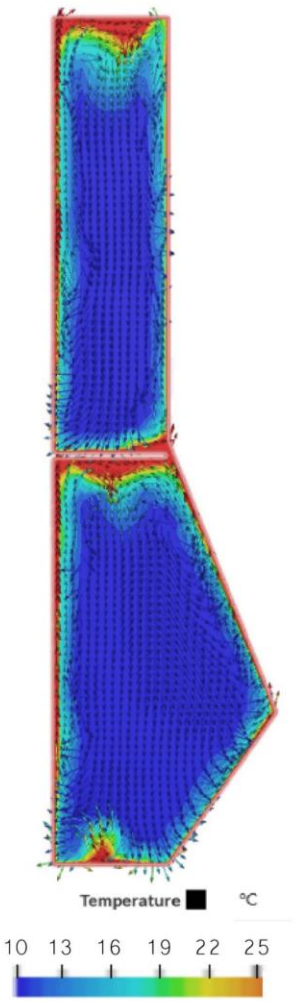
Multiple closed-air cavities (winter situation)

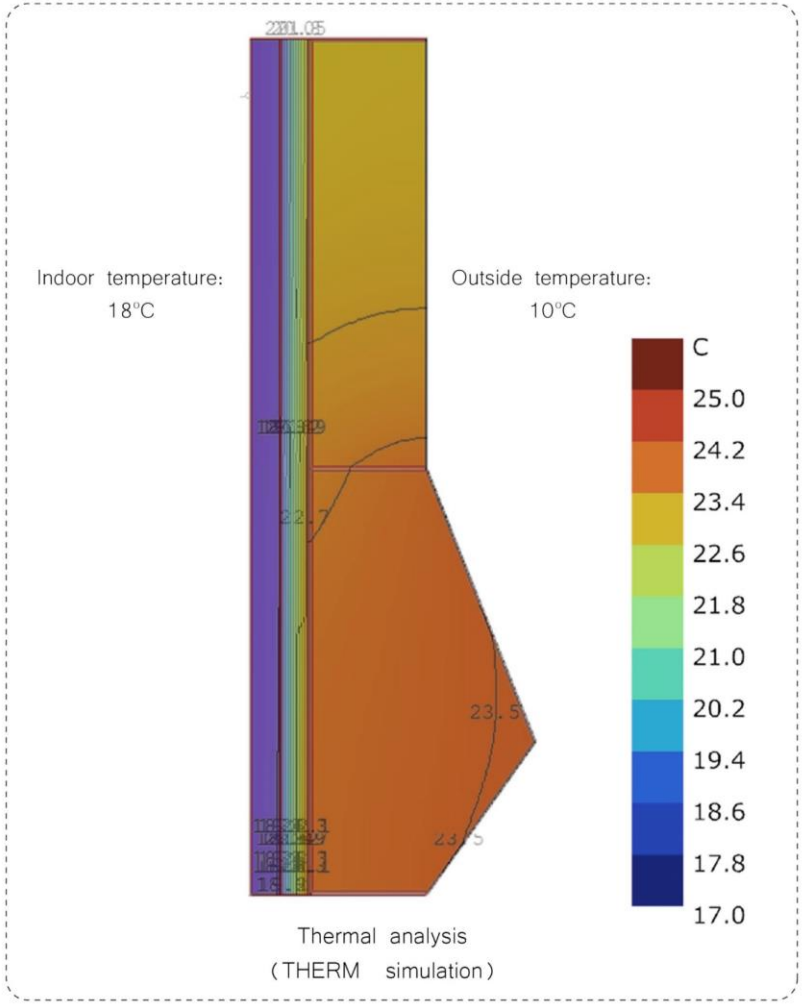




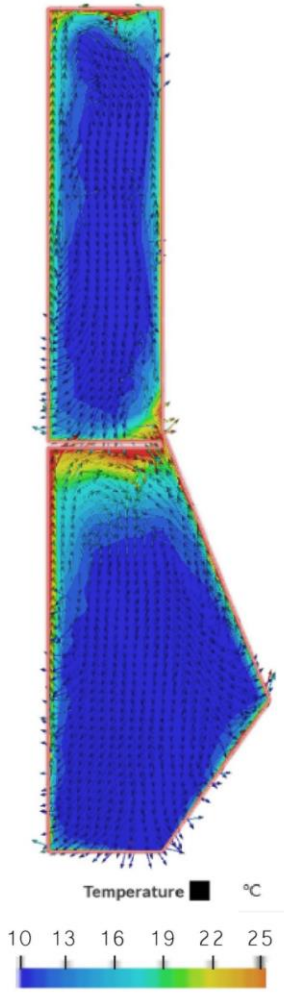
Convective heat transfer CFD simulations

Multiple closed-air cavities (winter situation)

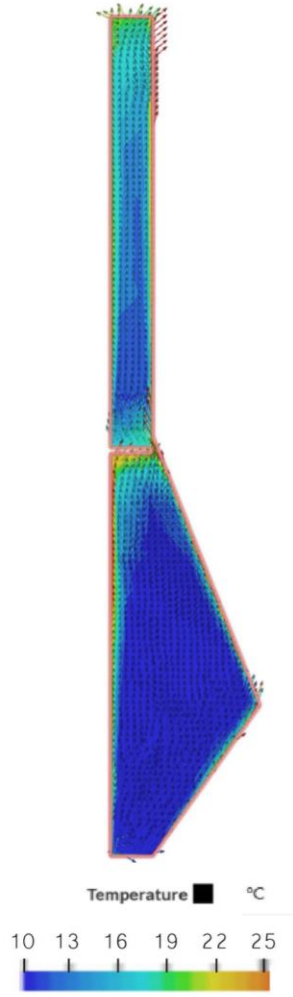




Simulation case #1



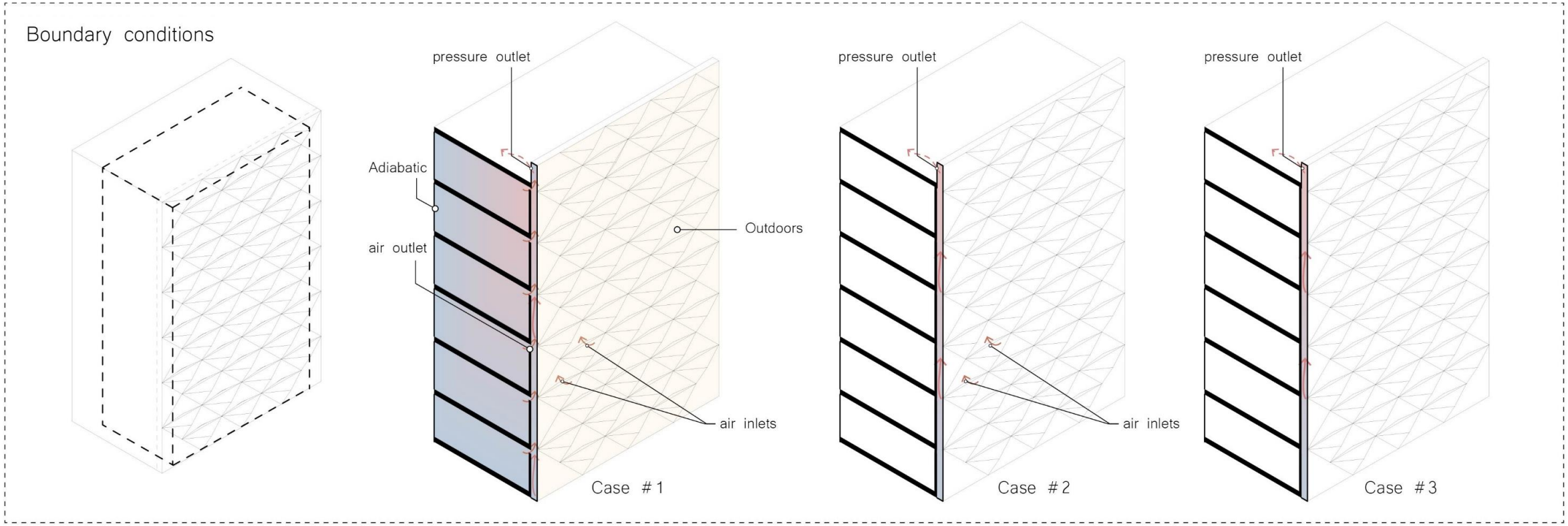
Simulation case #2



Simulation case #3

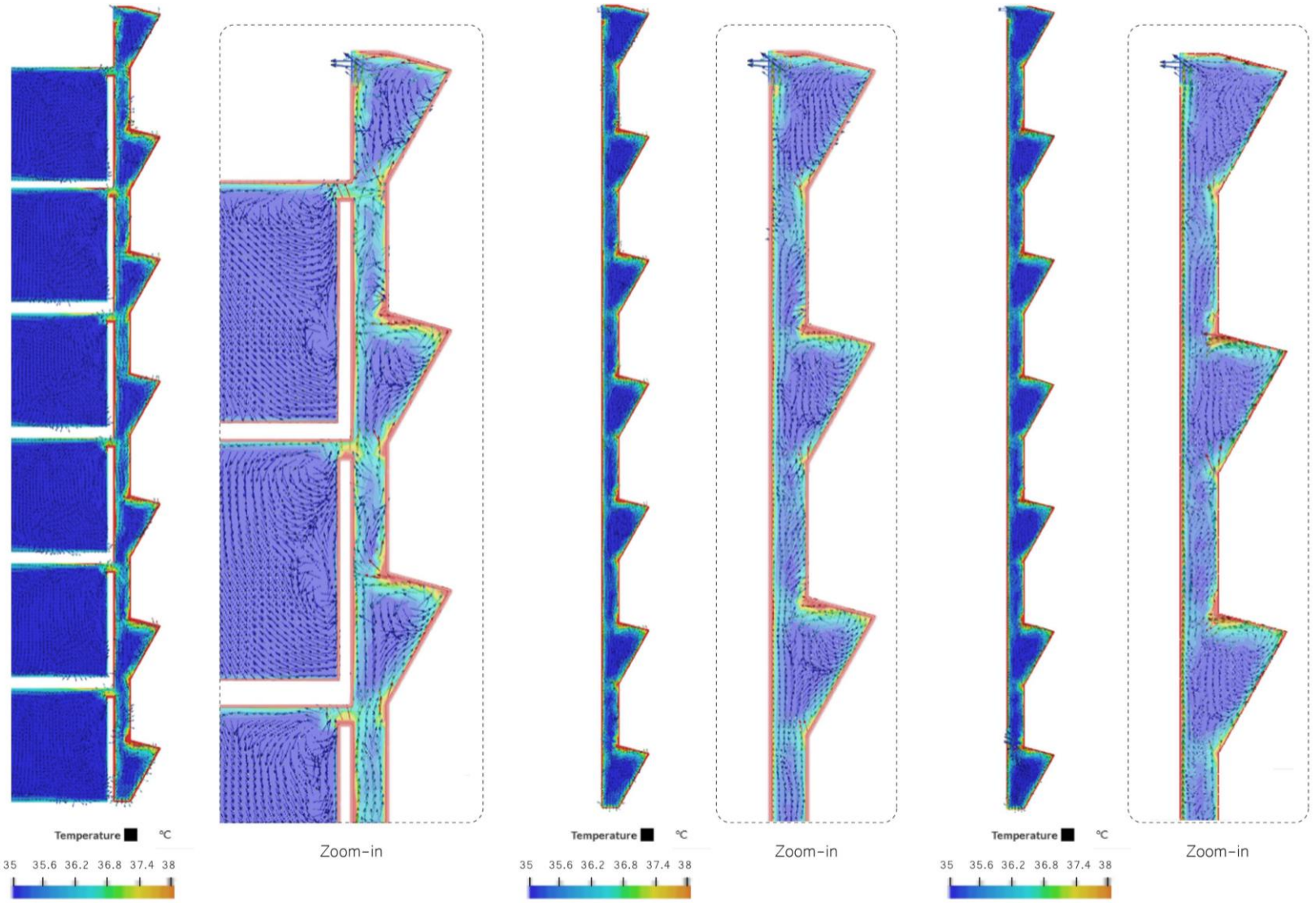
Convective heat transfer CFD simulations

Opened-air cavity （summer situation）



Convective heat transfer CFD simulations

Opened-air cavity （summer situation）



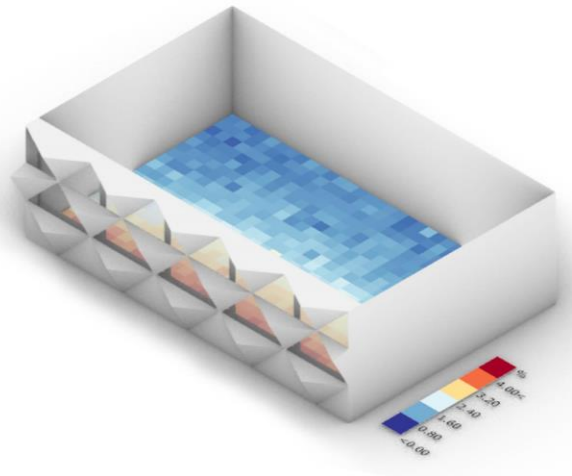
Simulation case #1　　Simulation case #2　　Simulation case #3

Daylight analysis studies

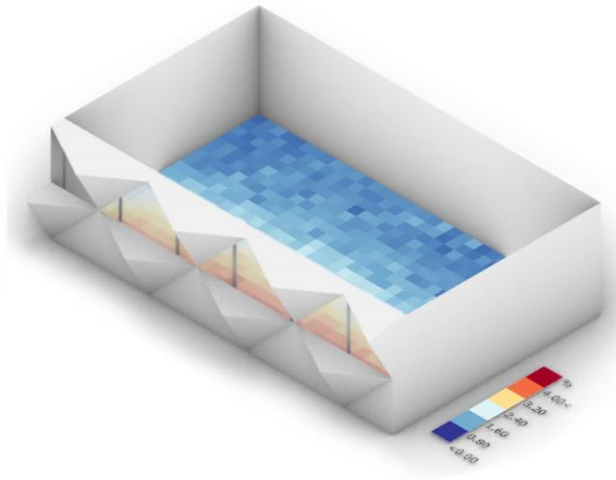
Case	Test variables		Room dimensions
#	Window-to-wall ratio	Component overall size	Length: 10m Depth: 6m Interior height: 3m
1	0.45	2000mm*2000mm	
2	0.45	3000mm*3000mm	
3	0.85	3000mm*3000mm	

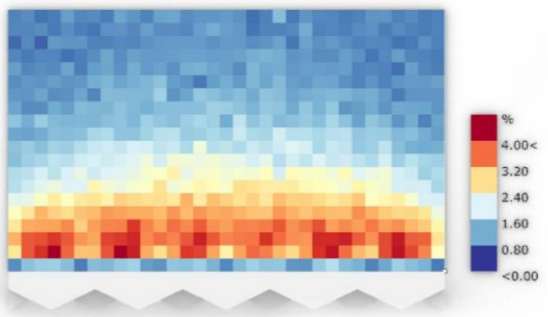
Case	Daylight factor (DF)	DF of 80% of test points	room depth within DF BREEAM limits	UDI within 100-2000 lux range
Existing single facade with no external sun-shading	**7.5%**	**5.3%**	**yes**	**56%**
#1	1.4%	2.15%	<=3.5m	80%
#2	1.3%	1.85%	<=3m	78%
#3	1.95%	3.2%	<=3.7m	84%

Case#1

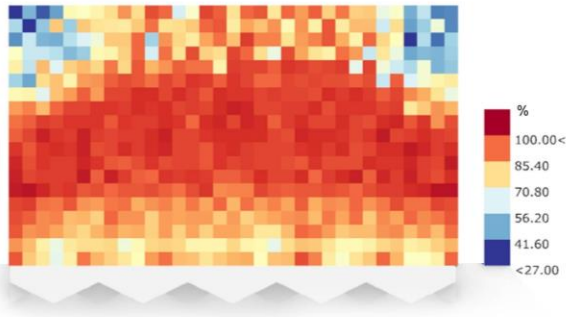


Case#2

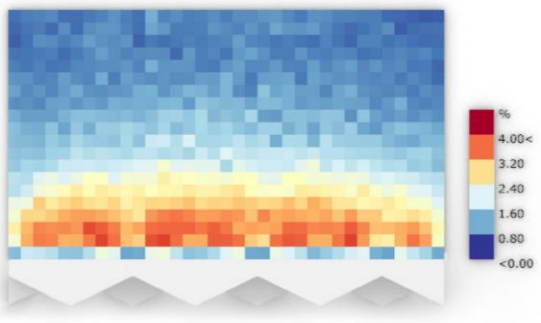




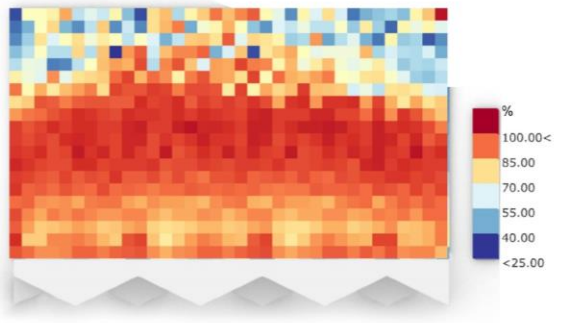
Daylight Factor (DF)



Useful Daylight Illuminance Index (UDI) 100-2000 lux

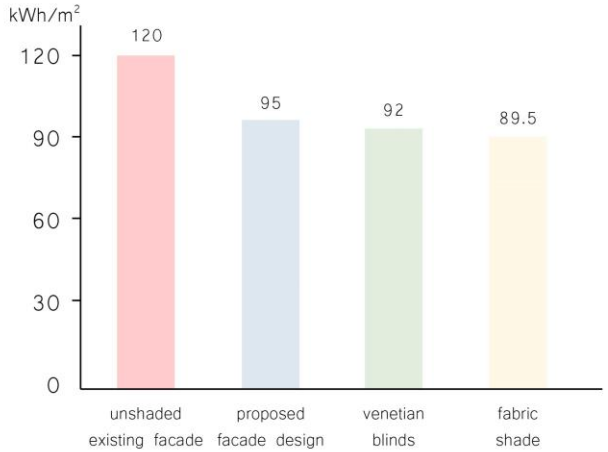


Daylight Factor (DF)

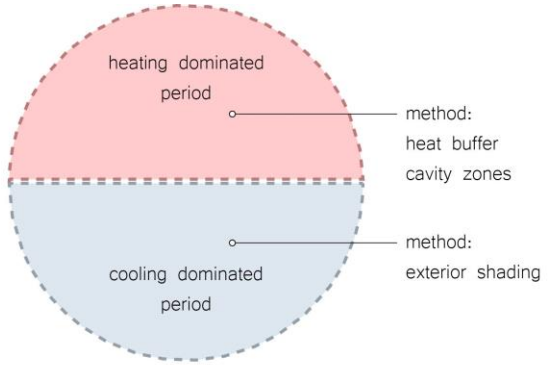


Useful Daylight Illuminance Index (UDI) 100-2000 lux

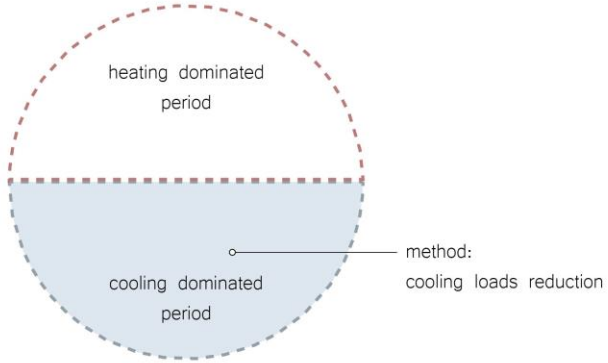
Conclusions



building's cooling loads per m^2 with different exterior shading systems
(April-October)
[building's indirect impact mitigation method]

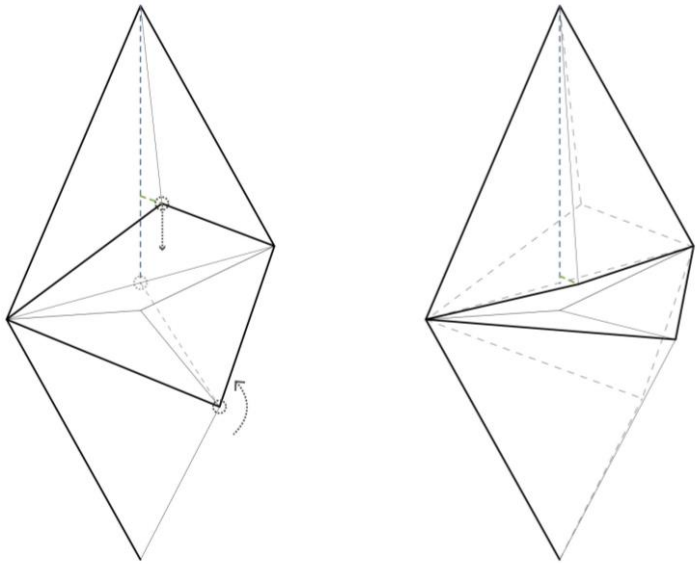


overall building's annual energy performance improvement with the proposed dynamic facade design

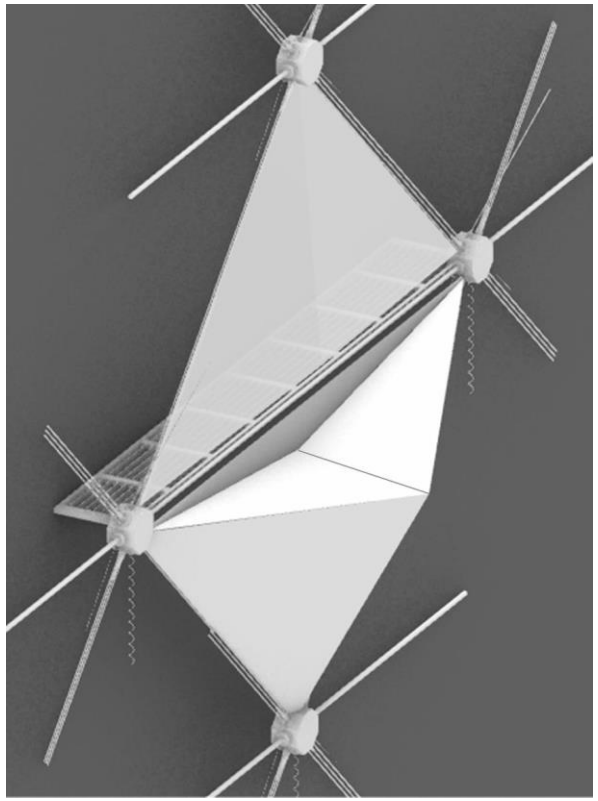


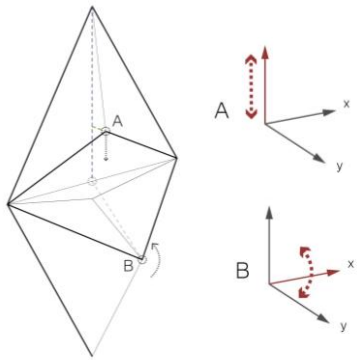
building's indirect UHI impact reduction
[building's annual environmental performance improvement]

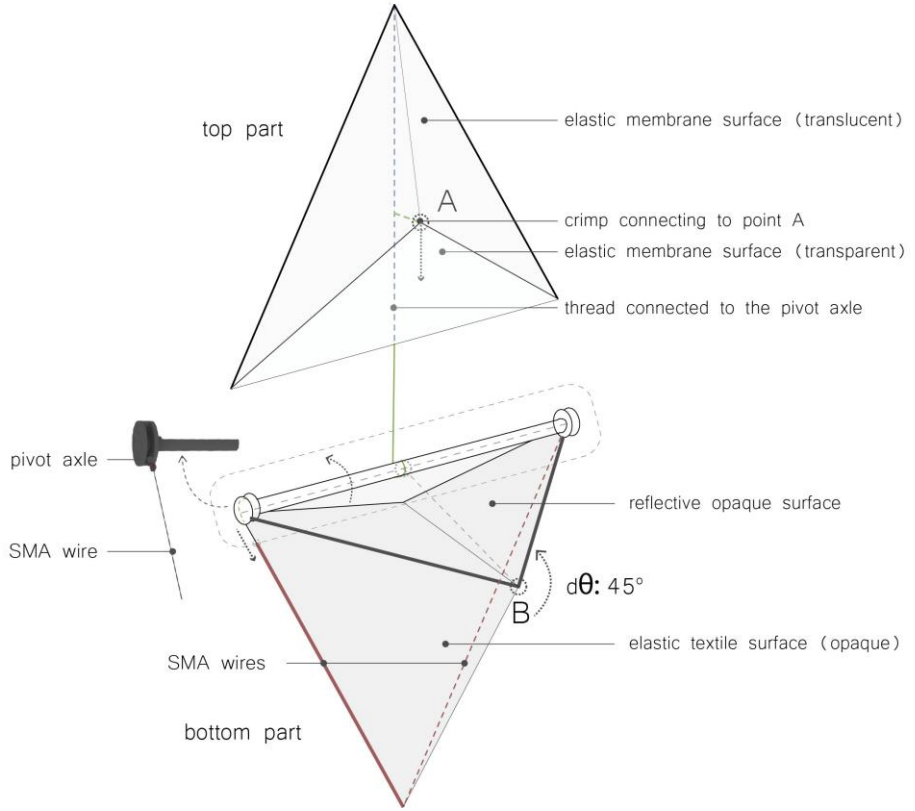
Final Design

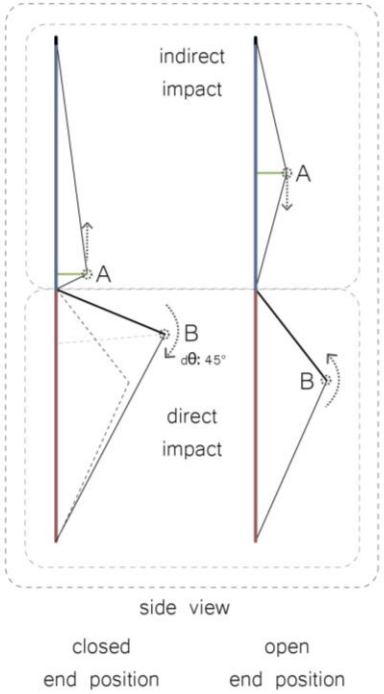


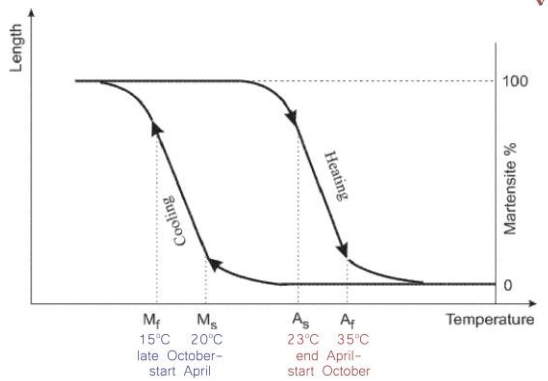
Concept development





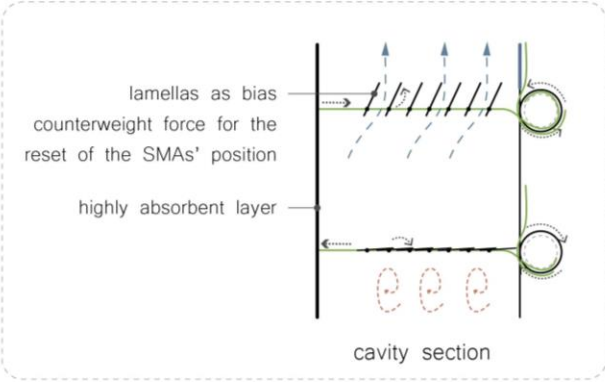




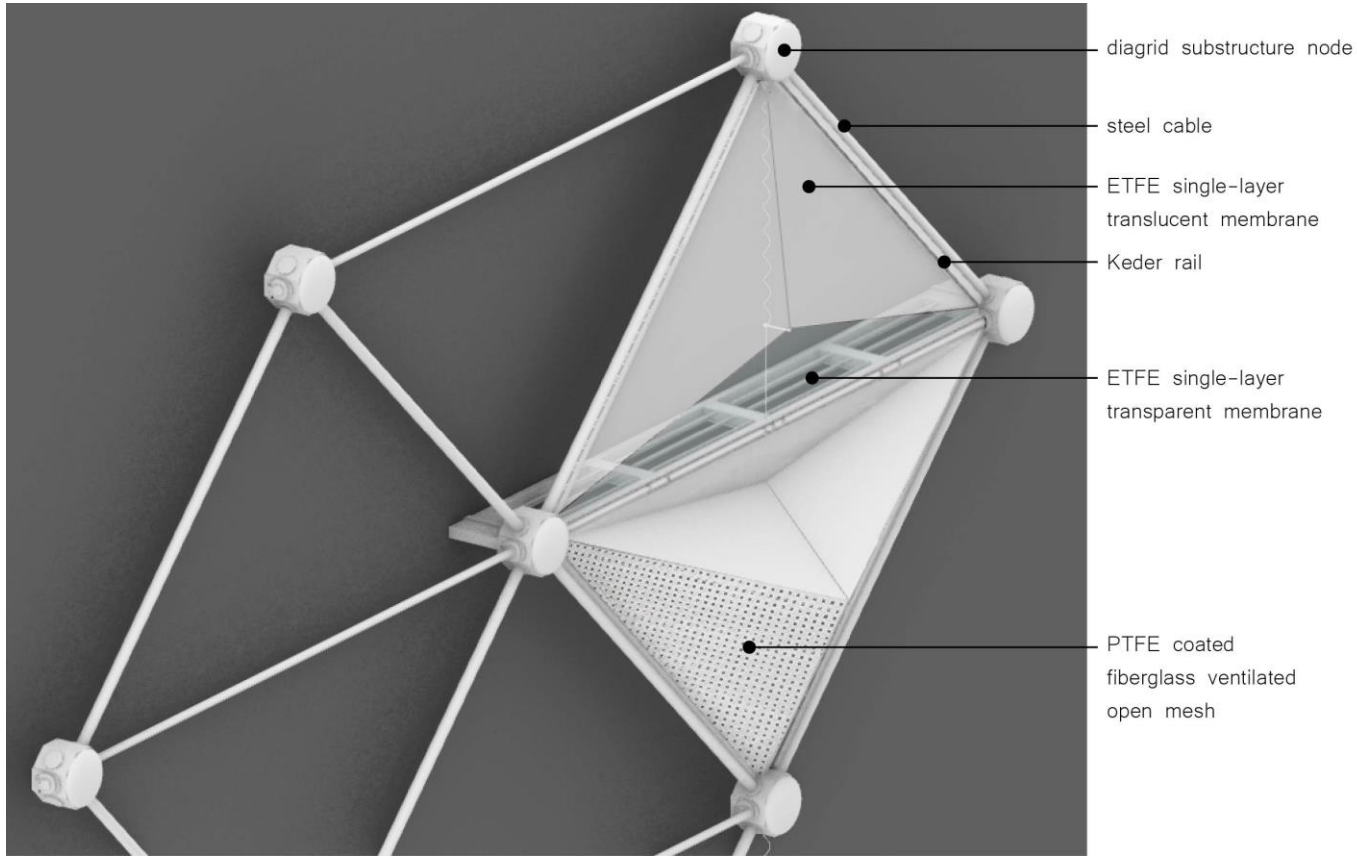


Actuation characteristics

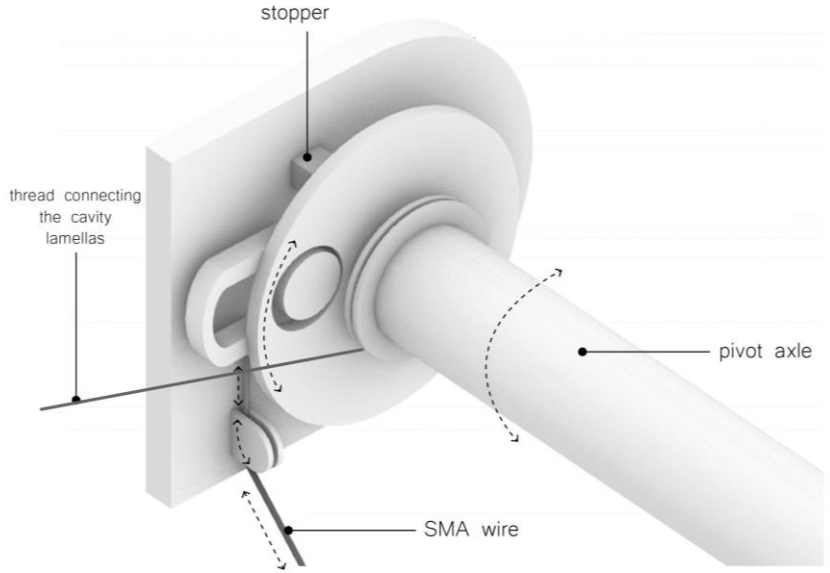
SMA actuation temperatures:
As: 23°C
Af: 35°C
Ms: 20°C
Mf: 15°C

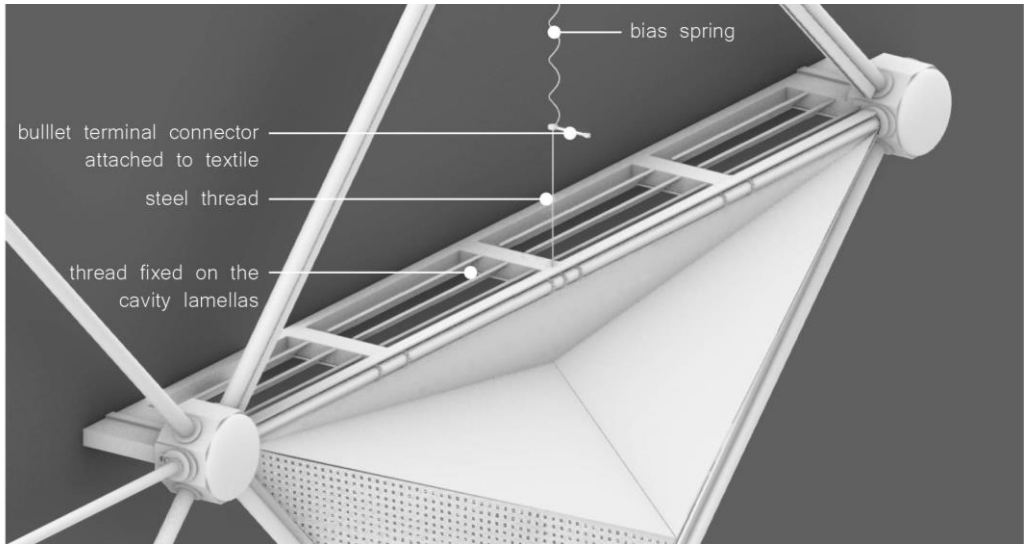


Component development – SMA mechanism

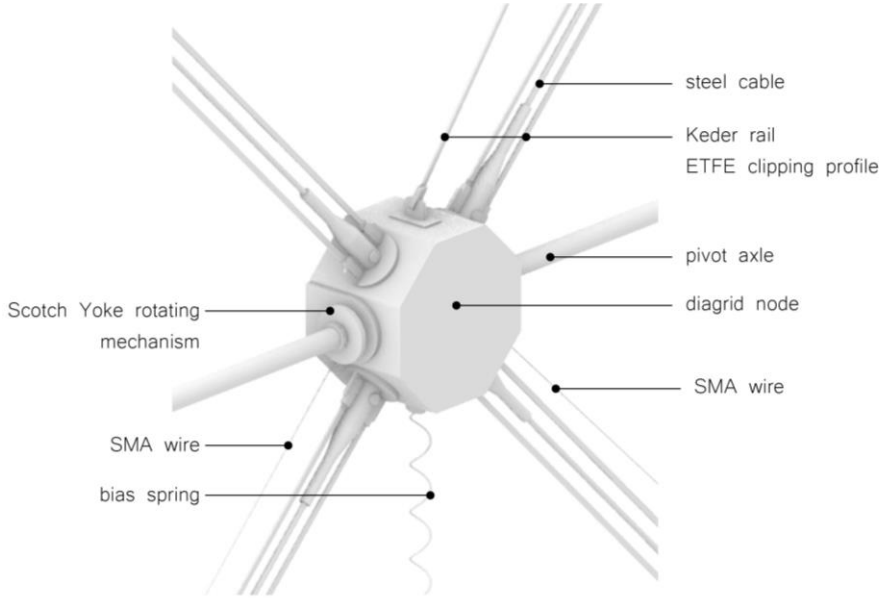


Scotch Yoke pivot mechanism



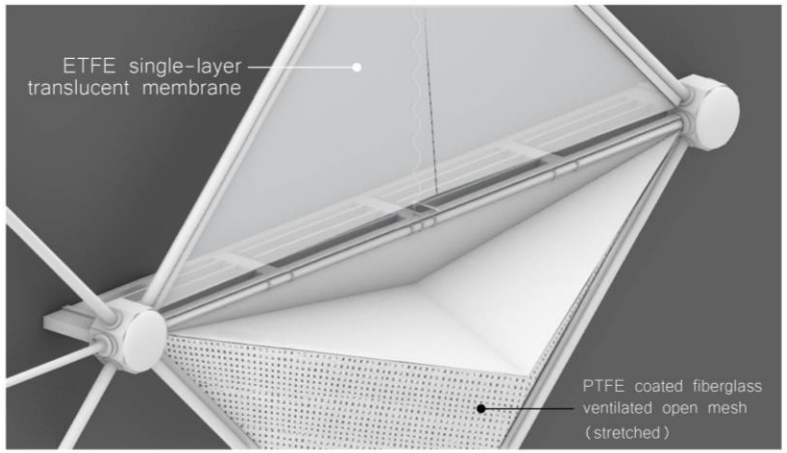


Component development

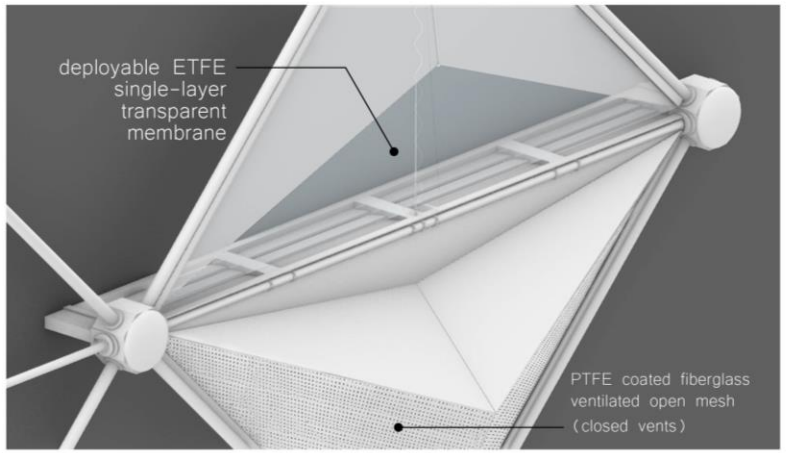


Diagrid node connection components

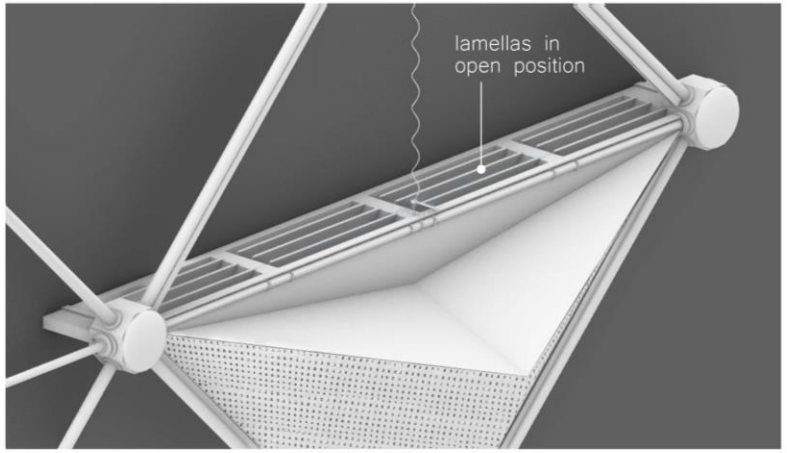
summer situation



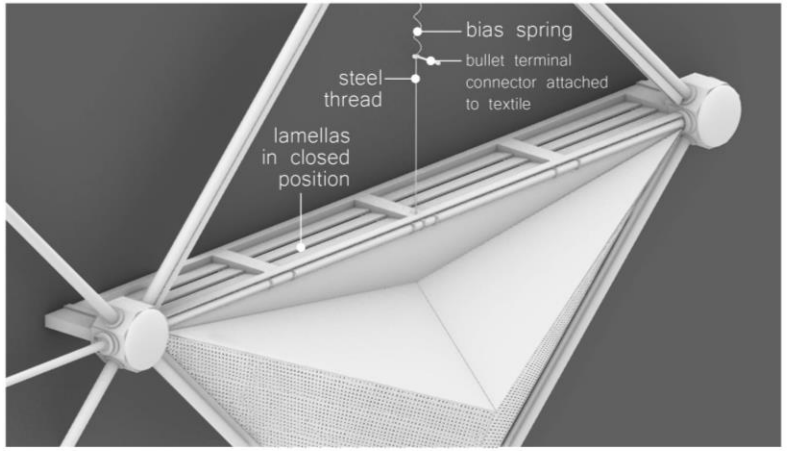
winter situation



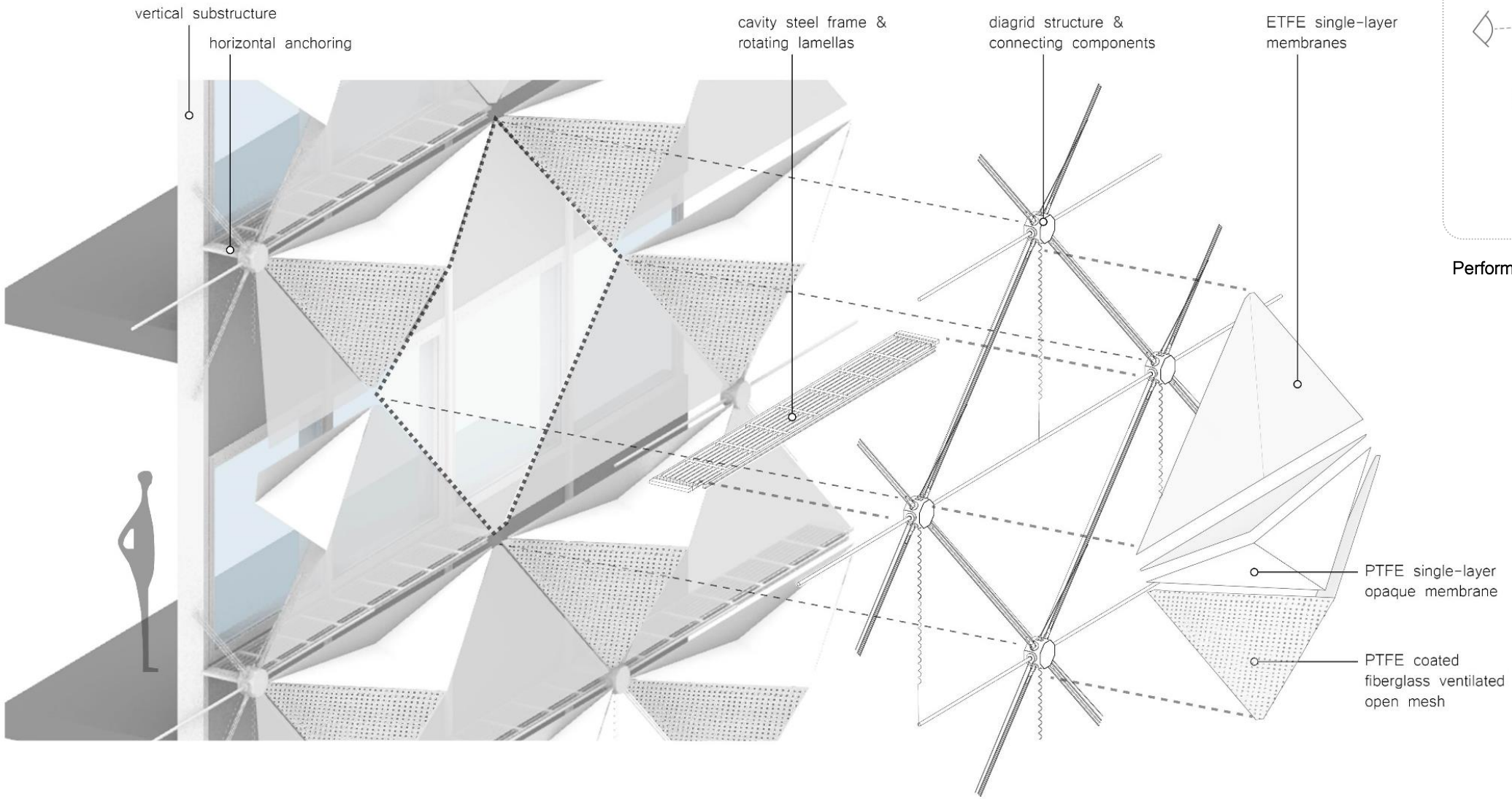
top mechanism zoom-in

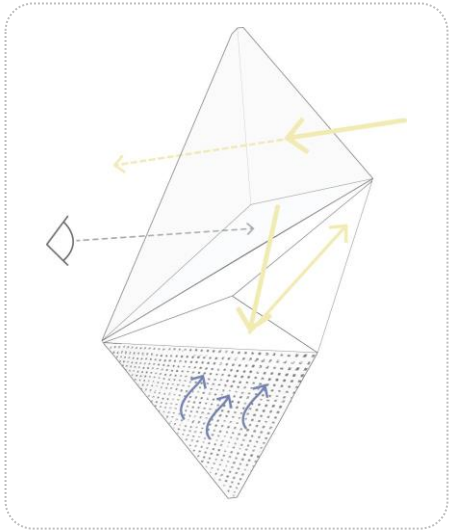


top mechanism zoom-in



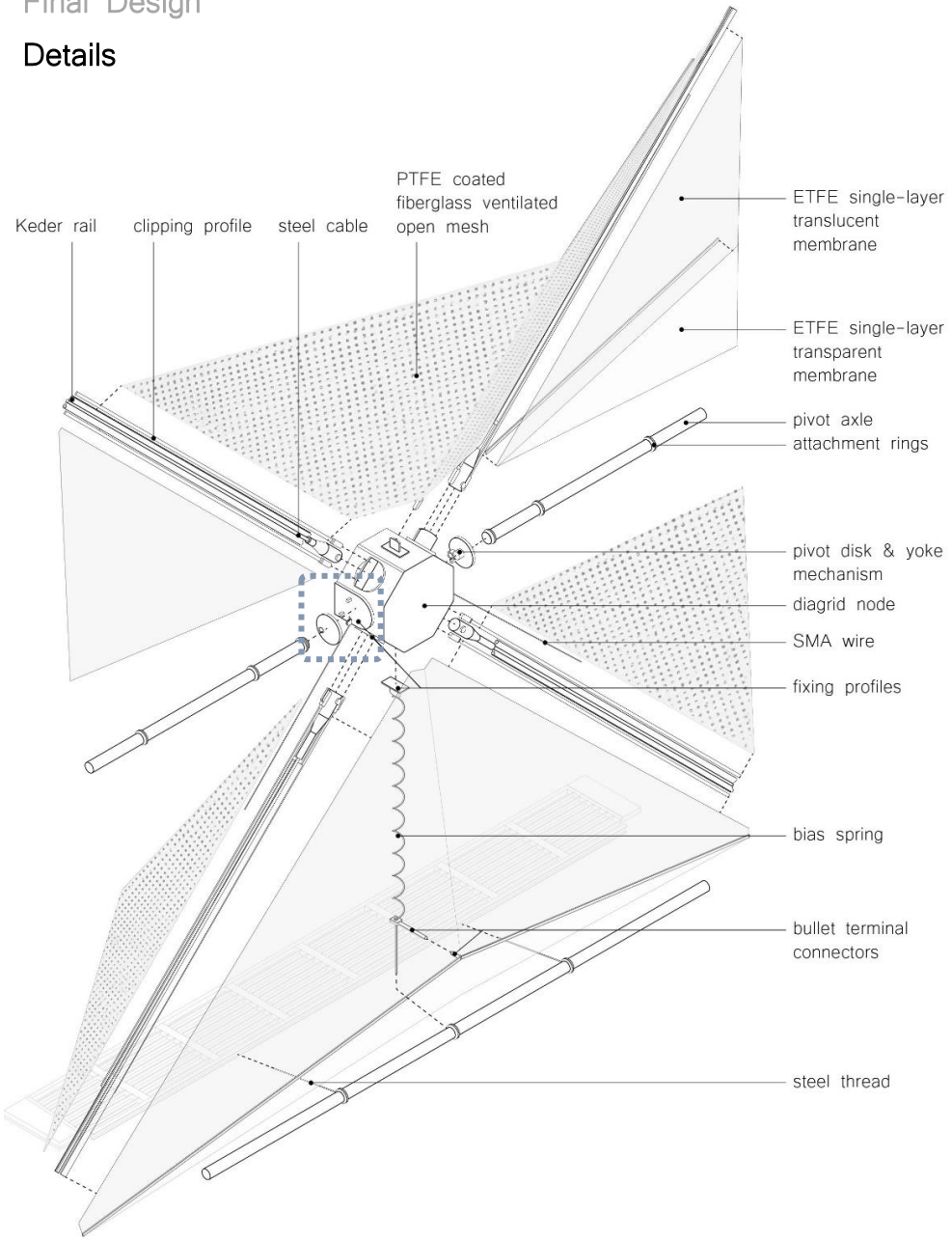
Component development

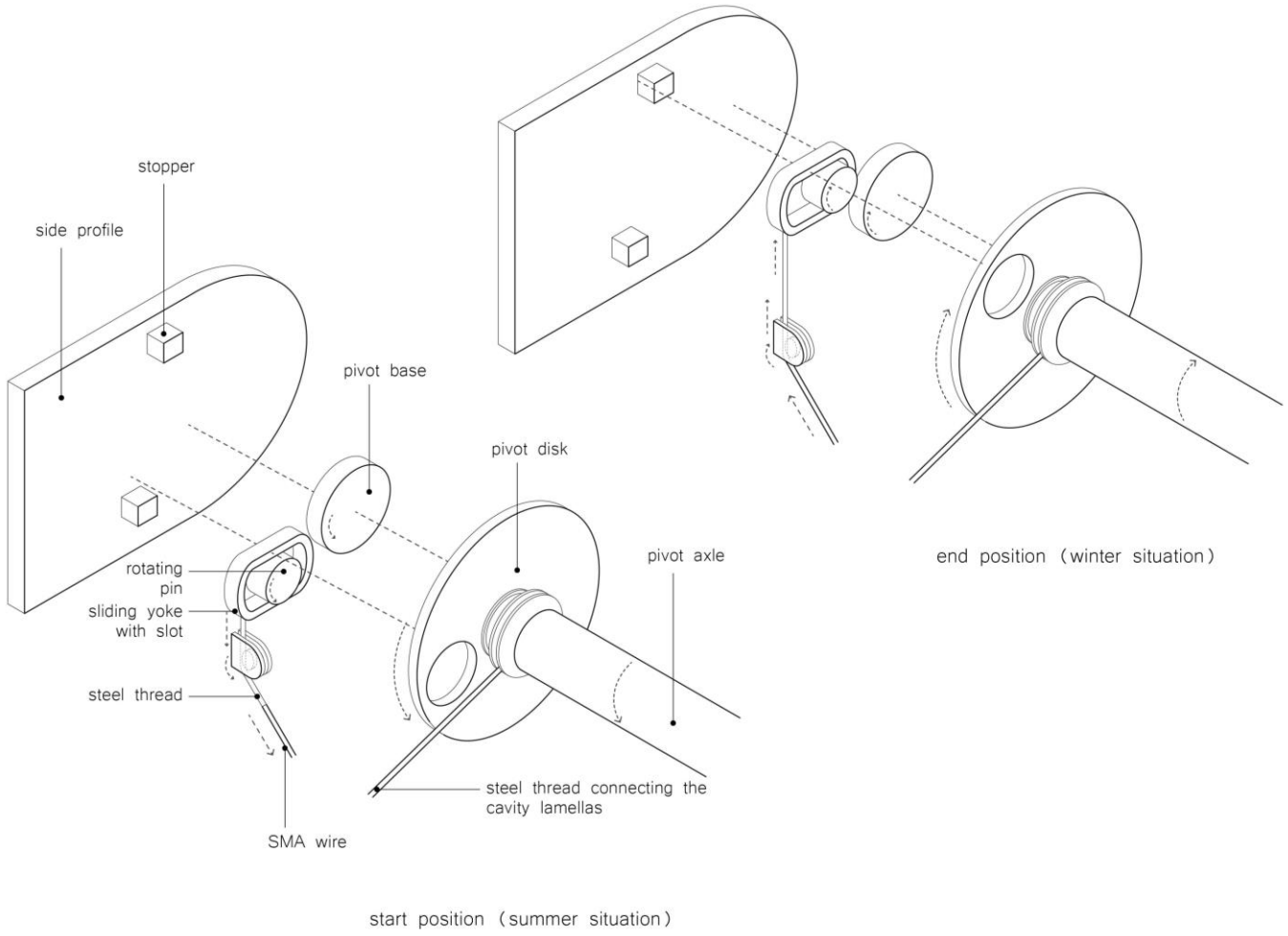




Performance-driven material selection

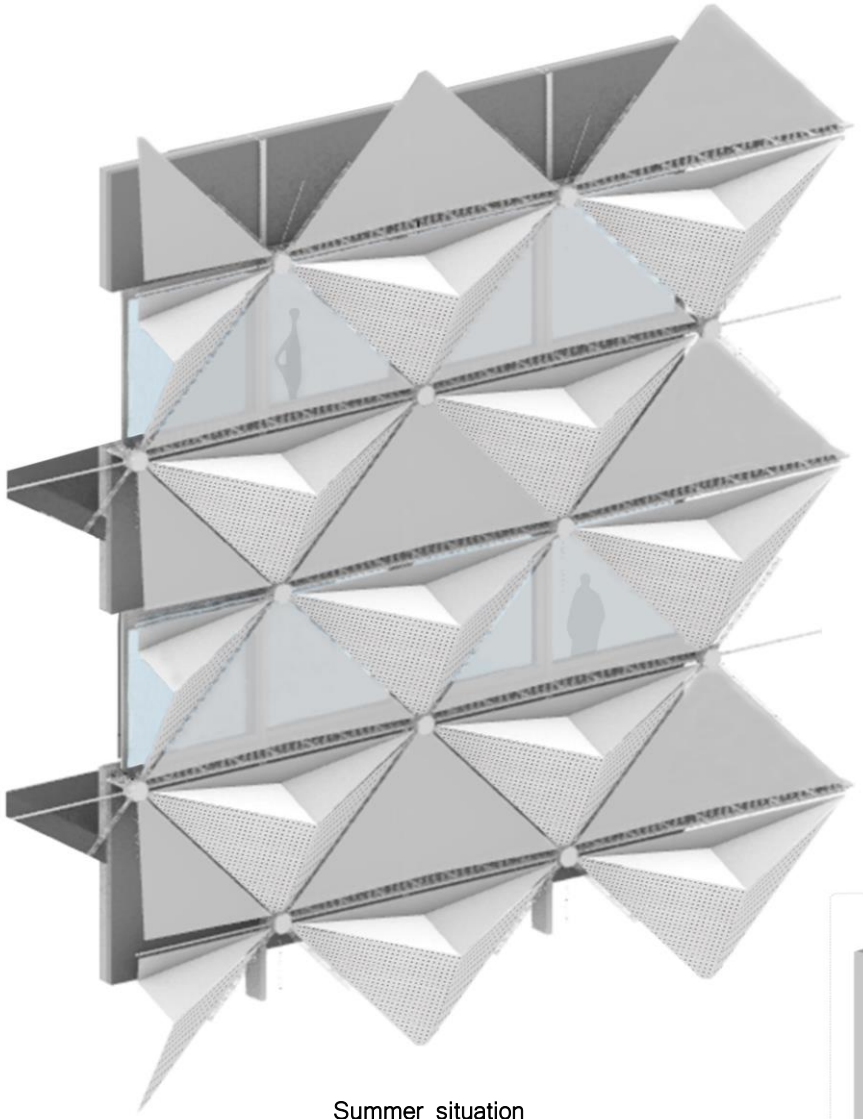
Details



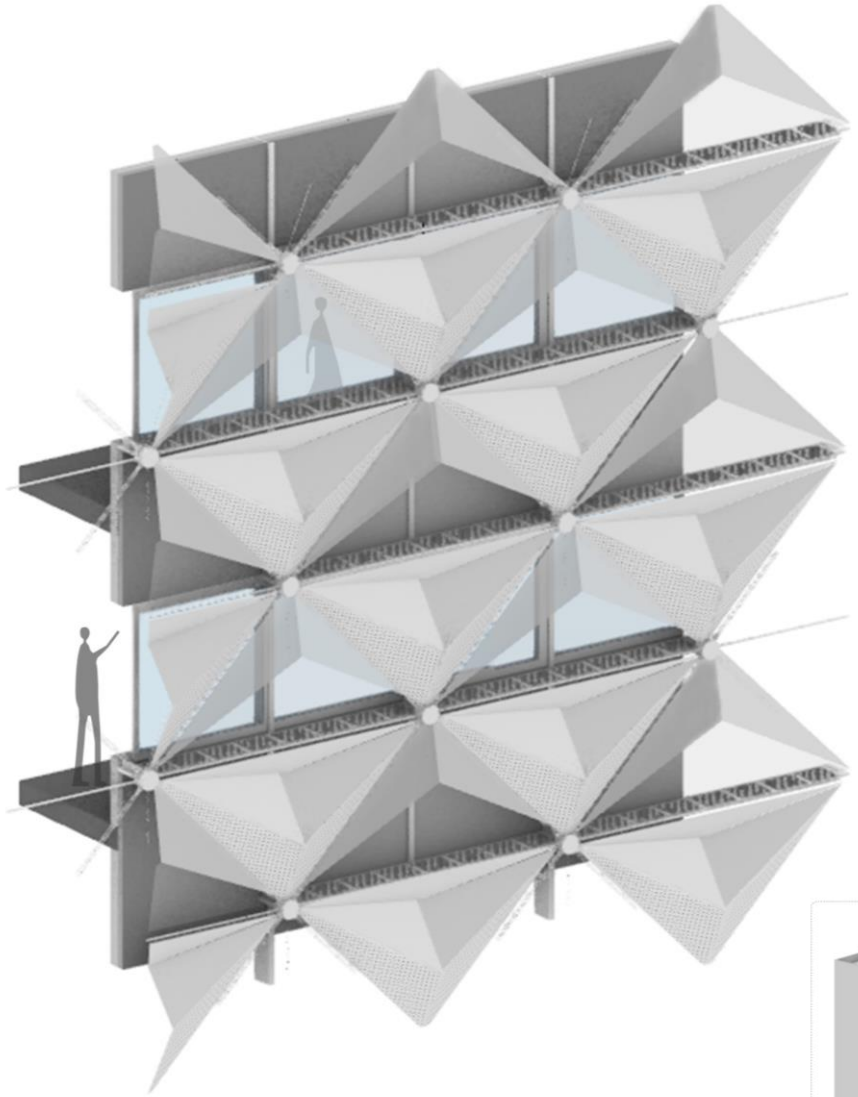


Pivot mechanism

Visualizations

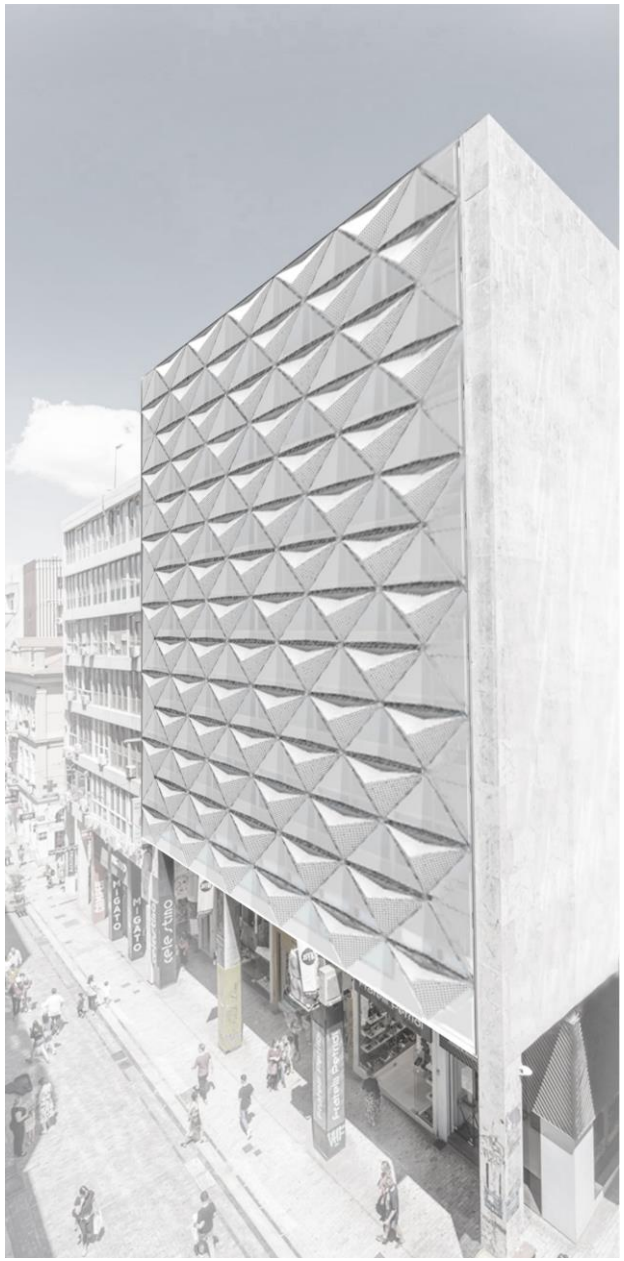


Summer situation

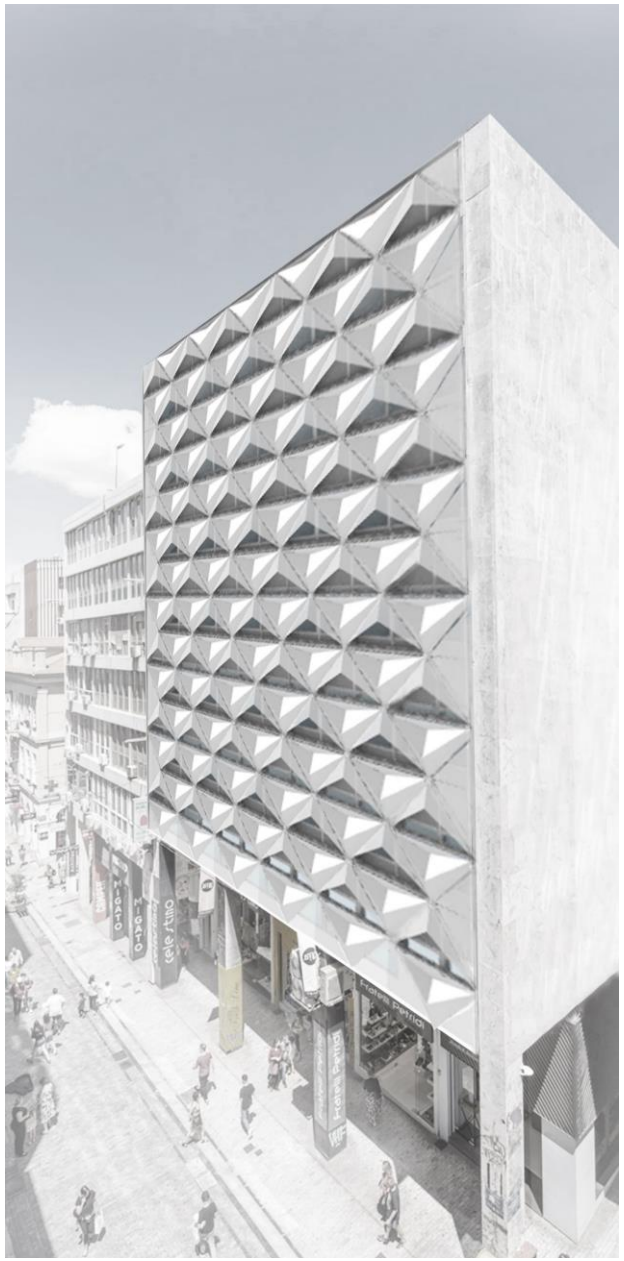


Winter situation

Visualizations

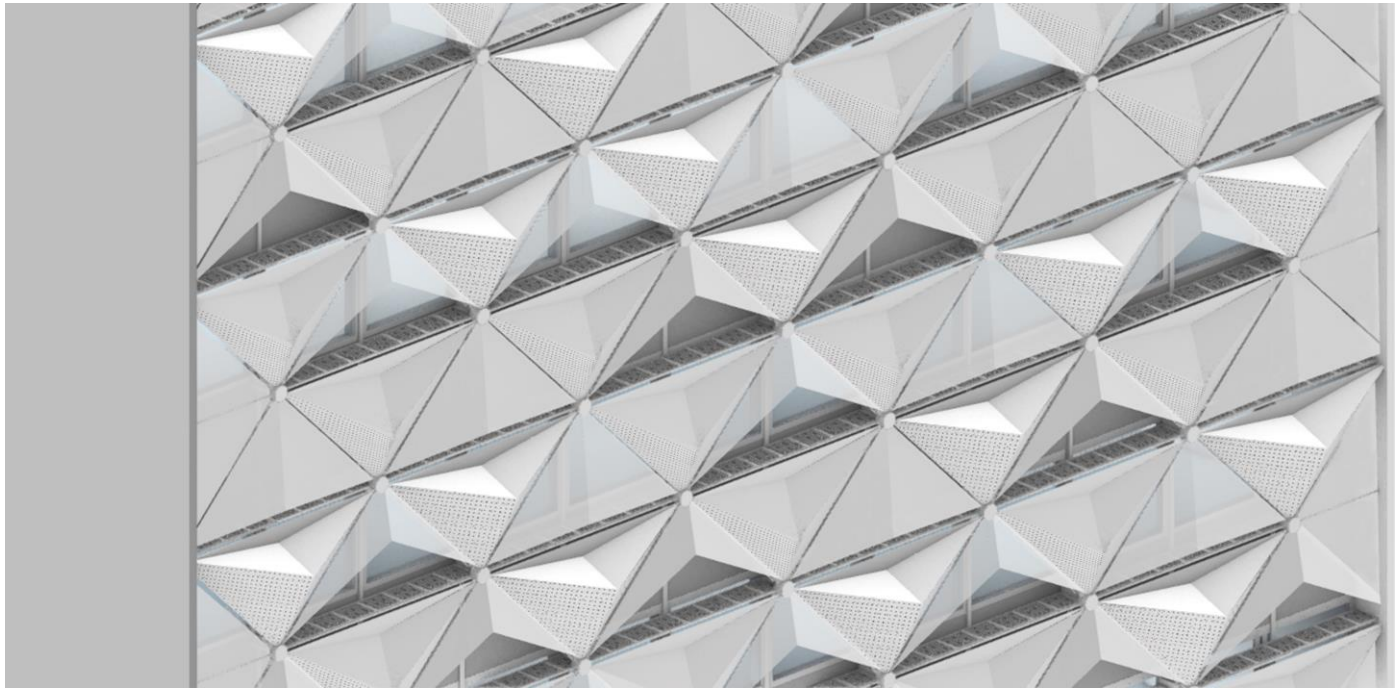


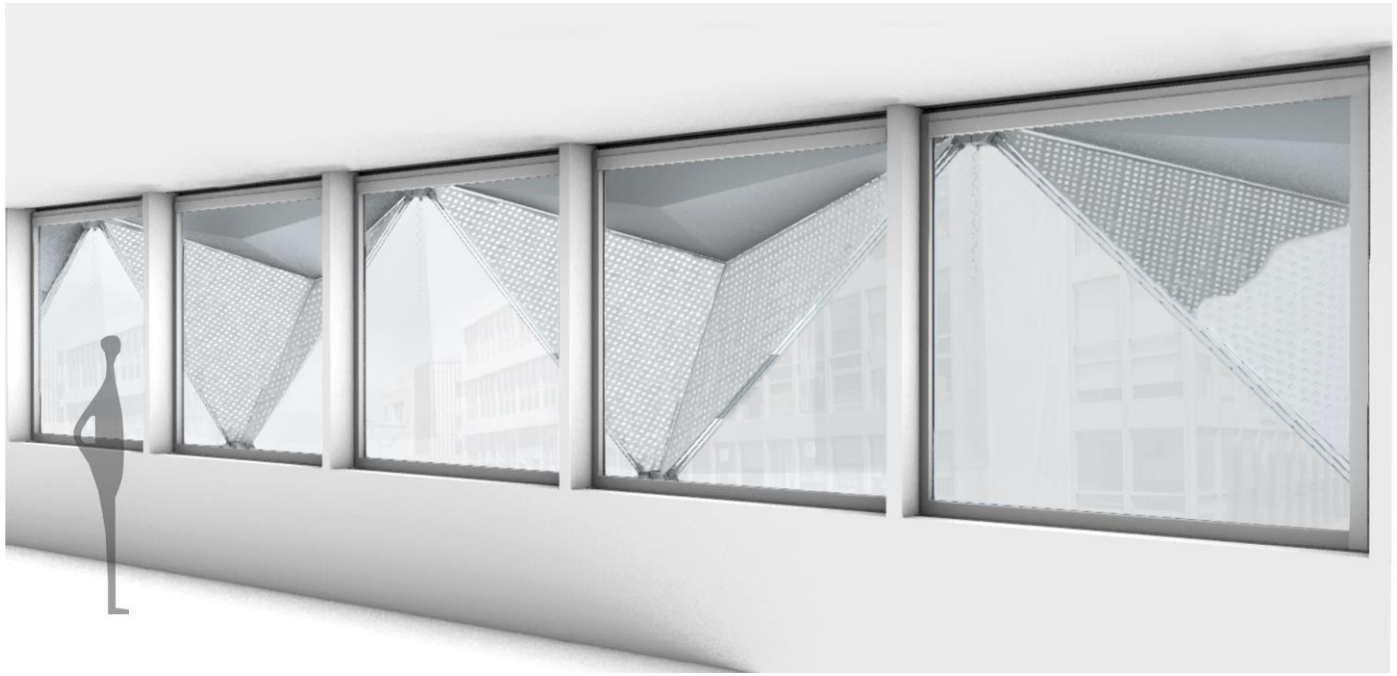
Summer situation



Winter situation

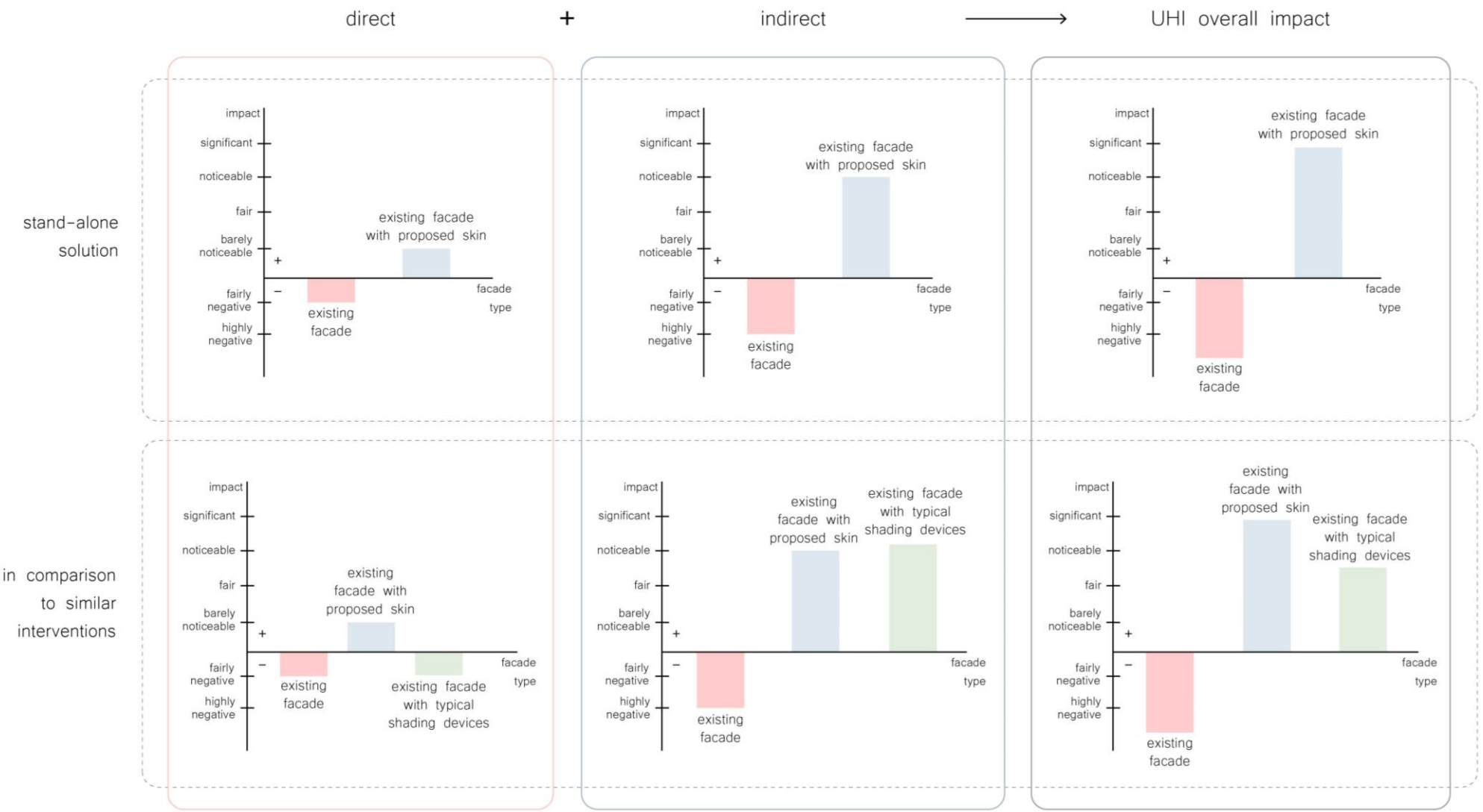
Visualizations



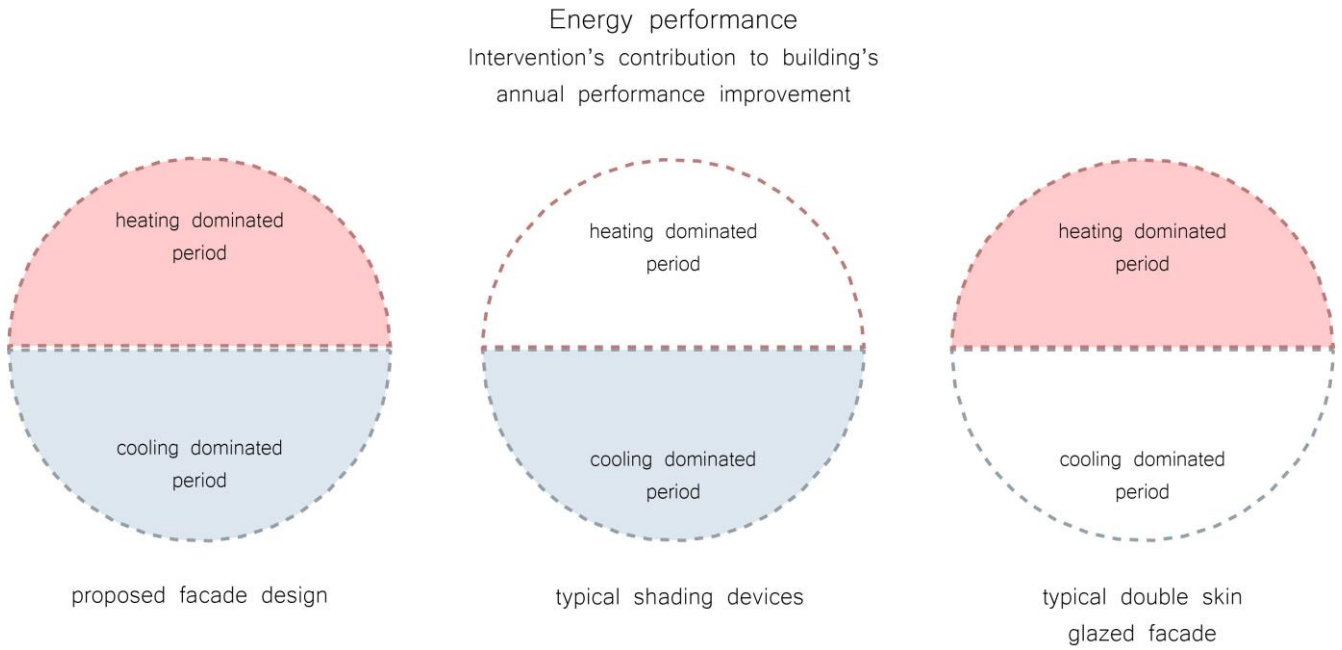


Environmental performance – Building's UHI impact

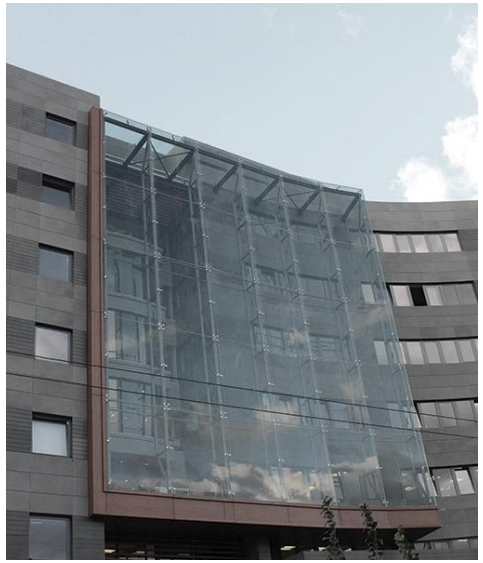
Environmental performance
Building's UHI impact
Qualitative comparative ranking
+ positive contribution
– negative contribution

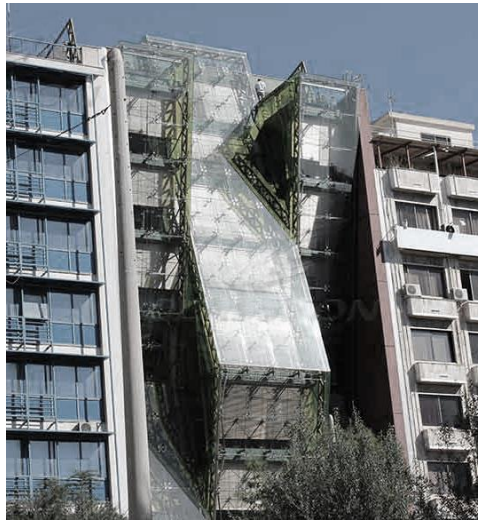


Building's energy performance



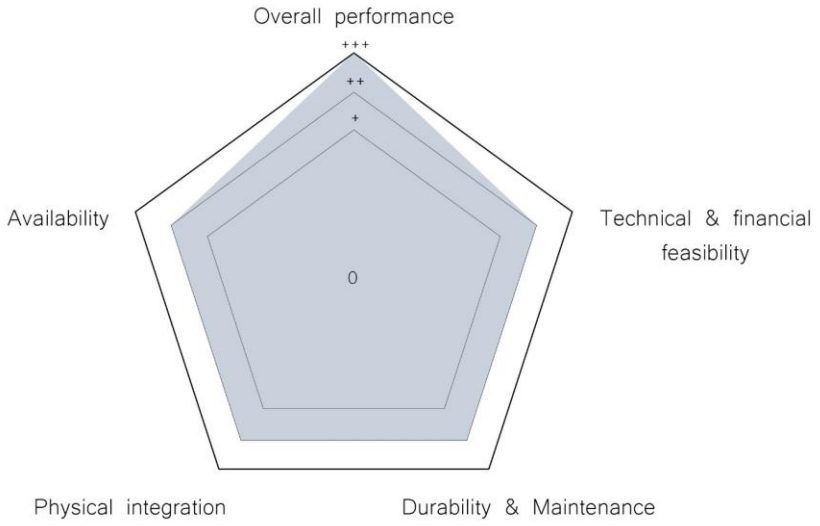
Feasibility assessment



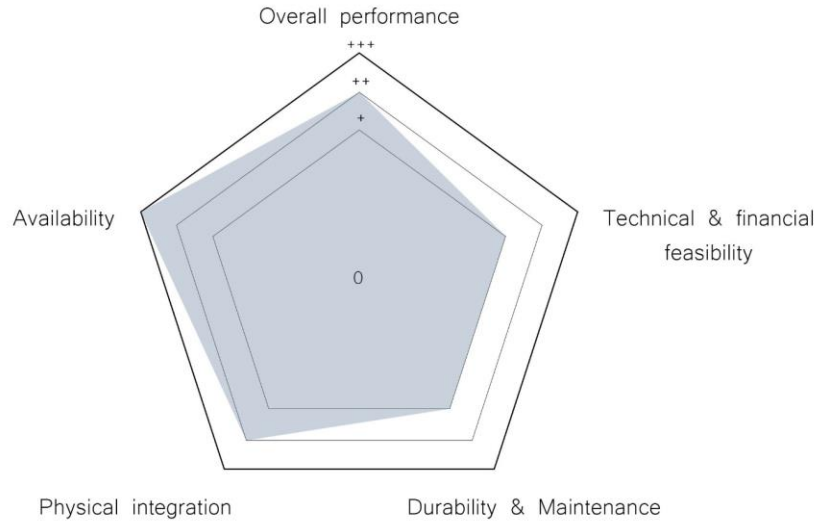


Double façade examples in Athens

Qualitative assessment map for the facade integration potential of responsive facade systems

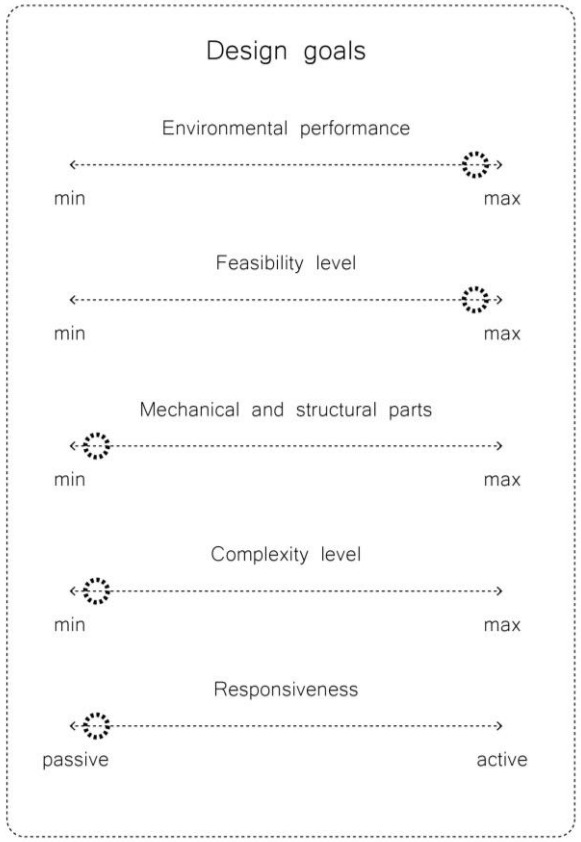


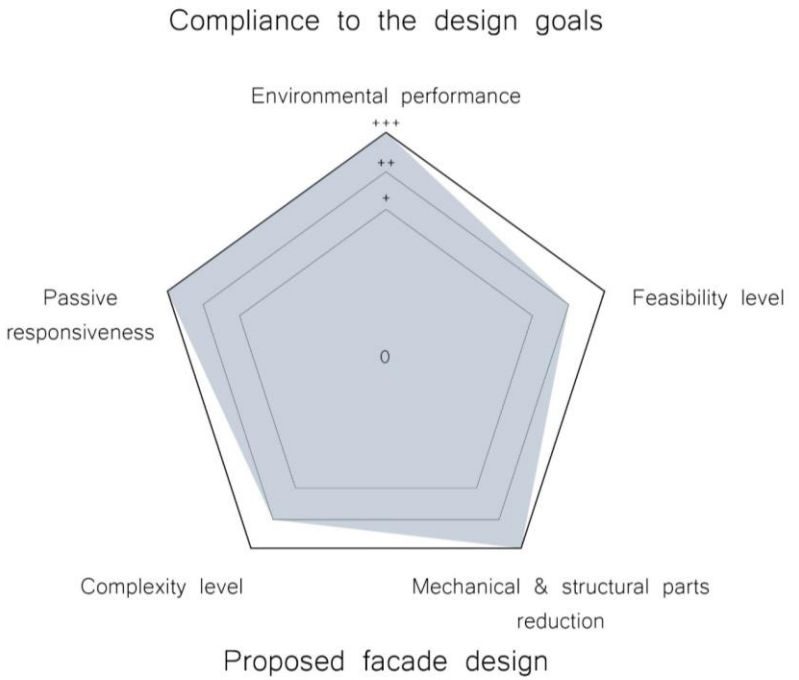
Proposed facade design



Double skin facade examples

Compliance to design goals – Answer to research question





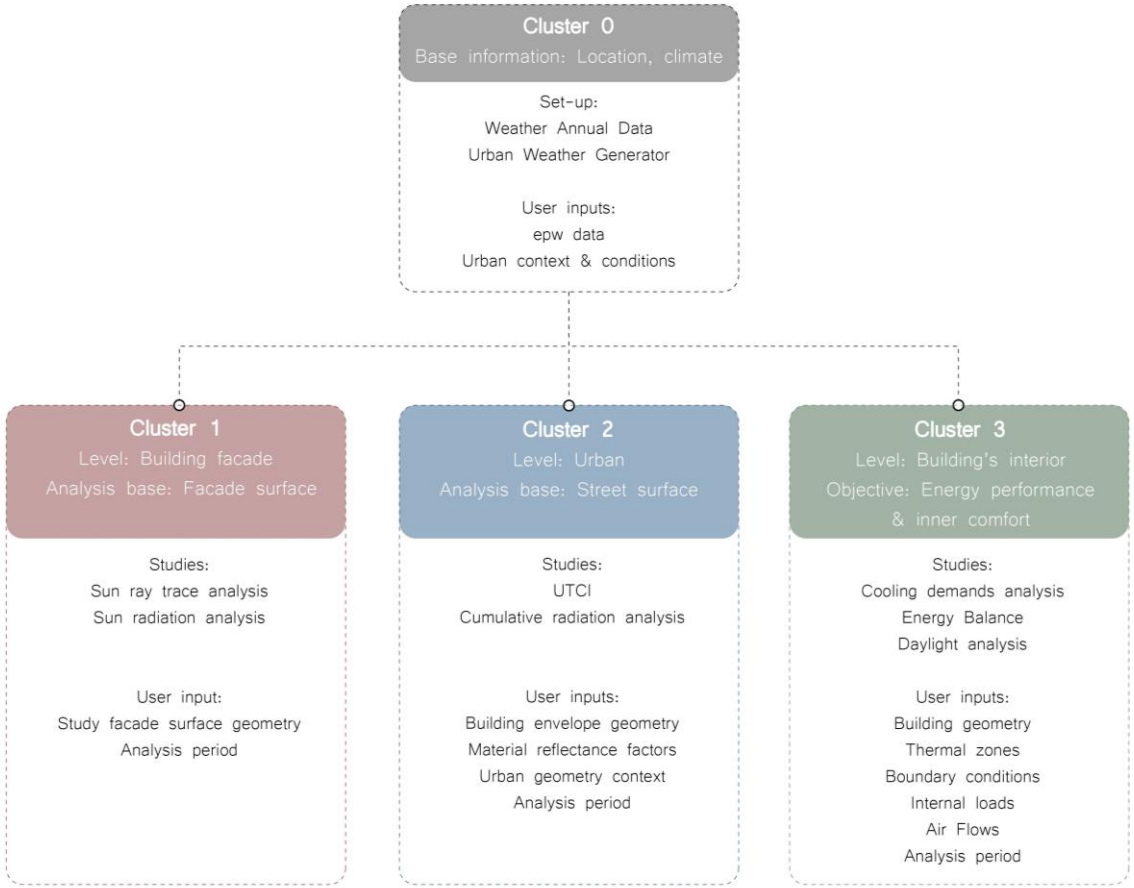
Proposed facade design

"whether, how and to what extent the implementation of SMMs in an integrated passive adaptive solar morphing system can contribute to the reduction of the building's impact on the UHI effect in an energy-efficient and autoreactive way"

Limitations & Challenges – Future developments – Open questions

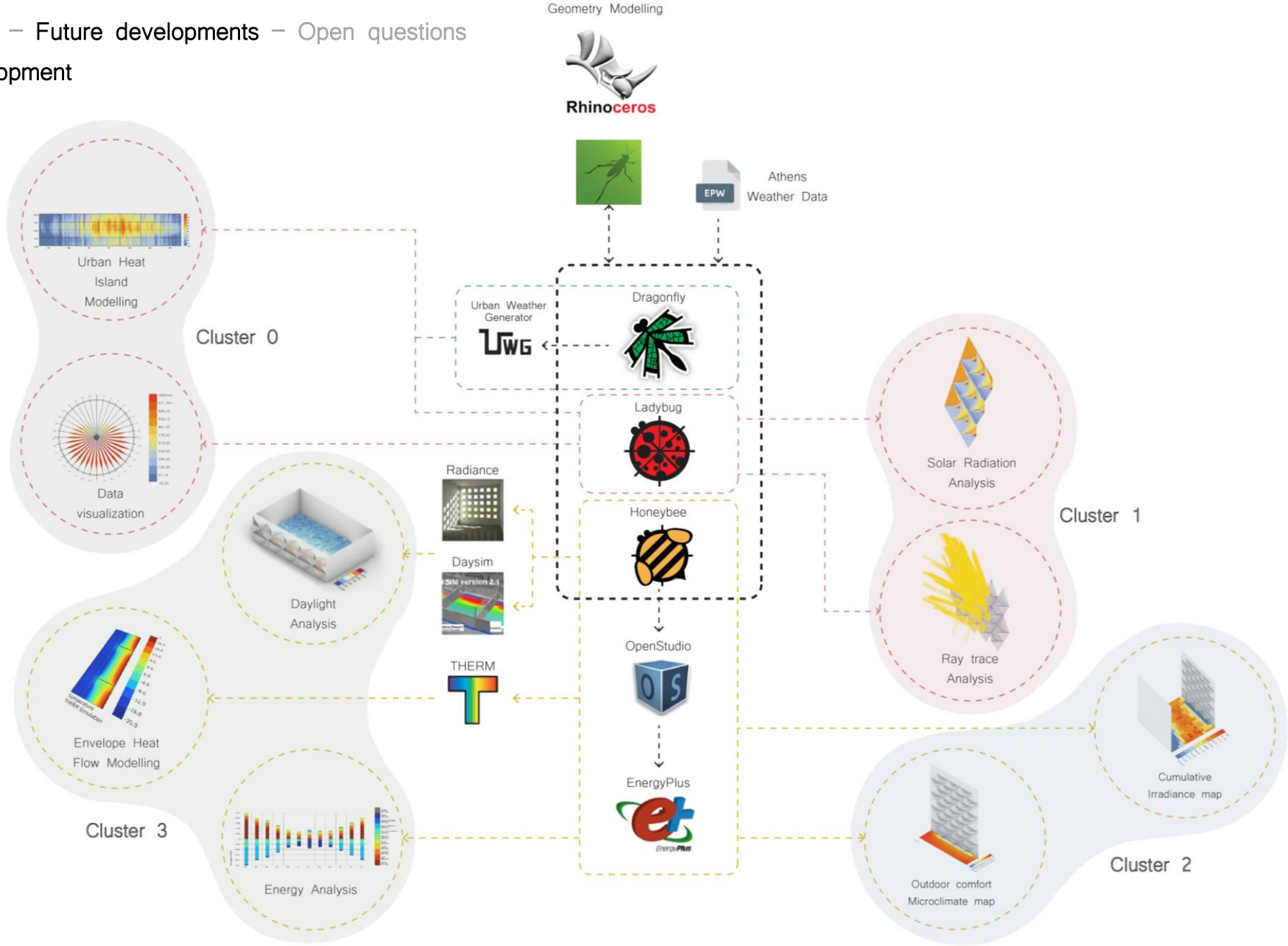
Graduation Process & Methodology:

- **Design tool limitations**: certain simplifications and assumptions during modelling → precise simulations with more known variables to be required in a more advanced design stage
- **Lack of prototyping** limited the evaluation of the SMA mechanism in practice, the operating system remained at a conceptual level
  → material tests, trial-and-error experiments to assess the thermal and dynamic performance under targeted conditions
- Further development of the **computational tool** focused on the façade energy and performance evaluation composed of simulation study clusters based on the analysis level

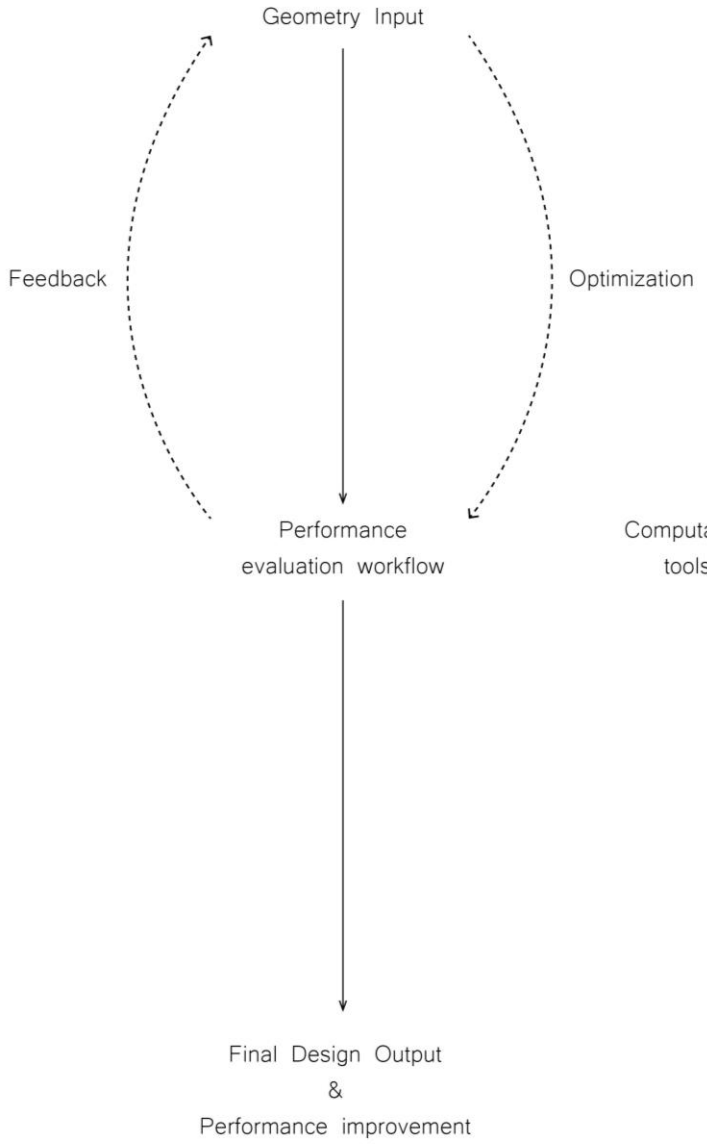


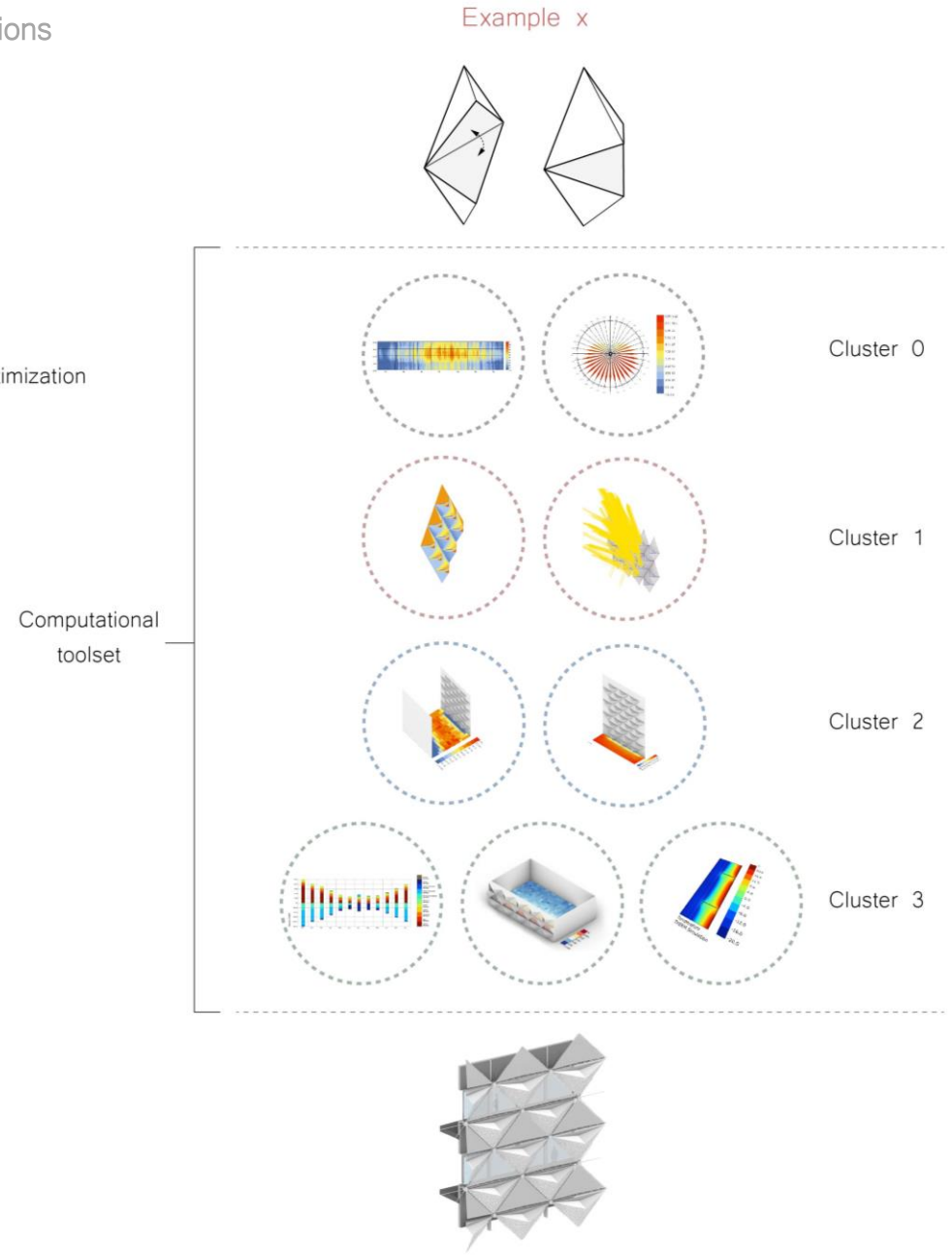
Computational tool cluster concept overview

Computational tool development



Computational tool development

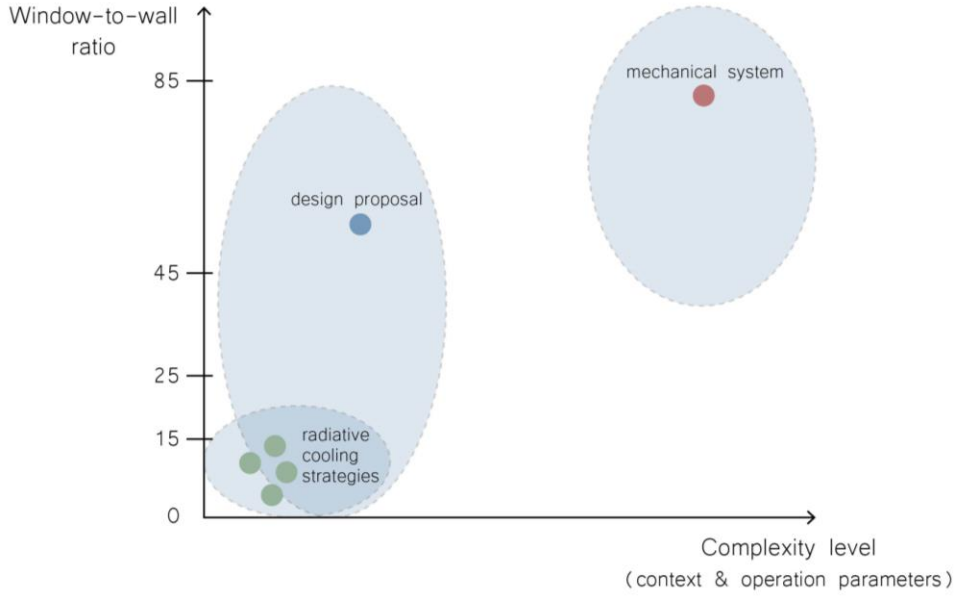


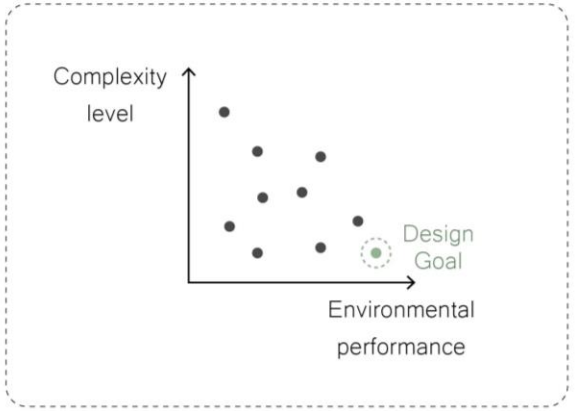


Comparison to other mitigation strategies – Radiative cooling passive technologies

Visual properties – Solar reflectance factors:

- PTFE → solar reflectance 70%
- Standard white paint → solar reflectance 86%
- Ultra-white paint → solar reflectance 97%
- Retro-reflective materials → solar reflectance 81%, retro-reflectance 44%
- Cool-colored white paint → solar reflectance VIS 85%

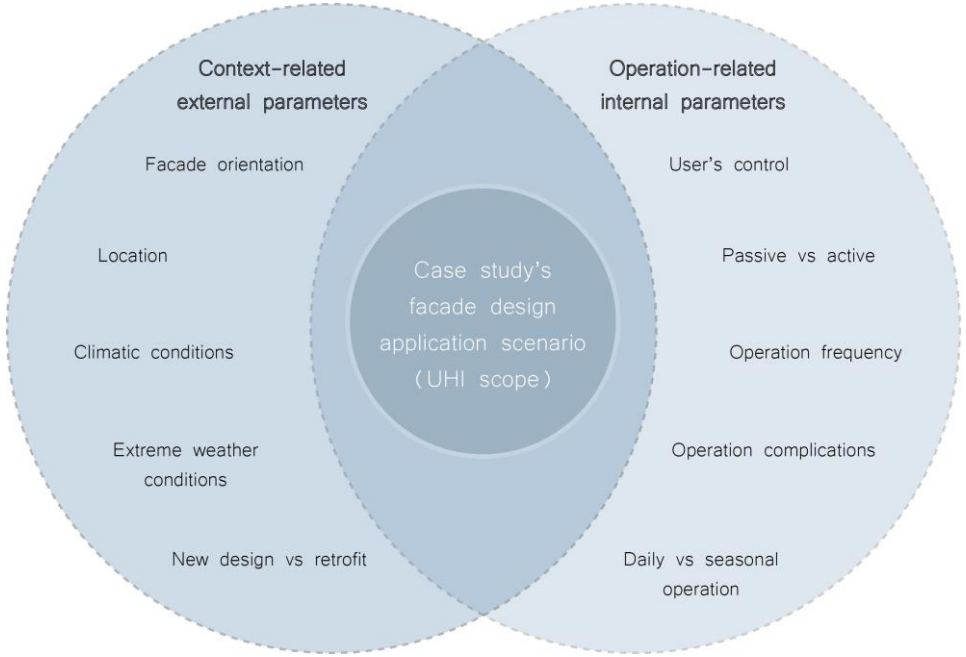


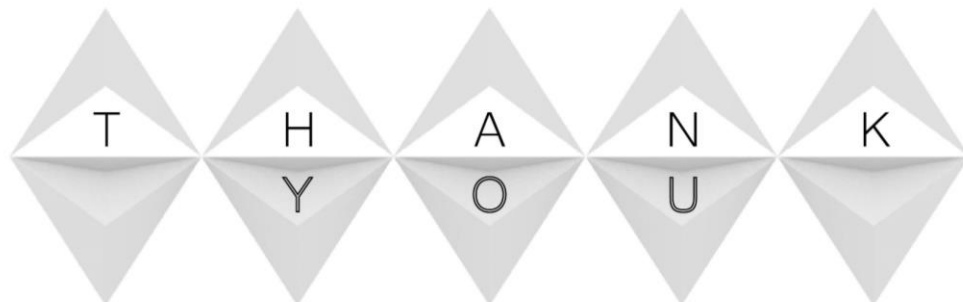


Limitations & Challenges – Future developments – Open questions

Façade design:

- Thesis project evaluated one isolated scenario under the UHI scope
- There are potentials for SMM-based integrated façade systems to passively regulate the building's energy and environmental performance
  - → Significance of feasibility evaluation in a **broader context** and not an isolated design application. Further research with more parameters involved:
    - Influence of a different **location, climatic context, orientation, application scenario**
    - Impact of exposure to **extreme weather conditions** to the operation, possibility for SMM deactivation, malfunction or deterioration
    - **Full-scale prototyping & annual performance testing** in a façade application under real conditions to give feedback for the design evaluation and optimization
    - **User's control**: fully passive practically unrealistic in non-opaque façades
    - **Operation schedule** to be further investigated and validated in practice
    - **Seasonal operation & frequency of dynamic changes:** *Is a dynamic movement justified in practice or is it limited to an operation a few times per year?*
    - **Advantages of smart materials & passive over active operation:** *To what extent and which conditions promote the use of passive operation with smart materials?*




THANK
YOU