COMPUTATIONAL OPTIMIZATION FOR THE FACADE DESIGN OF A NEARLY ZERO-ENERGY HIGH – RISE OFFICE BUILDING IN THE TEMPERATE CLIMATE

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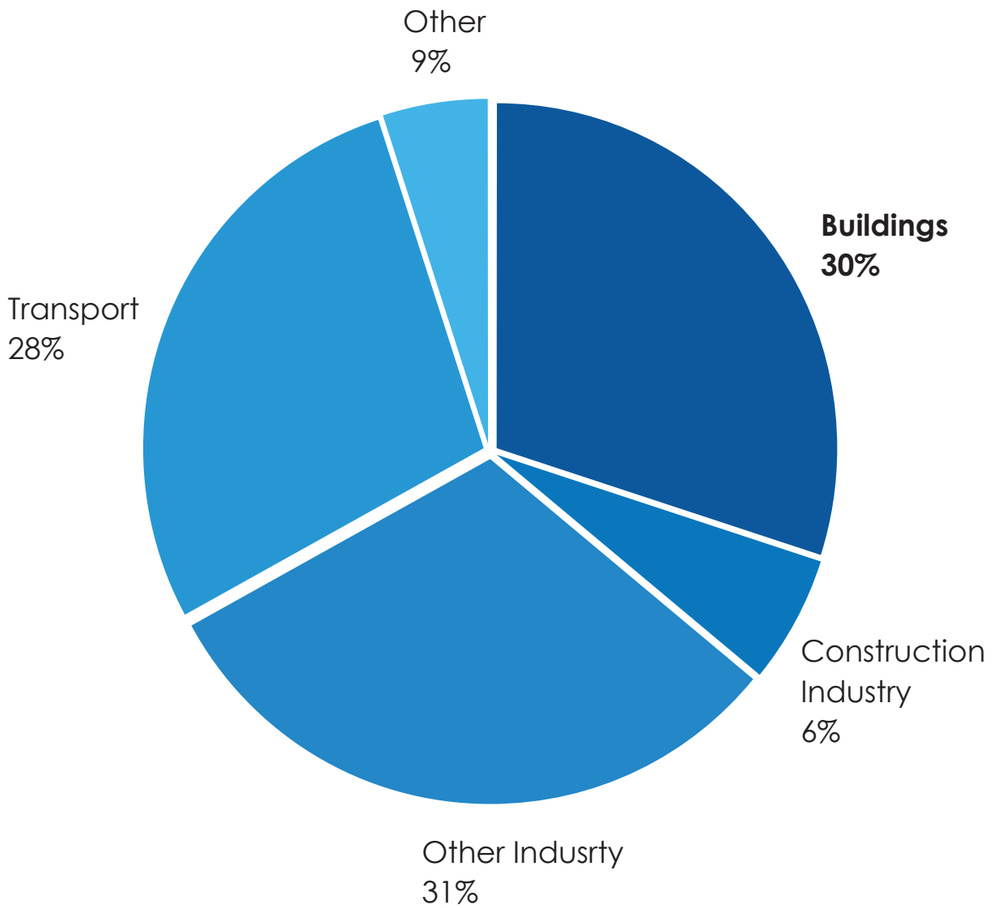
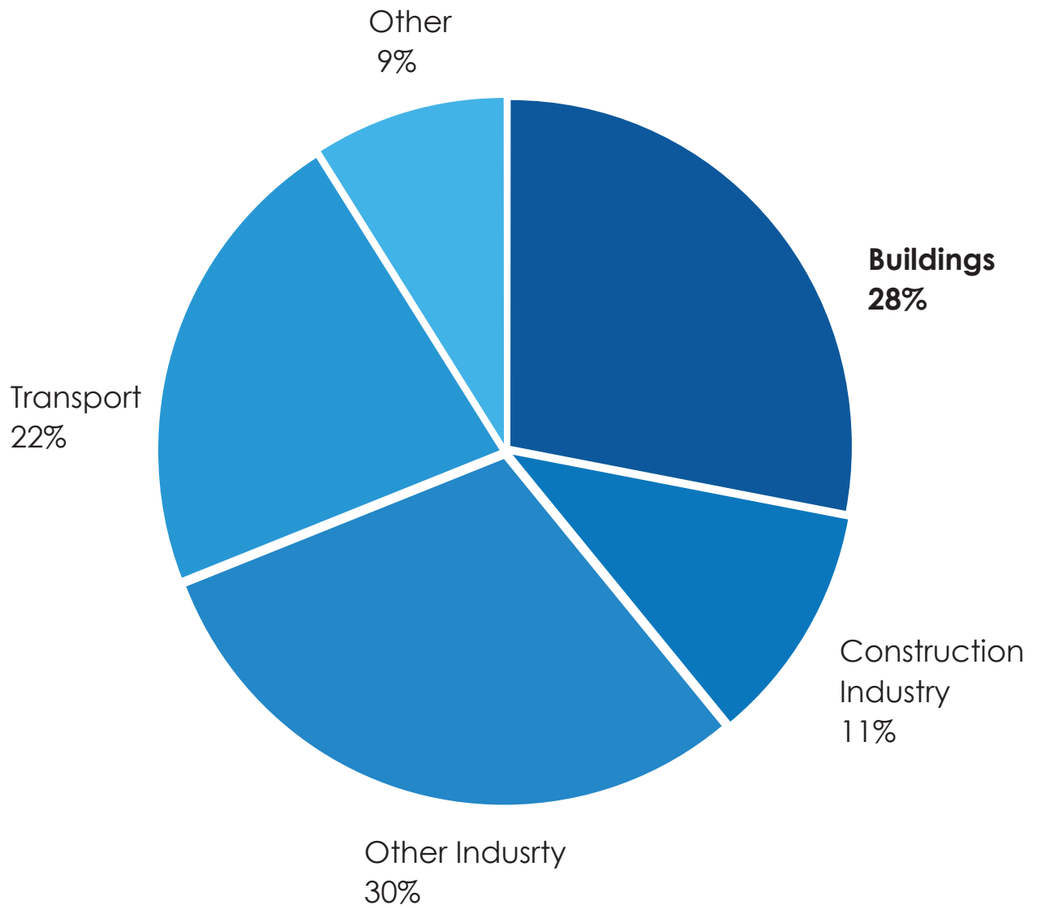
Energy performance of the building sector

Globally



Share of global final energy consumption by sector



Share of global energy-related CO_2 emissions by sector

Figure(left): Share of global final energy consumption by sector, 2016 (International Energy Agency, 2017)
Figure(right): Share of global energy-related CO2 emissions by sector, 2016 (International Energy Agency, 2017)

Final energy use in non-residential buildings in Europe

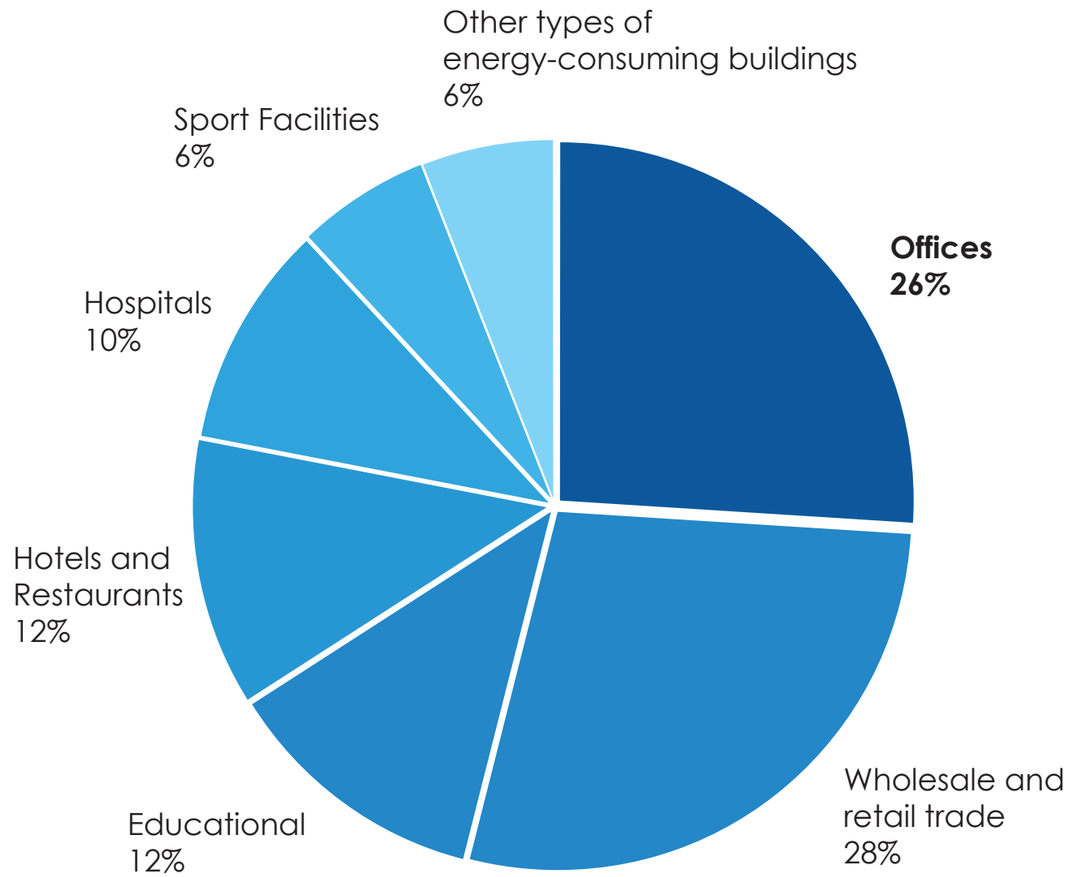


Figure: Share of total energy use in non-residential types in Europe (Buildings Performance Institute Europe, 2011)

Growing urban population worldwide

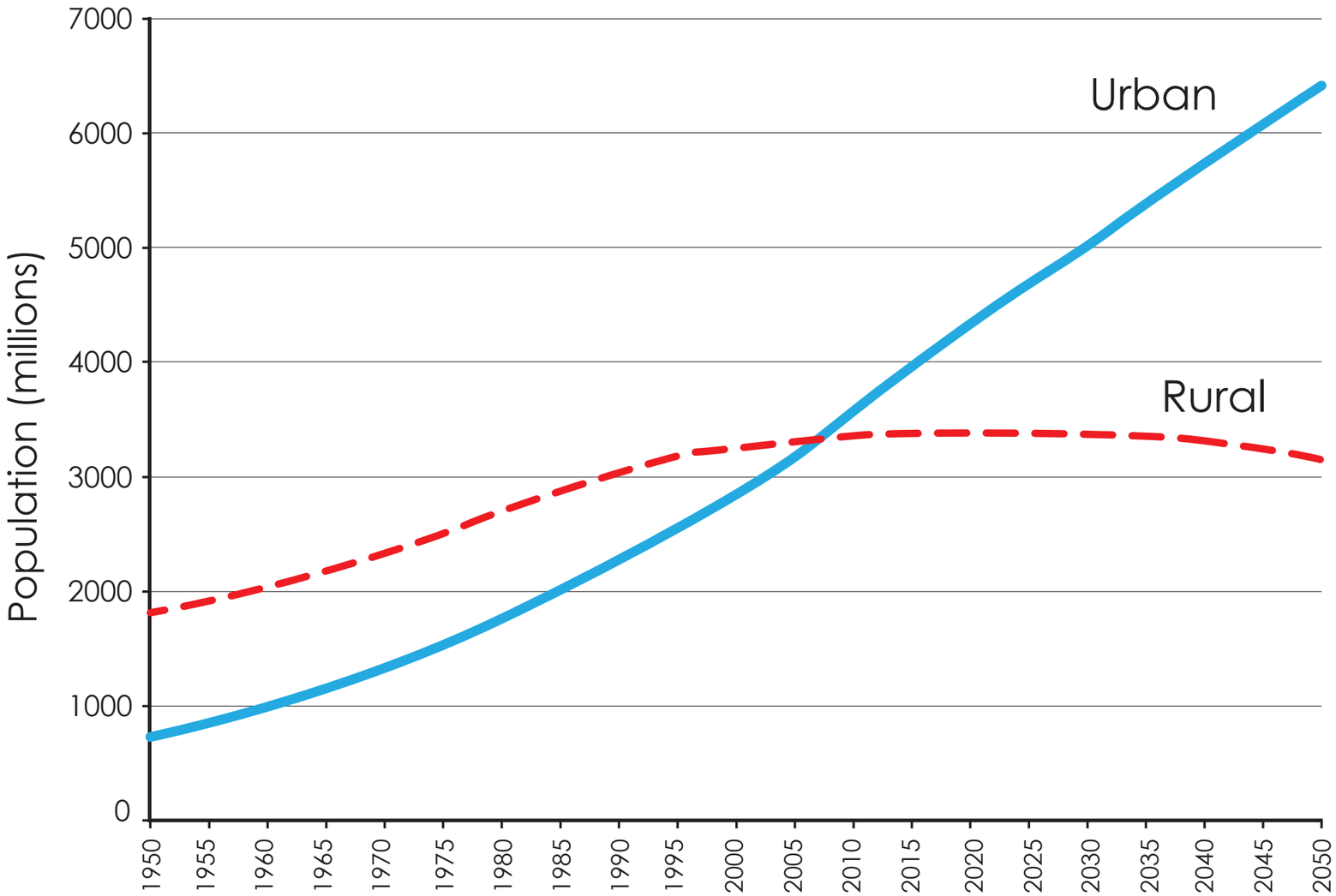


Figure: The world's urban and rural populations, 1950-2050 (United Nations, 2014).

Energy consumption of high-rise buildings

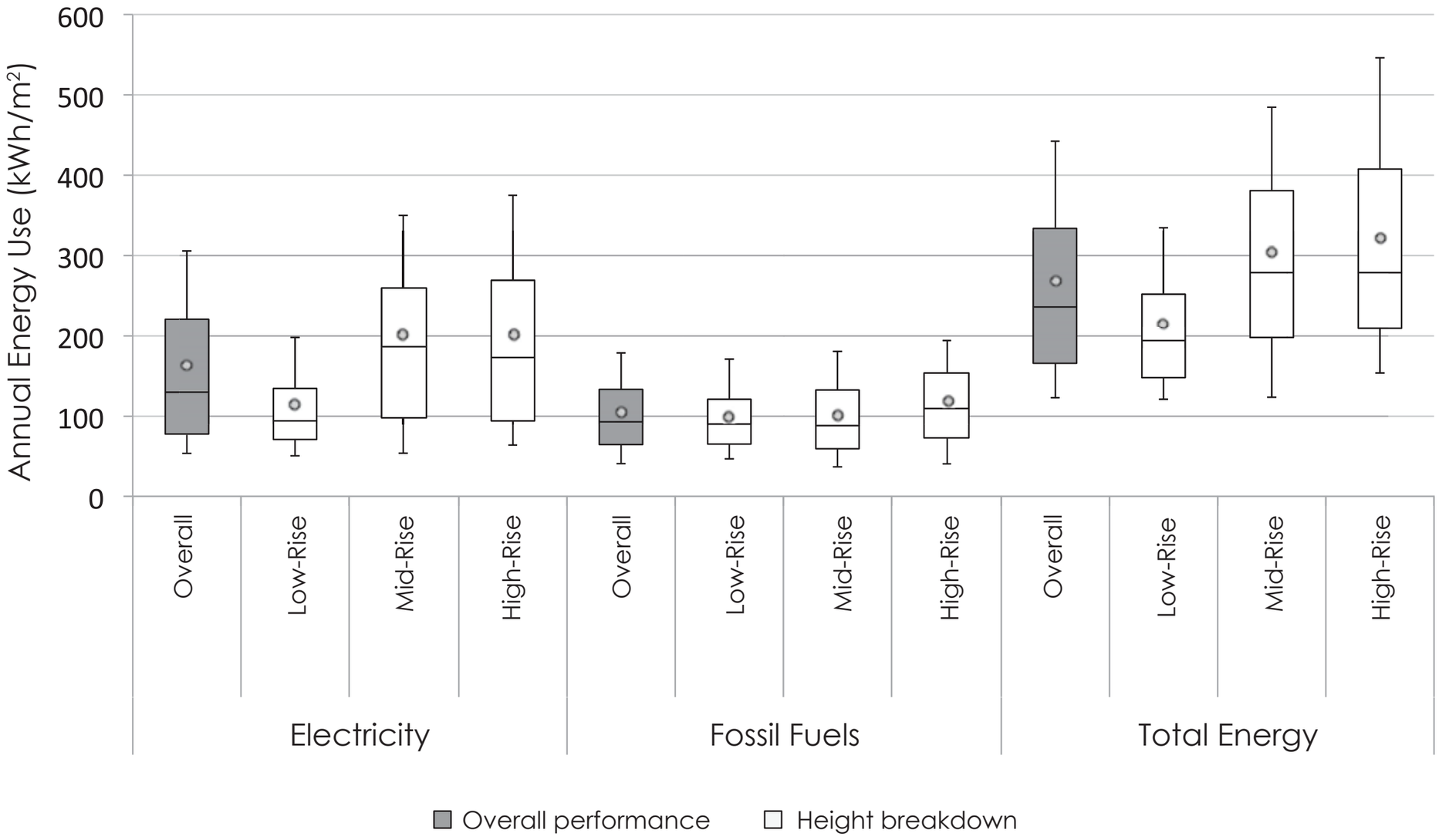


Figure: Electricity, fossil fuel and total energy use for the overall sample. (Godoy-Shimizu et al., 2018)

Particularities of the high-rise typology

- Climate changes according to altitude, affecting the **thermal transfer**
- The energy performance of the high-rise building is associated with the **relative height of the surrounding buildings**
- The extended façade area could be used for the **production of renewable energy**

Conventional design process vs Integrated design process

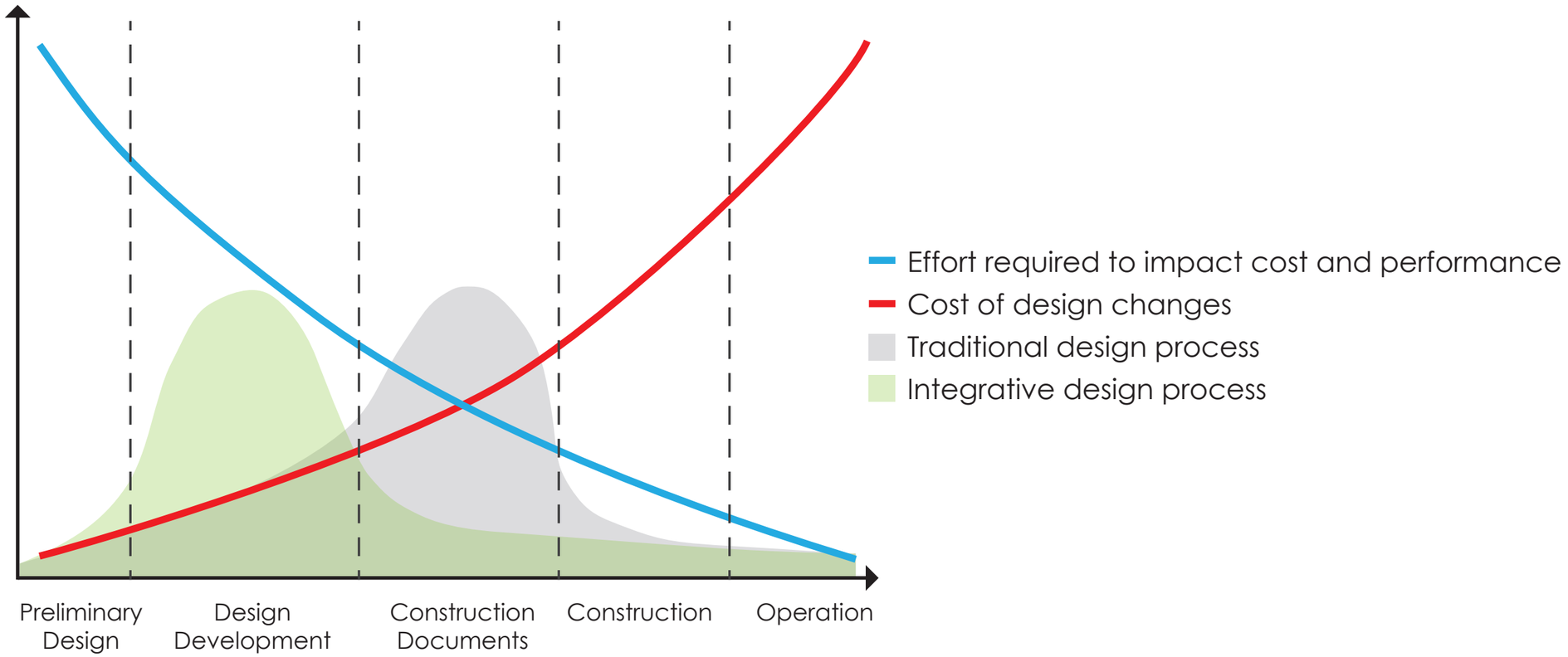


Figure: The MacLeamy curve. Adapted from:(Daniel Overbey, n.d.).

Conventional design process

VS

Integrated design process

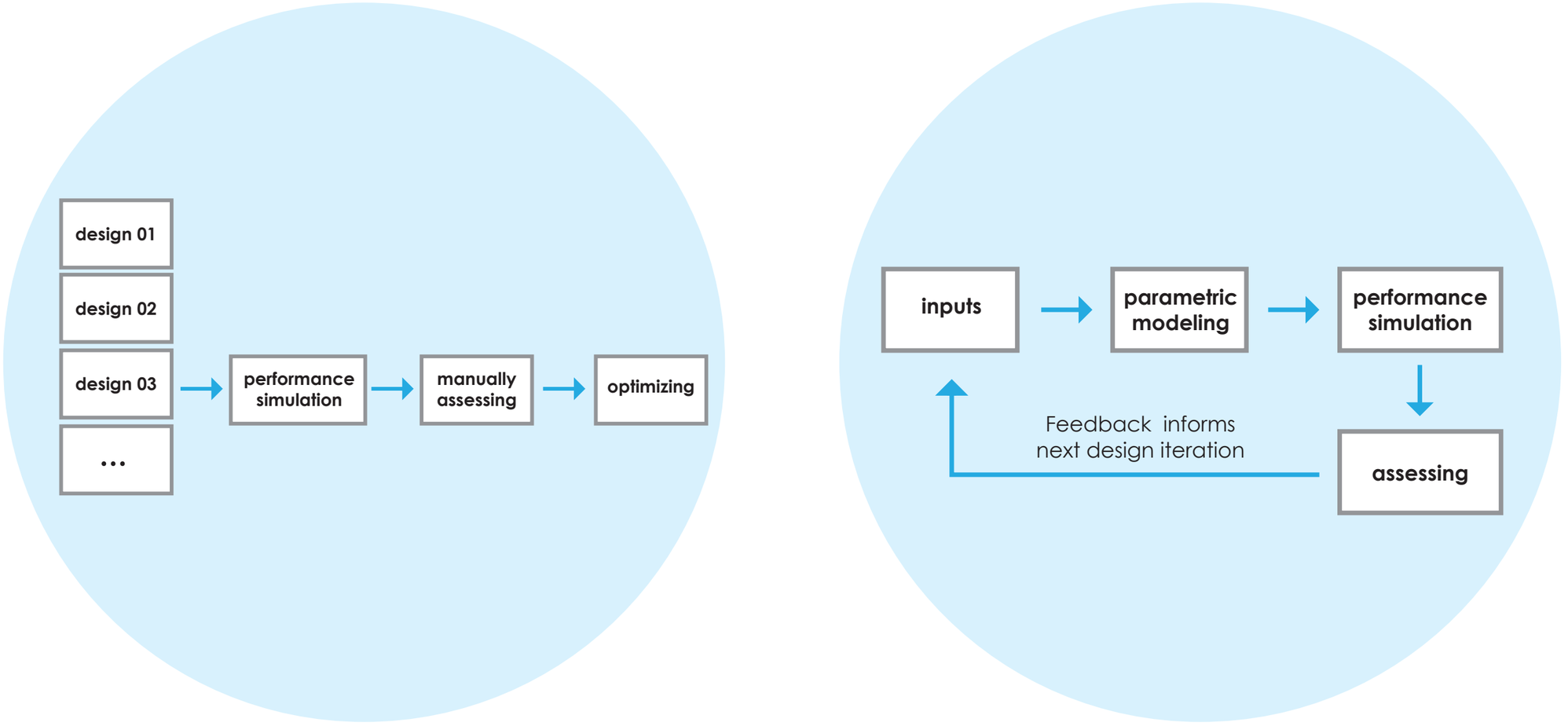


Figure: Schematic of the conventional and the integrated design process. Adapted from: (Shi, 2010).

Research questions

Main research question

How can designers and engineers quantify the performance, regarding energy and thermal comfort, of different façade designs of a nearly Zero - Energy high-rise office building, in the temperate climate, in the early design stages?

Sub-questions

A What is the most effective combination of façade design parameters that can lead to a nearly Zero - Energy high-rise office building in the temperate climate?

B What is the energy breakdown and the comfort performance for the best performing façade designs of a nearly Zero - Energy high-rise office building in the temperate climate?

Approach and methodology

Determine Research Question

Literature Review

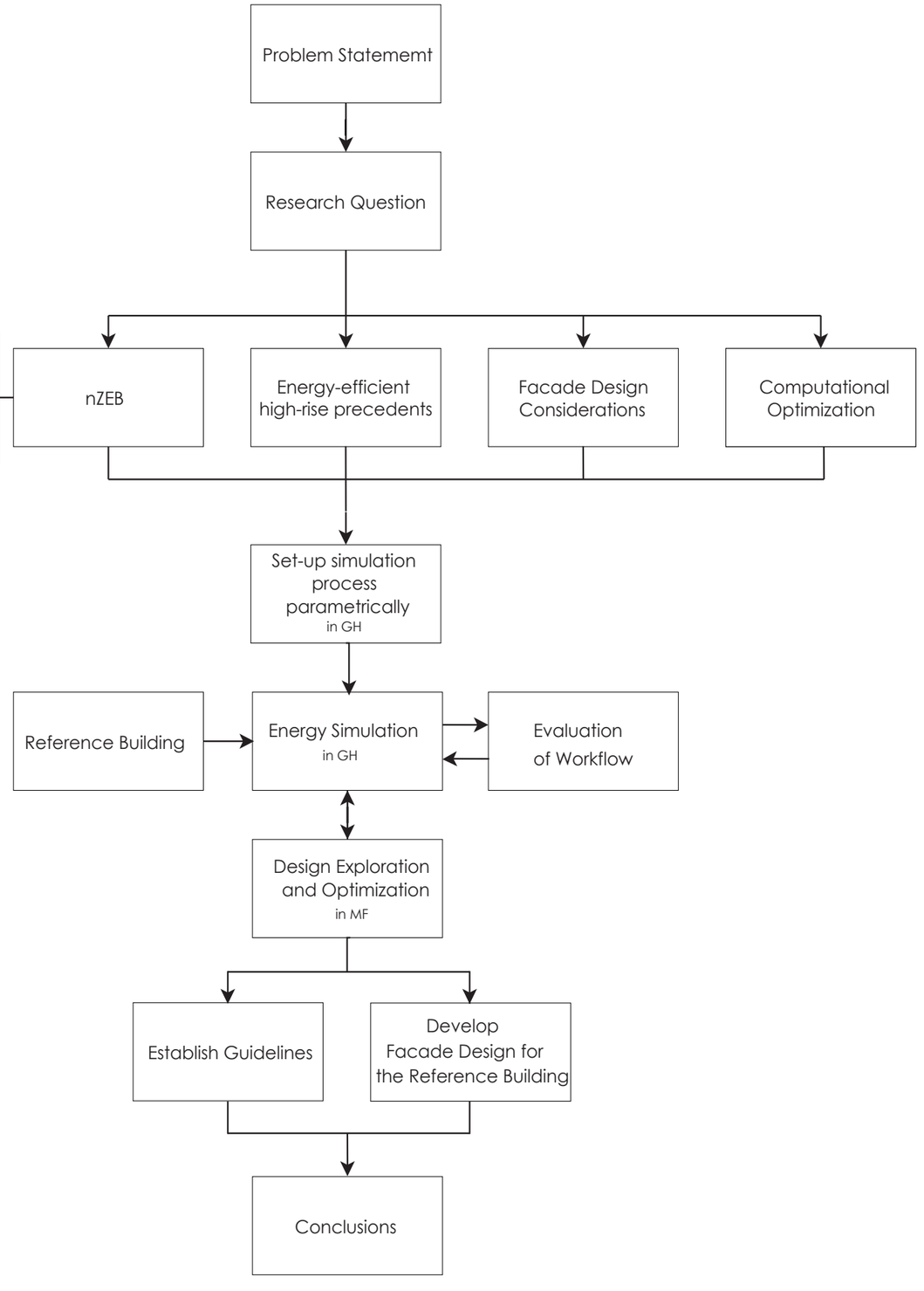
Parametric modeling

Energy Simulation

Optimization

nearly Zero-Energy High-rise Office Building Design

Conclusions



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Zero – Energy building definition

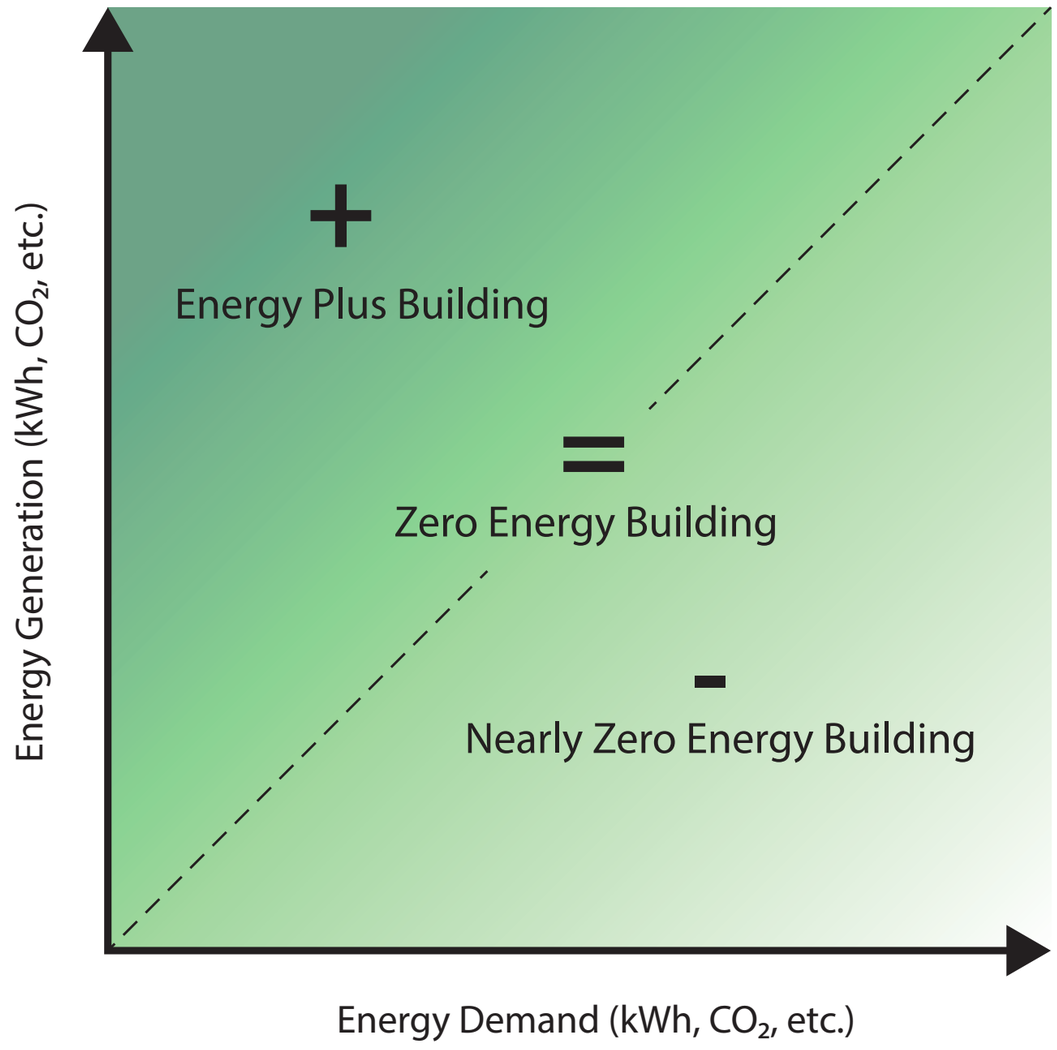

Figure: Definition of zero-energy building (Athienitis & O'Brien, 2015, pg.1).

BENG

1. The maximum **energy demand**, in kWh per m², per year
2. The maximum **primary fossil energy use**, in kWh per m², per year
3. The minimum **share of renewable energy**, in percentages

(DWA, 2016)

	BENG 1 [kWh/m².jr]	**BENG 2** [kWh/m².jr]	**BENG 3** [%]
Office	If Als/Ag ≤ 1,8, BENG 1 ≤ 90	≤ 40	≥ 30
	If Als/Ag > 1,8, BENG 1 ≤ 90 + 30 * (Als/Ag - 1,8)		

Table: The new BENG requirements for offices. Adapted from: (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019)

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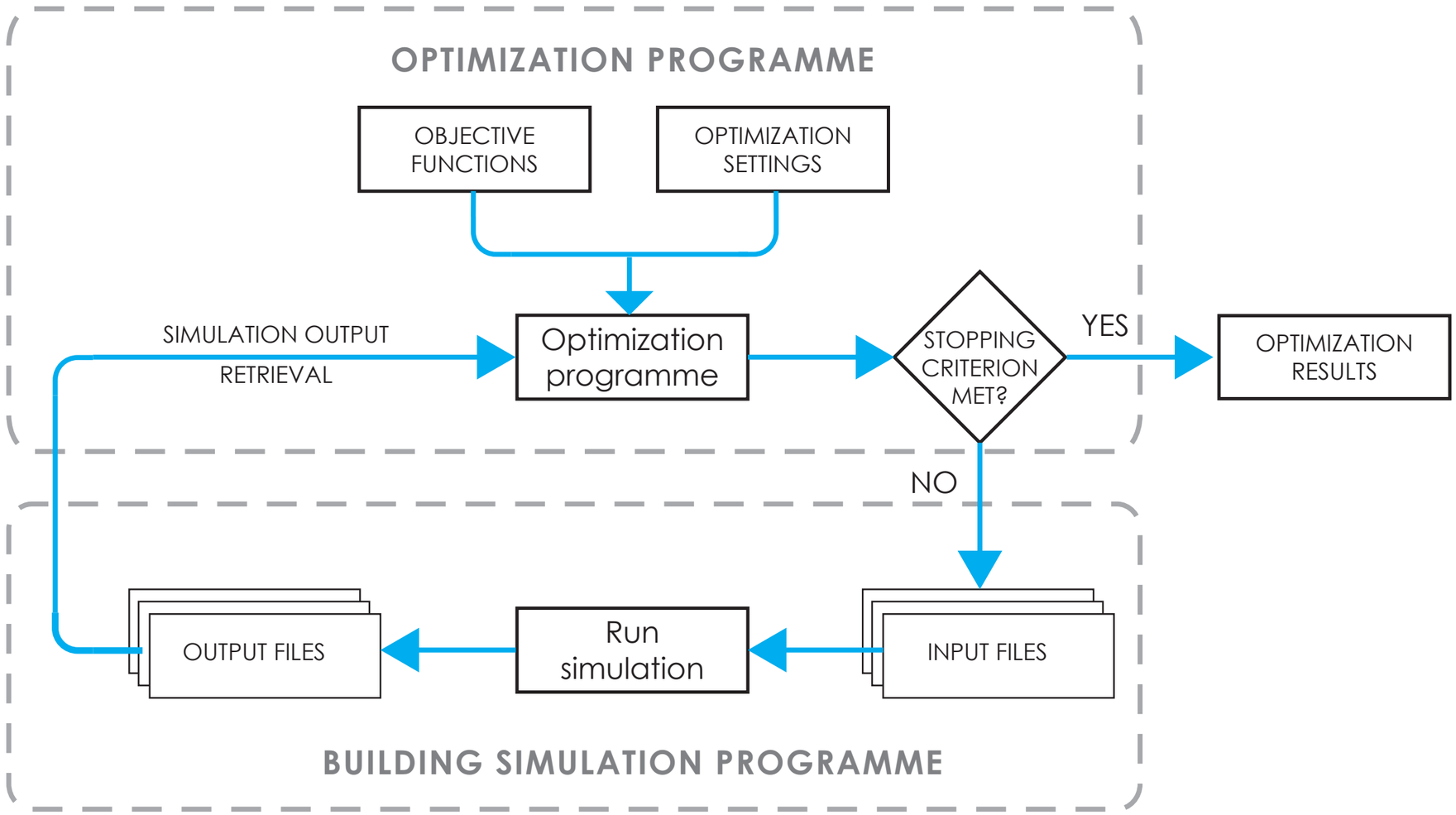

Figure: The most typical strategy applied for simulation-based optimizations in building performance studies (Nguyen et al., 2014).

Optimization and design space exploration

Performance-informed design solution exploration (DSE) supports:

1. **a meaningful selection** among design alternatives based on measurable criteria
2. **refinement** (direct parameter changes and indicate directions for potential improvement)
3. **understanding** (relationships between design parameters, aesthetics and performance)

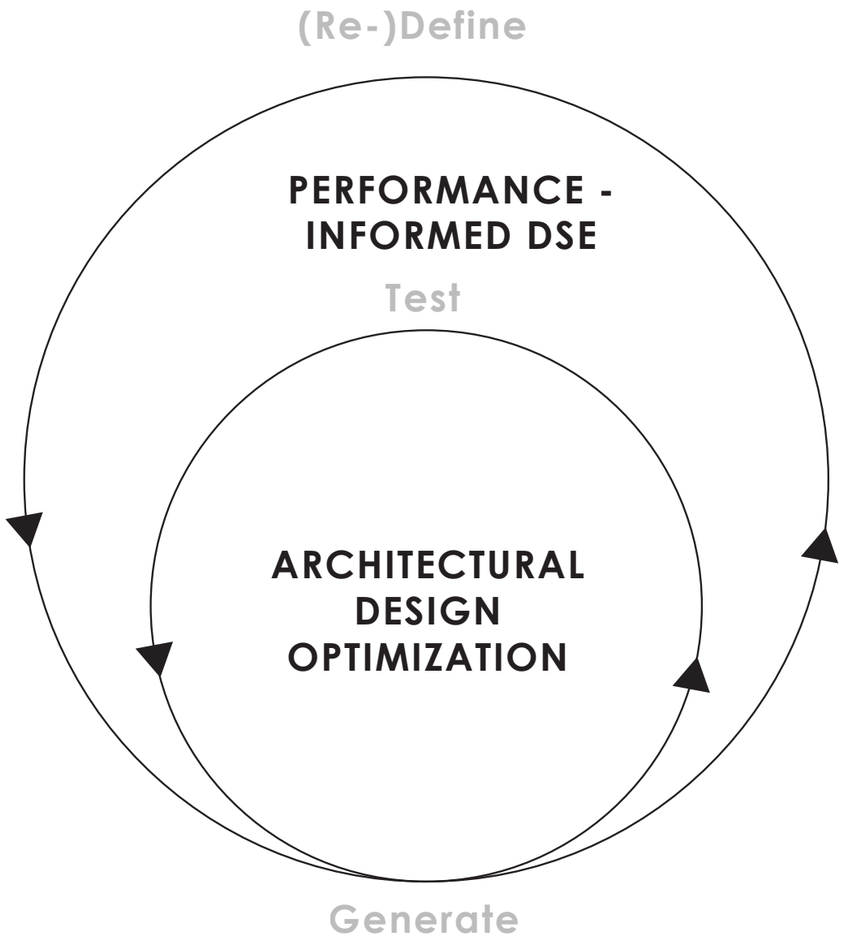

Figure: Architectural design optimization cycle with performance-informed design solution exploration (Wortmann et al., 2019).

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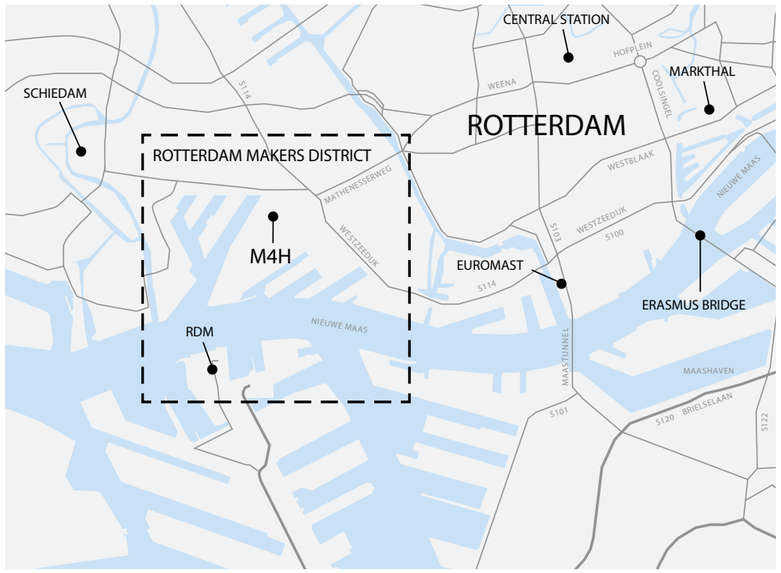
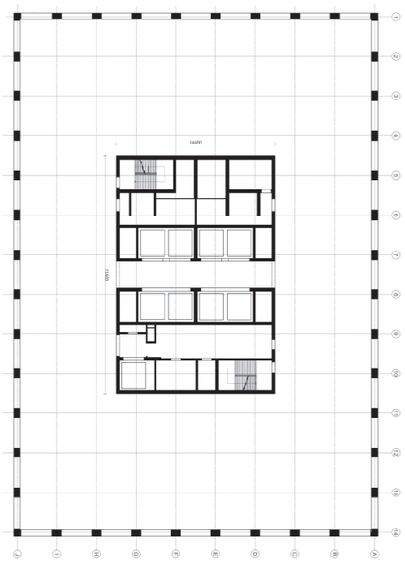
Reference building



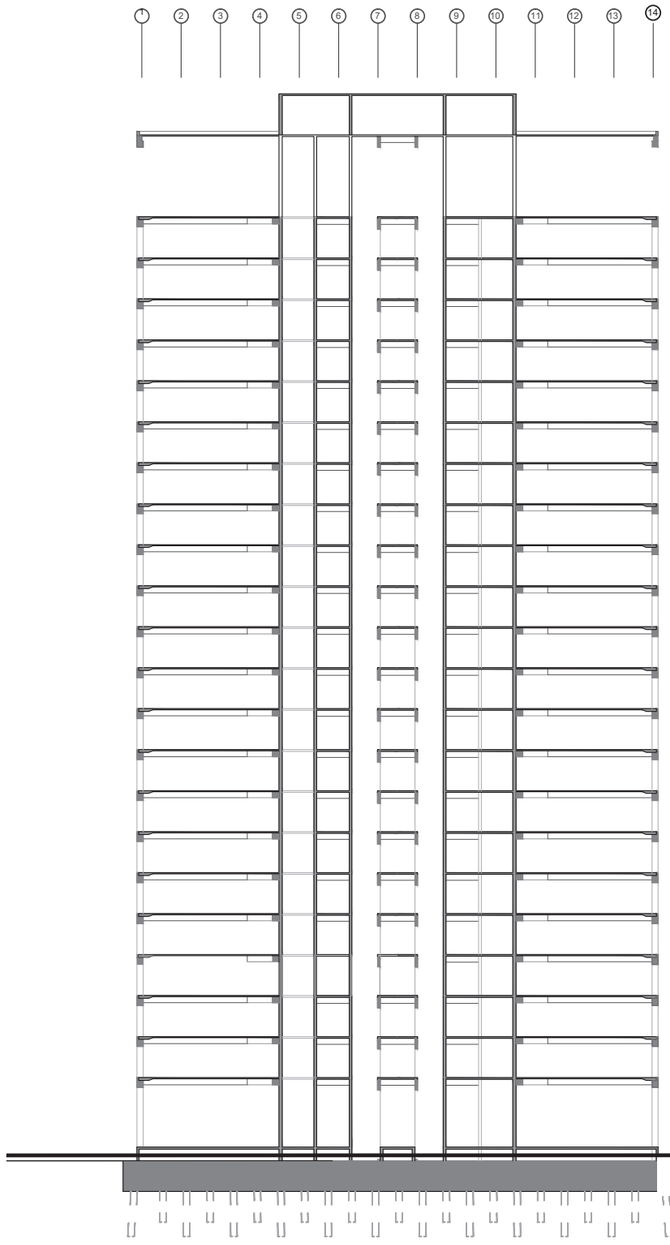
Europoint complex

Reference building

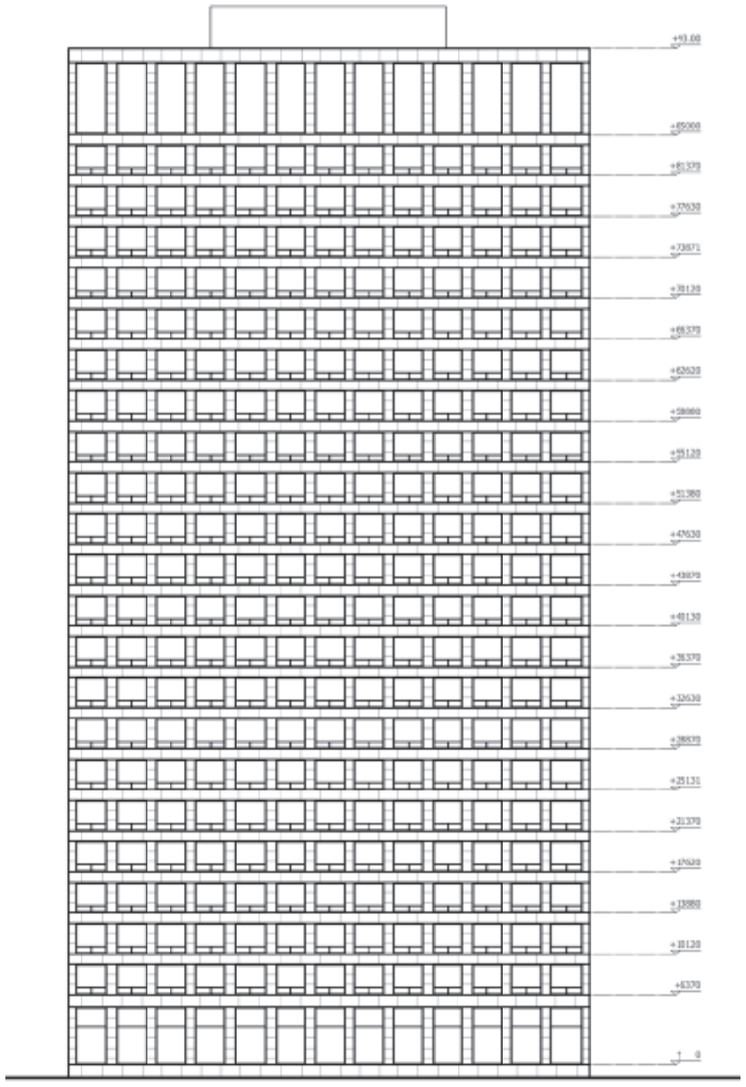
Rotterdam Science Tower



Typical Floor Plan



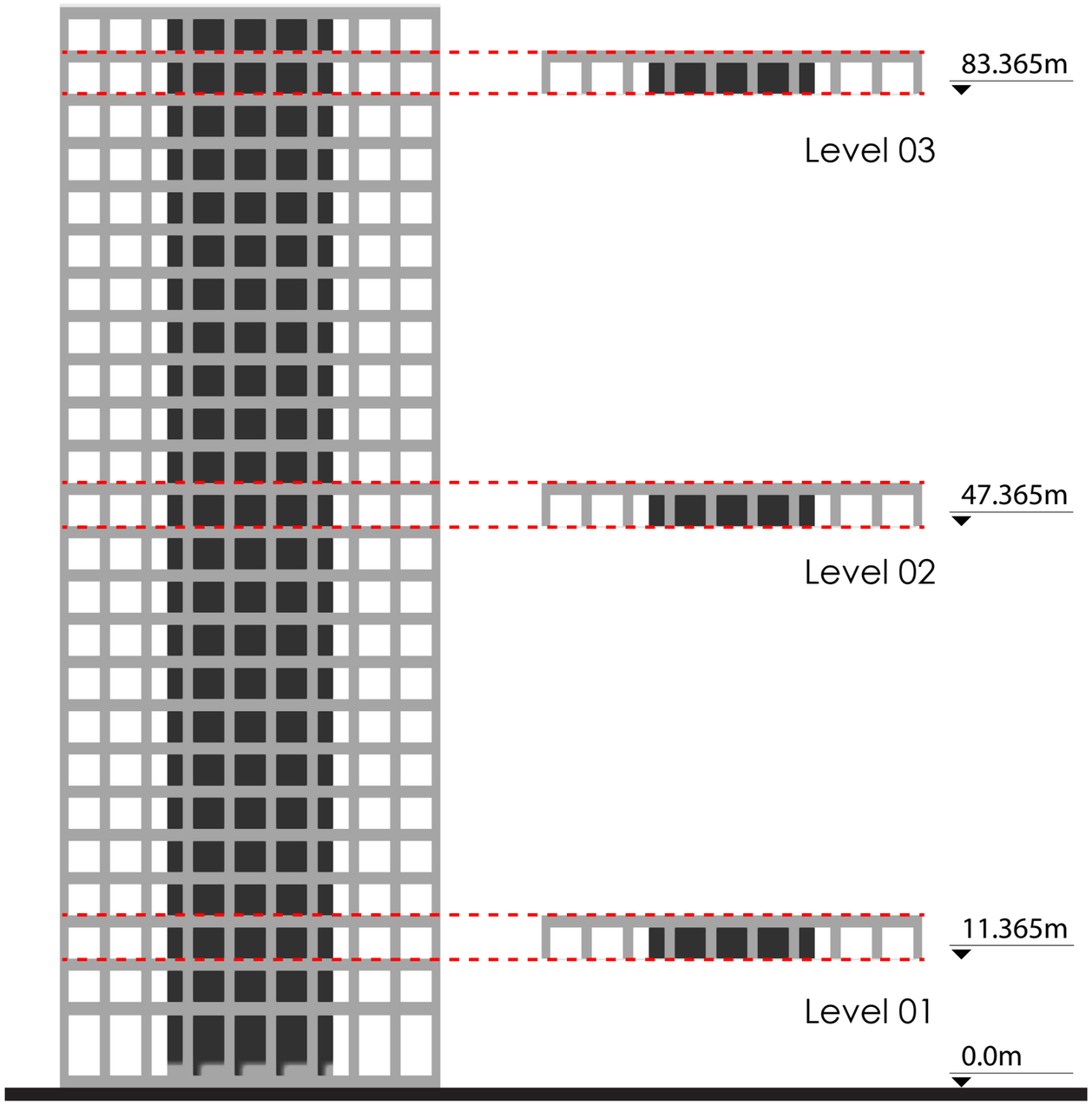
Vertical Section

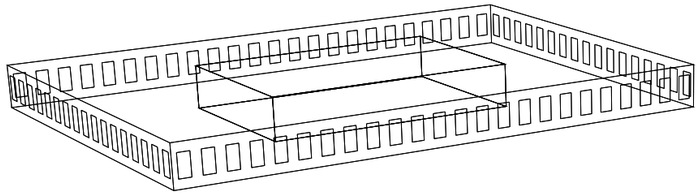


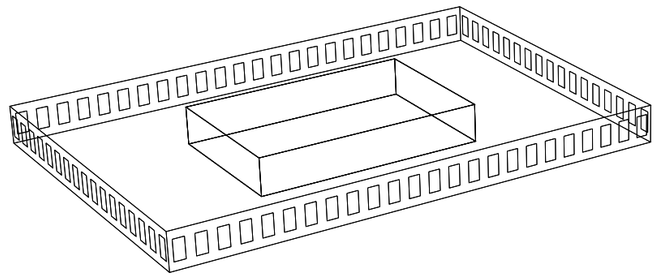
North Elevation

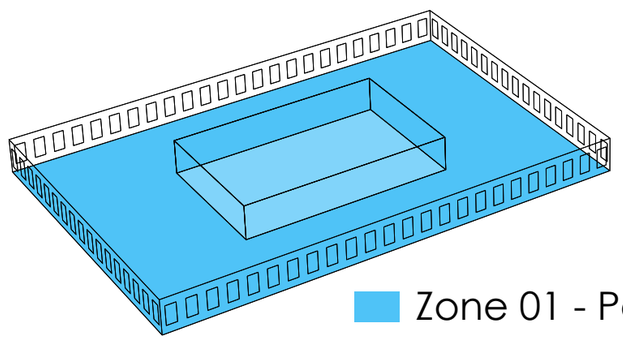
Drawings: MOR (2018)

Simulation set-up



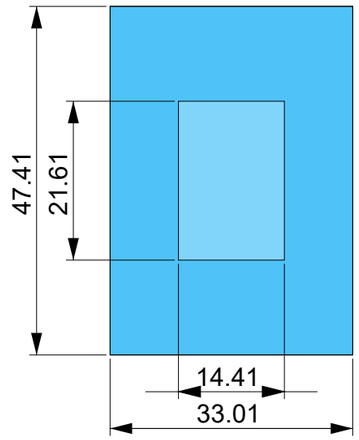




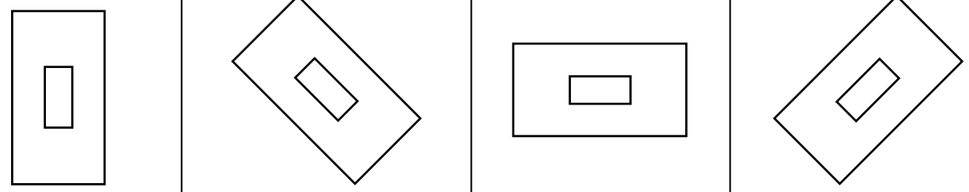


Geometry
shape and orientation

Shape 1

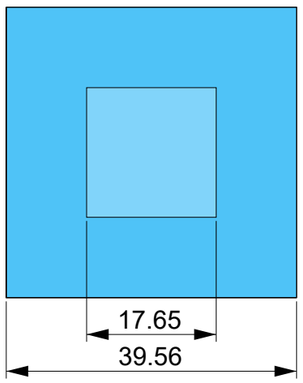


Floor area: 1.565,00m²
Volume: 5.634,01m³
Facade area: 579,02m²

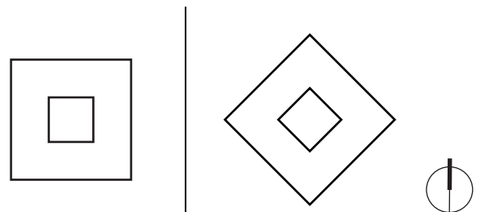


no_0 **no_01** **no_02** **no_03**

Shape 2



Floor area: 1.565,00m²
Volume: 5.634,00m³
Facade area: 569,66m²



no_04 **no_05**

Input data

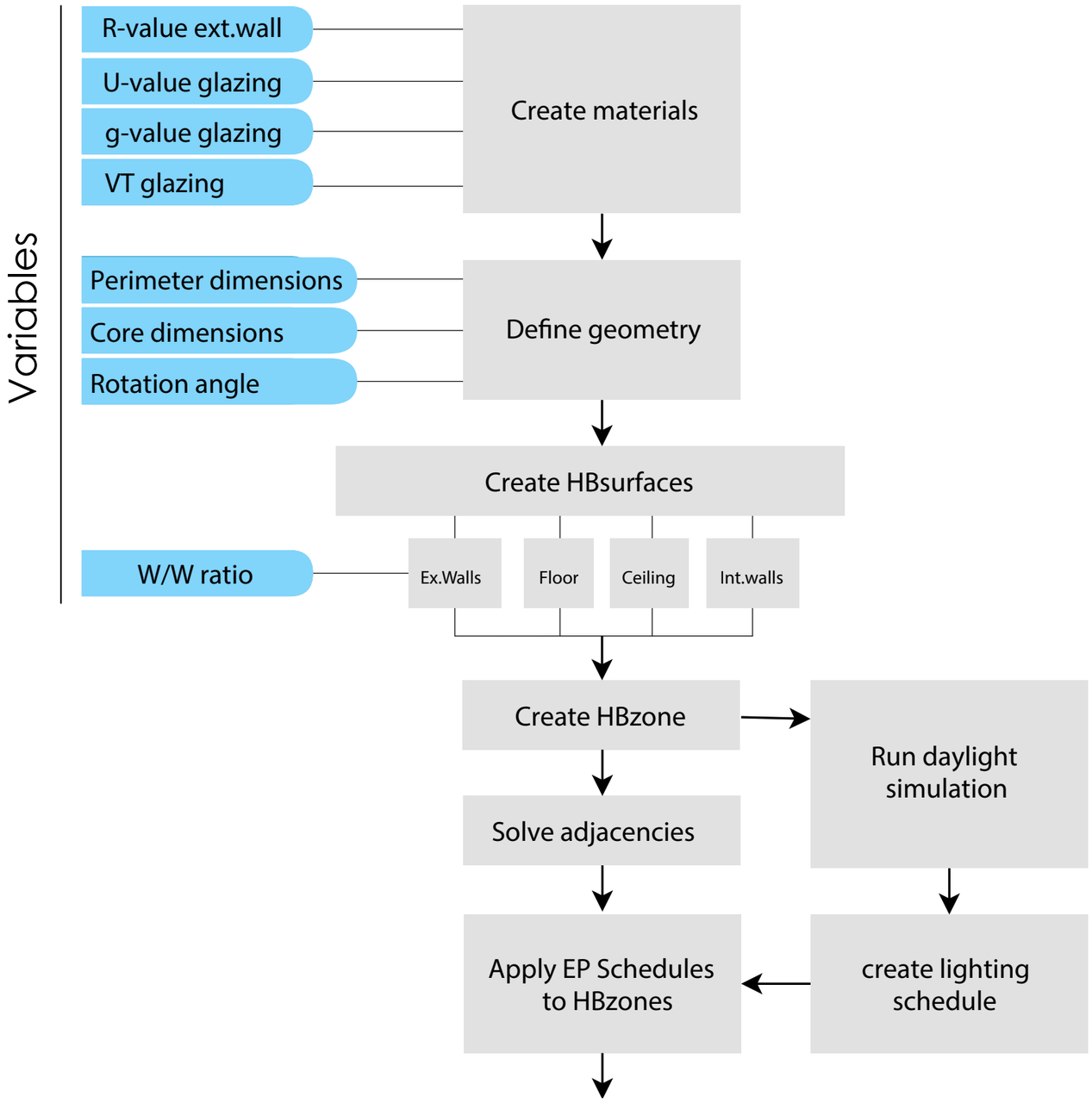
	Honeybee
Construction	Outermost to innermost layer
Exterior wall conctruction	R-value: variable
Interior wall conctruction	1. Plaster (0.013m)/ 2.Concrete block (0.15m)/ 3. Plaster(0.013m) R-value= 0.515 m2-K/W
Internal floor/ceiling conctruction	1. Concrete reinforced (0.14m)/ 2. Screed(0.02m)/ R-value= 0.669 m2-K/W
Glazing construction	U-value: variable G-value: variable VT-value: variable
Airtightness	Zone 01: 0.137 (ac/h) - 24/7 Zone 02: 0 (ac/h) - 24/7
Activity	
Occupancy schedule	8.00-17.00 - 5 days
Occupancy density	0.111 people/m2
Metabolic rate	Zone 01: 123 (W/per person) Zone 02: 140 (W/per person)
Heating setpoint	21 °C
Heating setback	16 °C
Cooling setpoint	25 °C
Cooling setback	30 °C
Office equipment - Power density	Zone 01: 15 (W/m2) Zone 02: 0 (W/m2)

Lighting	
Power density	2.5 (W/m2) - 100lux
Target Illuminance	Zone 01: 500 lux Zone 02: 200 lux
Lighting control	On
HVAC	
HVAC system	Fan Coil Units + DOAS
HVAC availability	all year - 5 days
Economiser (type)	Differential dry bulb
Outside air definition method (Mechanical ventilation)	Sum(per person + per area + per zone + ac/h)
Natural Ventilation Outdoor temperatures limits	On Min. temperature: 21°C Max.temperature: 25°C

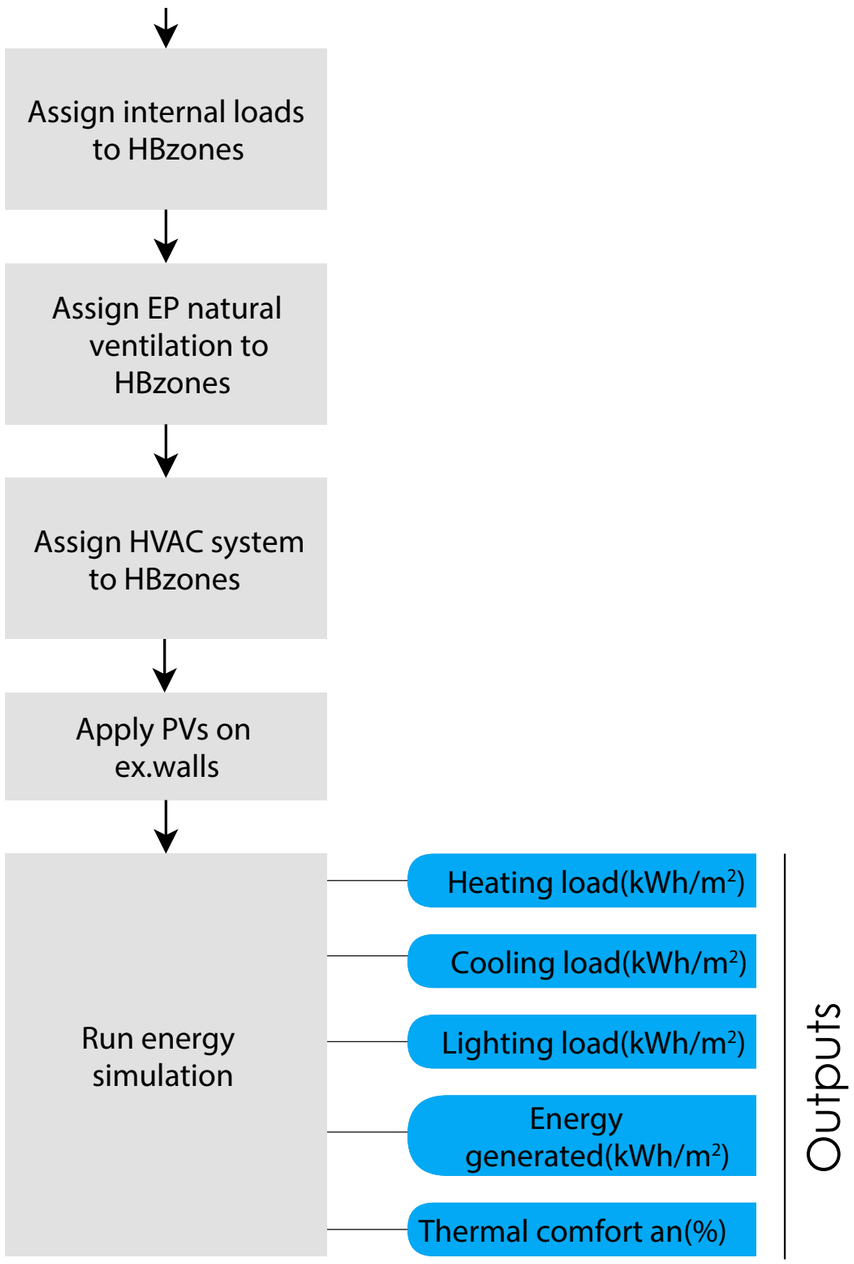
Variables of optimization

w/w (per facade and per floor)	[30 / 40 / 50 / 60 / 70 / 80] %
R-value ext.wall	[4.5 / 5.5 / 6.5 / 7.5] m^2K/W
U-value glazing and frame	[0.8 / 1.2 / 1.6] W/m^2K
g-value glazing	[0.3 / 0.4 / 0.5]
VT glazing	[0.5 / 0.6 / 0.7]

Simulation set-up



Simulation set-up



Outputs and objectives

Outputs

Per floor and total (average value):
Heating load (kWh/m^2)
Cooling load (kWh/m^2)
Lighting load (kWh/m^2)
PV energy generated (kWh/m^2)
Thermal comfort (%/occupancy time)

Objective

Min. (Energy demand total) - (PV energy generated total) (kWh/m^2) ↓

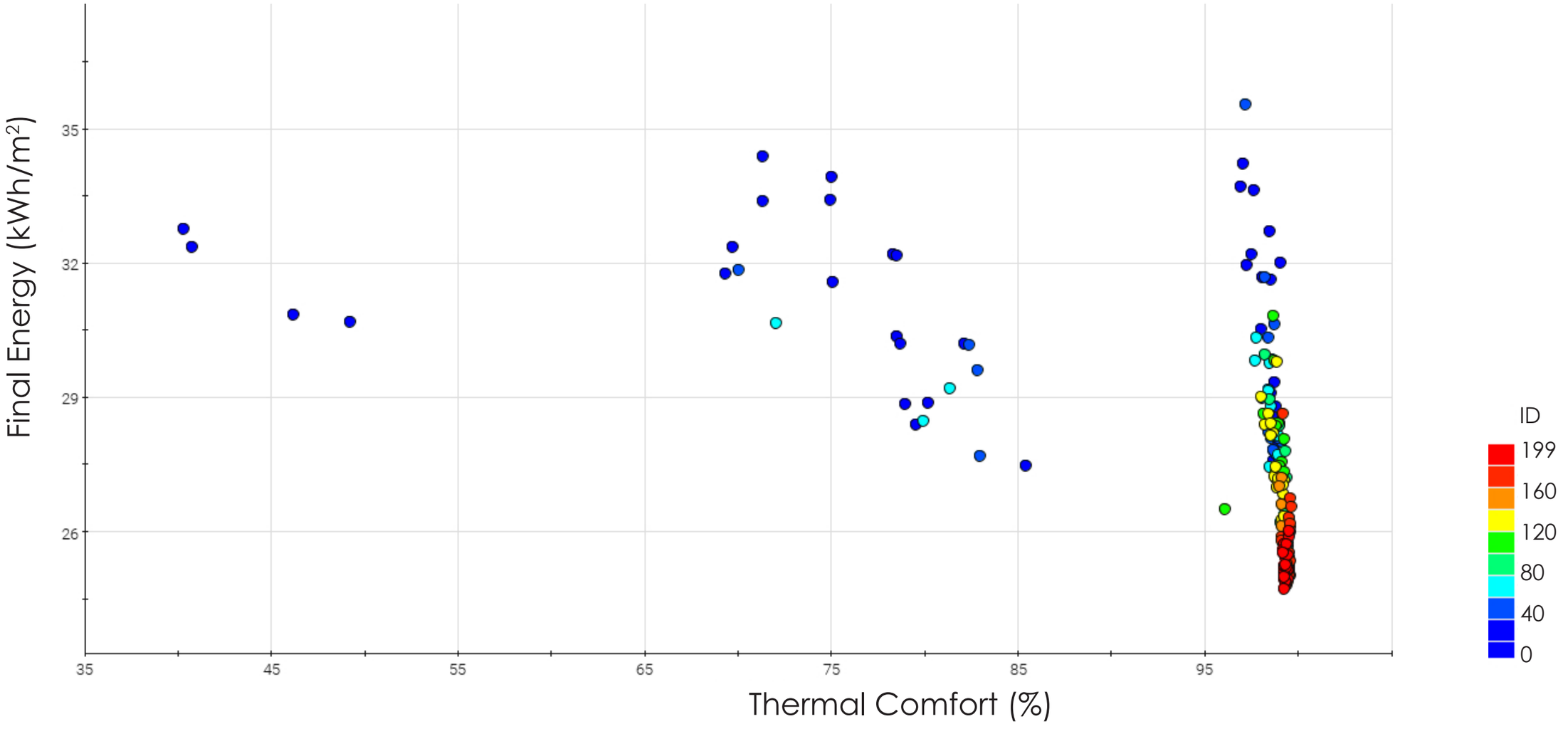
Energy demand total = **Heating load total + Cooling load total + Lighting load total** (kWh/m^2)

Constraint

Thermal comfort > 90%

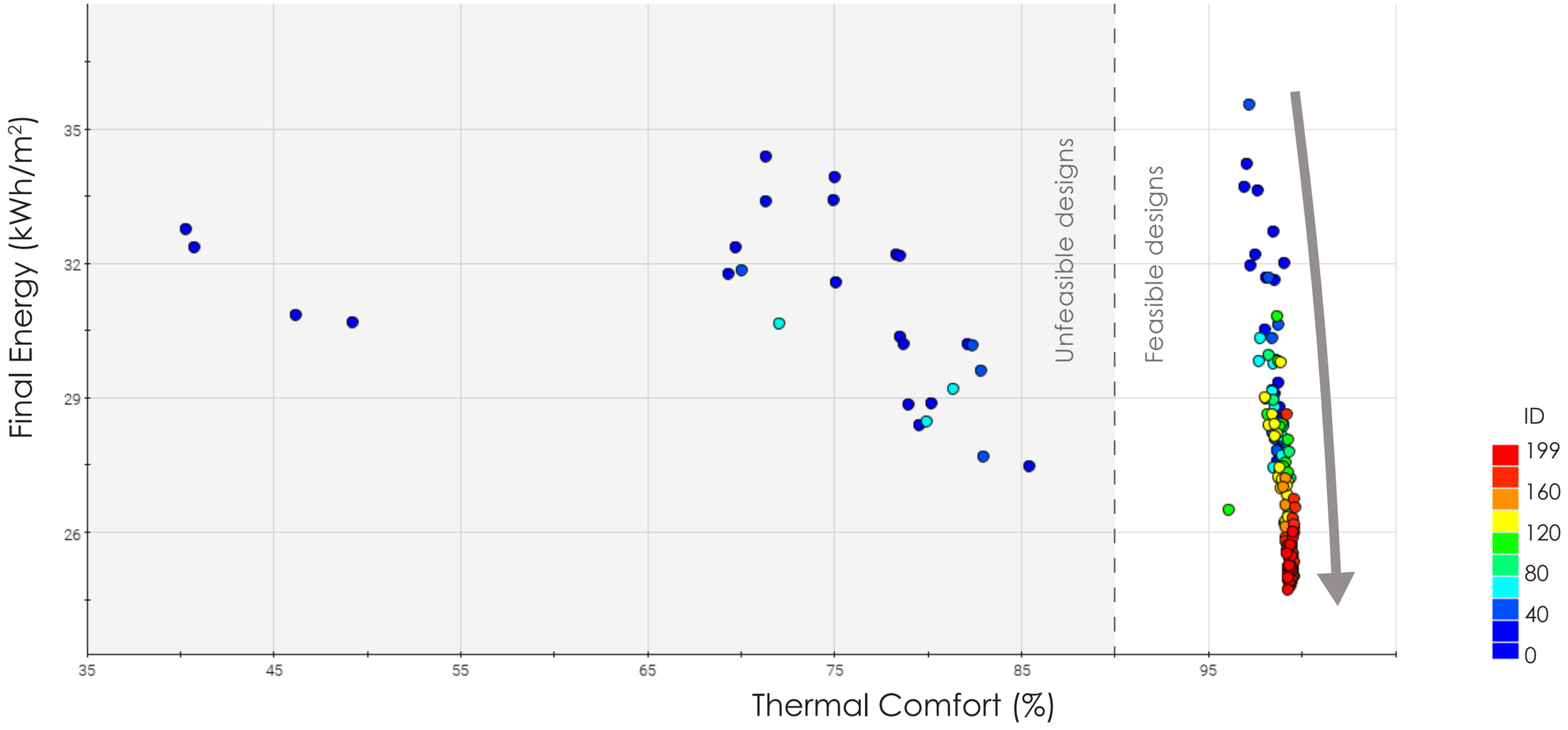
Design Exploration

Design solution space



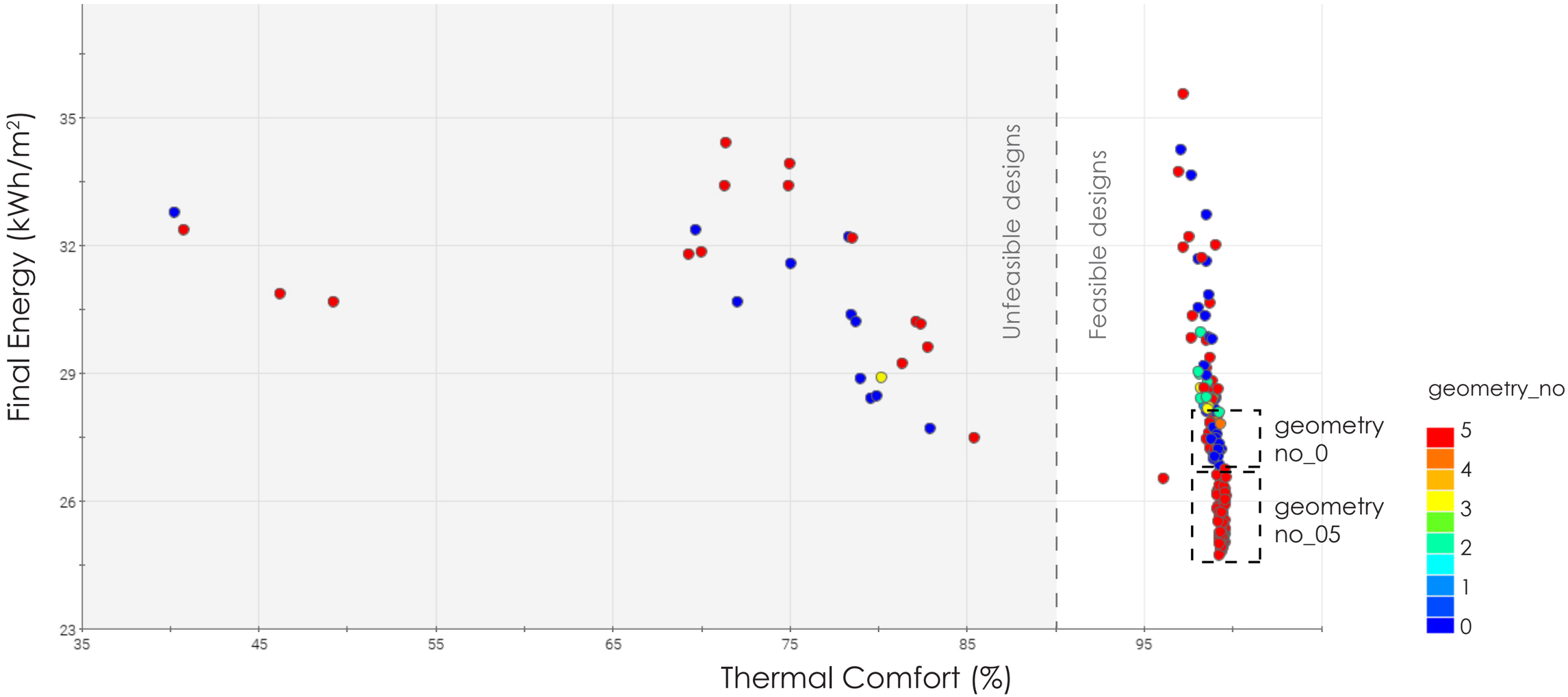
Design Exploration

Design solution space



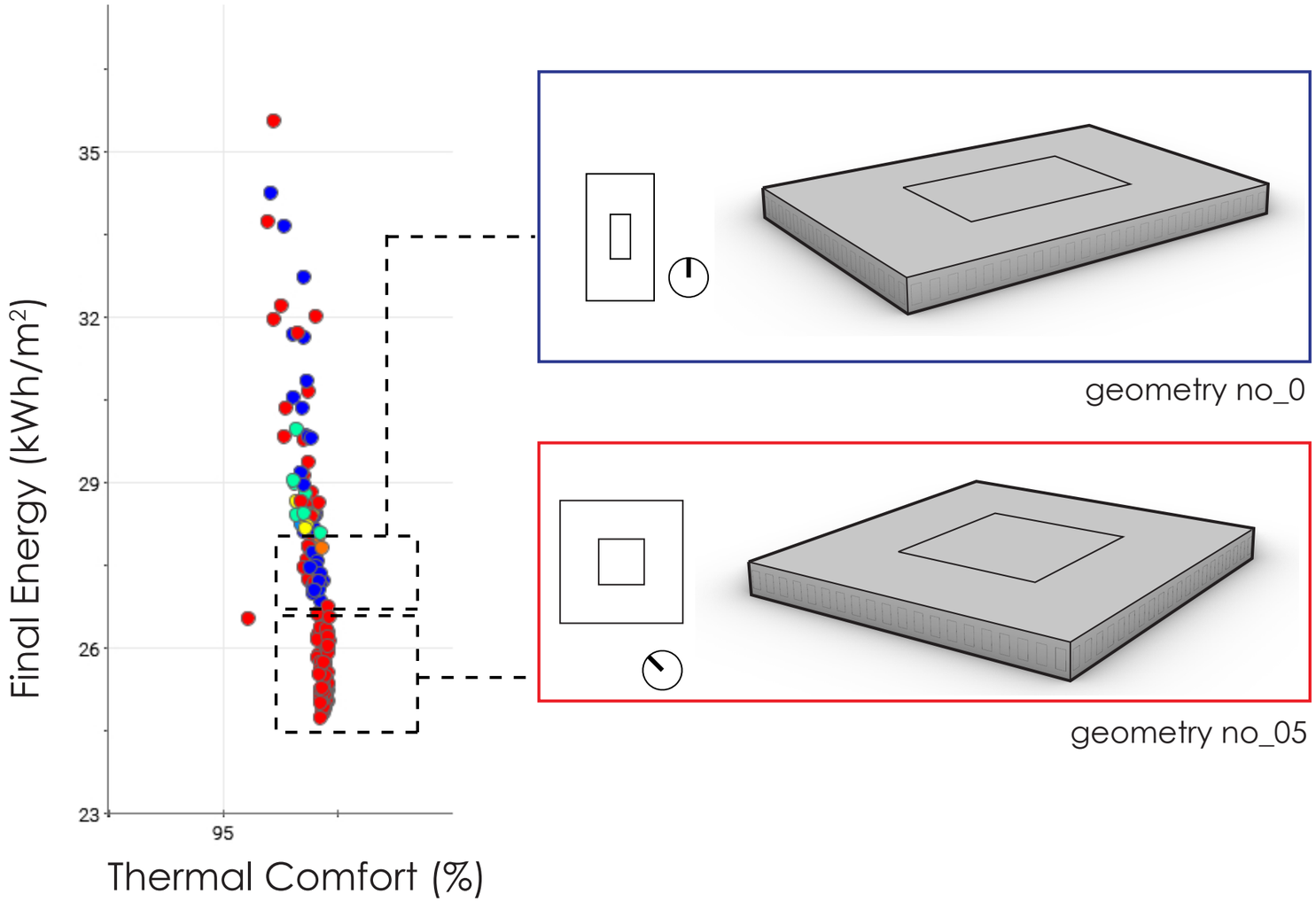
Design Exploration

Geometry type

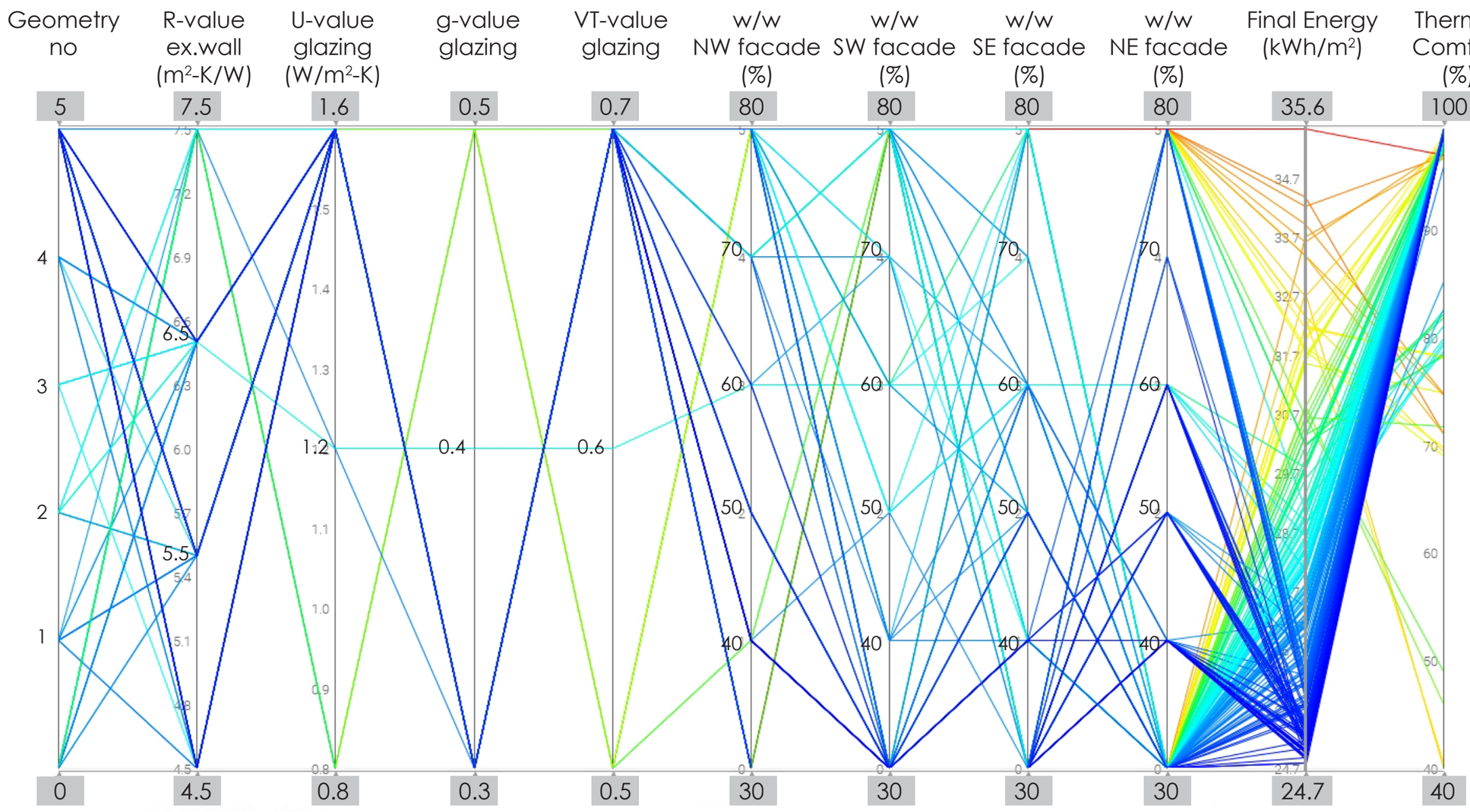


Design Exploration

Geometry type



Filtering out designs with the parallel coordinate chart



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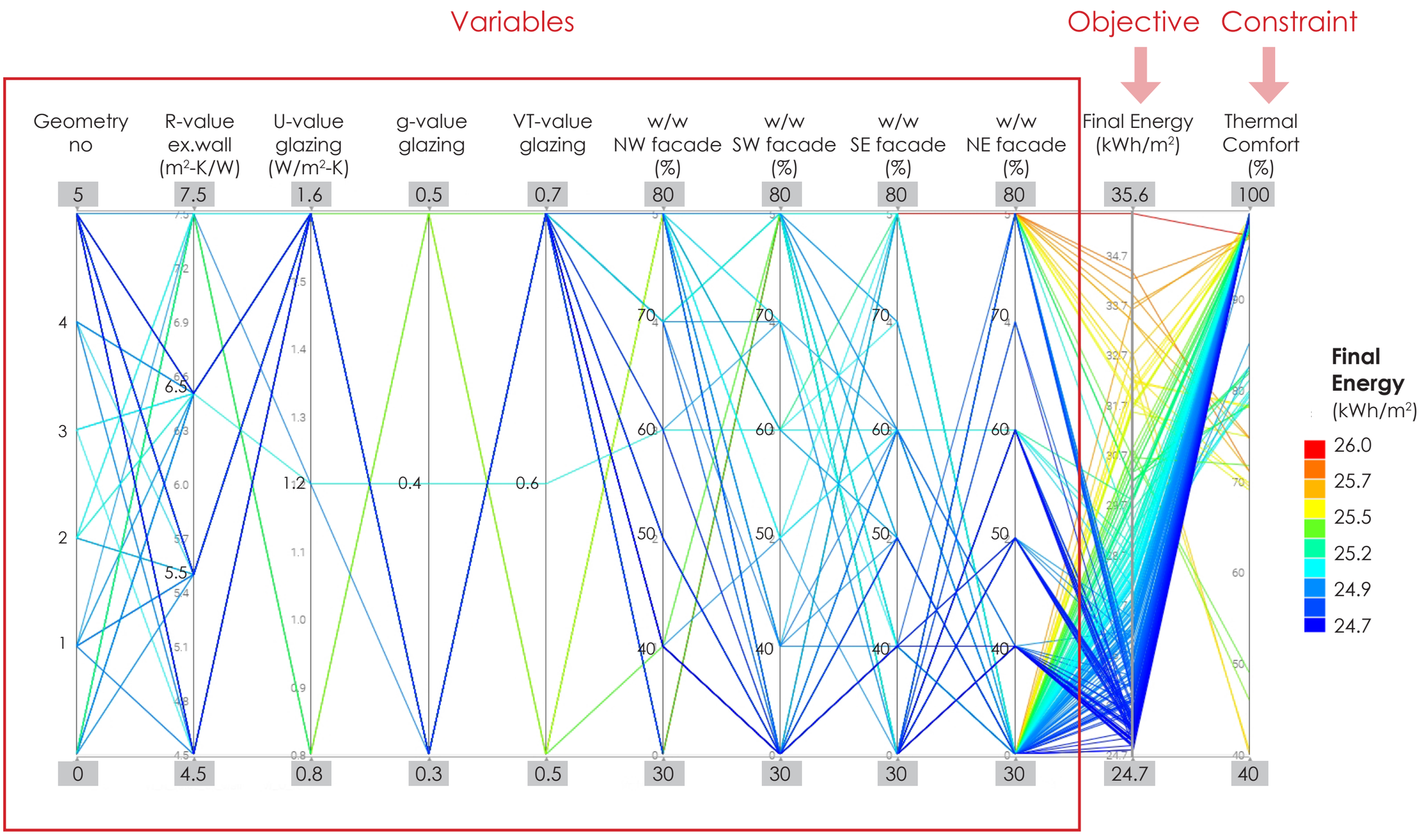
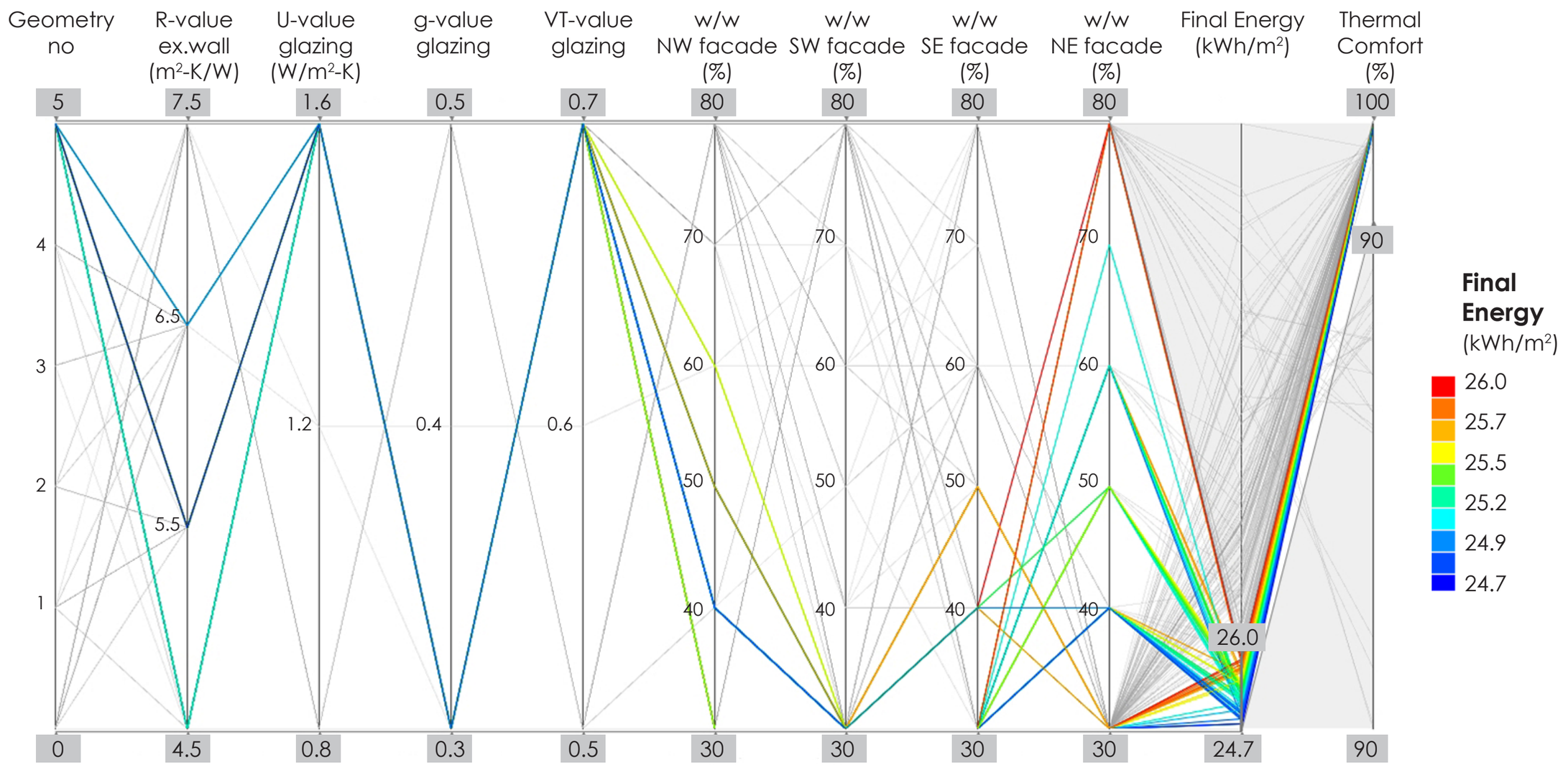


The most effective combination of façade design parameters



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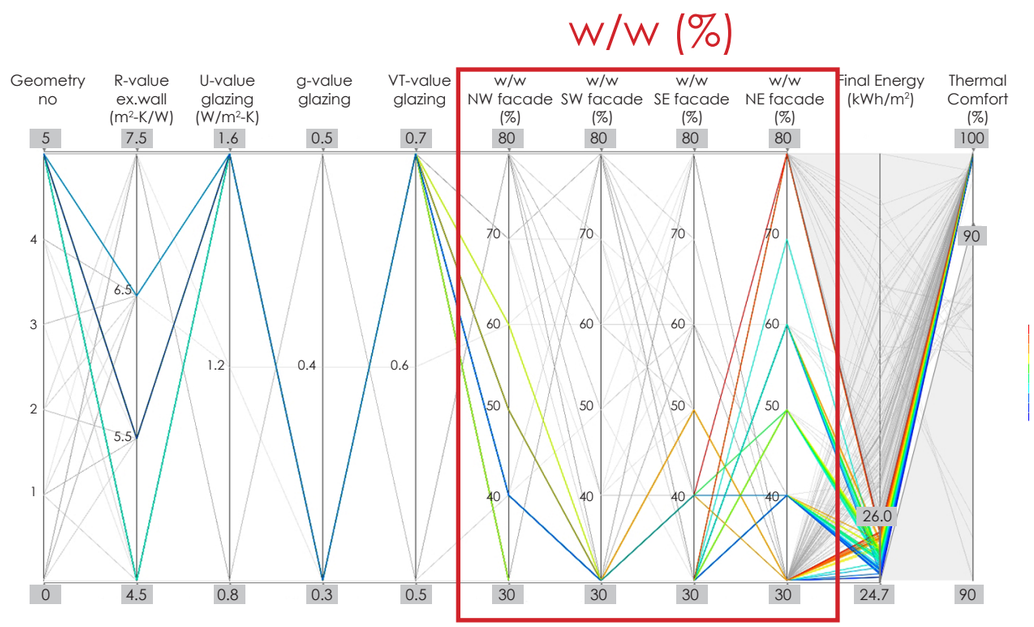
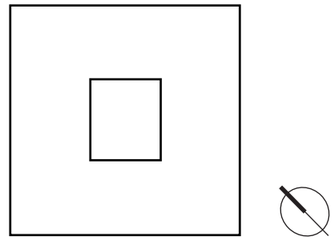


The **most effective combination** of façade design parameters that can lead to a nearly Zero - Energy high-rise office building in the temperate climate

design_no	1	2	3	4	5
geometry_no	5	5	5	5	5
R-value ext. wal (m2-K/W)	5.5	5.5	5.5	5.5	6.5
U-value glazing (W/m2-K)	1.6	1.6	1.6	1.6	1.6
g-value glazing	0.3	0.3	0.3	0.3	0.3
VT-value glazing	0.7	0.7	0.7	0.7	0.7
w/w - level 01 - NW (%)	40	40	40	40	40
w/w - level 01 - SW (%)	30	30	30	30	30
w/w - level 01 - SE (%)	30	30	30	30	40
w/w - level 01 - NE (%)	30	30	40	40	50
w/w - level 02 - NW(%)	40	40	40	40	40
w/w - level 02 - SW (%)	30	30	30	30	30
w/w - level 02 - SE (%)	30	30	30	30	30
w/w - level 02 - NE (%)	30	50	40	50	30
w/w - level 03 - NW (%)	40	40	40	40	40
w/w - level 03 - SW (%)	30	30	30	30	30
w/w - level 03 - SE (%)	30	30	30	30	30
w/w - level 03 - NE (%)	30	30	30	30	30
Final Energy (total) (kWh/m2)	24.7	24.8	24.9	24.9	24.9
Thermal Comfort (total) (%)	99	99	99	99	99

The **most effective combination** of façade design parameters that can lead to a nearly Zero - Energy high-rise office building in the temperate climate

design_no	1	2	3	4	5
geometry_no	5	5	5	5	5
R-value ext. wal (m2-K/W)	5.5	5.5	5.5	5.5	6.5
U-value glazing (W/m2-K)	1.6	1.6	1.6	1.6	1.6
g-value glazing	0.3	0.3	0.3	0.3	0.3
VT-value glazing	0.7	0.7	0.7	0.7	0.7
w/w - level 01 - NW (%)	40	40	40	40	40
w/w - level 01 - SW (%)	30	30	30	30	30
w/w - level 01 - SE (%)	30	30	30	30	40
w/w - level 01 - NE (%)	30	30	40	40	50
w/w - level 02 - NW(%)	40	40	40	40	40
w/w - level 02 - SW (%)	30	30	30	30	30
w/w - level 02 - SE (%)	30	30	30	30	30
w/w - level 02 - NE (%)	30	50	40	50	30
w/w - level 03 - NW (%)	40	40	40	40	40
w/w - level 03 - SW (%)	30	30	30	30	30
w/w - level 03 - SE (%)	30	30	30	30	30
w/w - level 03 - NE (%)	30	30	30	30	30
Final Energy (total) (kWh/m2)	24.7	24.8	24.9	24.9	24.9
Thermal Comfort (total) (%)	99	99	99	99	99



no_05

The **most effective combination** of façade design parameters that can lead to a nearly Zero - Energy high-rise office building in the temperate climate

design_no	1	2	3	4	5
geometry_no	5	5	5	5	5
R-value ext. wal (m2-K/W)	5.5	5.5	5.5	5.5	6.5
U-value glazing (W/m2-K)	1.6	1.6	1.6	1.6	1.6
g-value glazing	0.3	0.3	0.3	0.3	0.3
VT-value glazing	0.7	0.7	0.7	0.7	0.7
w/w - level 01 - NW (%)	40	40	40	40	40
w/w - level 01 - SW (%)	30	30	30	30	30
w/w - level 01 - SE (%)	30	30	30	30	40
w/w - level 01 - NE (%)	30	30	40	40	50
w/w - level 02 - NW(%)	40	40	40	40	40
w/w - level 02 - SW (%)	30	30	30	30	30
w/w - level 02 - SE (%)	30	30	30	30	30
w/w - level 02 - NE (%)	30	50	40	50	30
w/w - level 03 - NW (%)	40	40	40	40	40
w/w - level 03 - SW (%)	30	30	30	30	30
w/w - level 03 - SE (%)	30	30	30	30	30
w/w - level 03 - NE (%)	30	30	30	30	30
Final Energy (total) (kWh/m2)	24.7	24.8	24.9	24.9	24.9
Thermal Comfort (total) (%)	99	99	99	99	99

The **most effective combination** of façade design parameters that can lead to a nearly Zero - Energy high-rise office building in the temperate climate

design_no	1	2	3	4	5
geometry_no	5	5	5	5	5
R-value ext. wal (m2-K/W)	5.5	5.5	5.5	5.5	6.5
U-value glazing (W/m2-K)	1.6	1.6	1.6	1.6	1.6
g-value glazing	0.3	0.3	0.3	0.3	0.3
VT-value glazing	0.7	0.7	0.7	0.7	0.7
w/w - level 01 - NW (%)	40	40	40	40	40
w/w - level 01 - SW (%)	30	30	30	30	30
w/w - level 01 - SE (%)	30	30	30	30	40
w/w - level 01 - NE (%)	30	30	40	40	50
w/w - level 02 - NW(%)	40	40	40	40	40
w/w - level 02 - SW (%)	30	30	30	30	30
w/w - level 02 - SE (%)	30	30	30	30	30
w/w - level 02 - NE (%)	30	50	40	50	30
w/w - level 03 - NW (%)	40	40	40	40	40
w/w - level 03 - SW (%)	30	30	30	30	30
w/w - level 03 - SE (%)	30	30	30	30	30
w/w - level 03 - NE (%)	30	30	30	30	30
Final Energy (total) (kWh/m2)	24.7	24.8	24.9	24.9	24.9
Thermal Comfort (total) (%)	99	99	99	99	99

The **most effective combination** of façade design parameters that can lead to a nearly Zero - Energy high-rise office building in the temperate climate

design_no	1	2	3	4	5
geometry_no	5	5	5	5	5
R-value ext. wal (m2-K/W)	5.5	5.5	5.5	5.5	6.5
U-value glazing (W/m2-K)	1.6	1.6	1.6	1.6	1.6
g-value glazing	0.3	0.3	0.3	0.3	0.3
VT-value glazing	0.7	0.7	0.7	0.7	0.7
w/w - level 01 - NW (%)	40	40	40	40	40
w/w - level 01 - SW (%)	30	30	30	30	30
w/w - level 01 - SE (%)	30	30	30	30	40
w/w - level 01 - NE (%)	30	30	40	40	50
w/w - level 02 - NW(%)	40	40	40	40	40
w/w - level 02 - SW (%)	30	30	30	30	30
w/w - level 02 - SE (%)	30	30	30	30	30
w/w - level 02 - NE (%)	30	50	40	50	30
w/w - level 03 - NW (%)	40	40	40	40	40
w/w - level 03 - SW (%)	30	30	30	30	30
w/w - level 03 - SE (%)	30	30	30	30	30
w/w - level 03 - NE (%)	30	30	30	30	30
Final Energy (total) (kWh/m2)	24.7	24.8	24.9	24.9	24.9
Thermal Comfort (total) (%)	99	99	99	99	99

The **most effective combination** of façade design parameters that can lead to a nearly Zero - Energy high-rise office building in the temperate climate

design_no	1	2	3	4	5
geometry_no	5	5	5	5	5
R-value ext. wal (m2-K/W)	5.5	5.5	5.5	5.5	6.5
U-value glazing (W/m2-K)	1.6	1.6	1.6	1.6	1.6
g-value glazing	0.3	0.3	0.3	0.3	0.3
VT-value glazing	0.7	0.7	0.7	0.7	0.7
w/w - level 01 - NW (%)	40	40	40	40	40
w/w - level 01 - SW (%)	30	30	30	30	30
w/w - level 01 - SE (%)	30	30	30	30	40
w/w - level 01 - NE (%)	30	30	40	40	50
w/w - level 02 - NW(%)	40	40	40	40	40
w/w - level 02 - SW (%)	30	30	30	30	30
w/w - level 02 - SE (%)	30	30	30	30	30
w/w - level 02 - NE (%)	30	50	40	50	30
w/w - level 03 - NW (%)	40	40	40	40	40
w/w - level 03 - SW (%)	30	30	30	30	30
w/w - level 03 - SE (%)	30	30	30	30	30
w/w - level 03 - NE (%)	30	30	30	30	30
Final Energy (total) (kWh/m2)	24.7	24.8	24.9	24.9	24.9
Thermal Comfort (total) (%)	99	99	99	99	99

The **energy breakdown and the comfort performance** for the best performing façade designs of a nearly Zero - Energy high-rise office building in the temperate climate

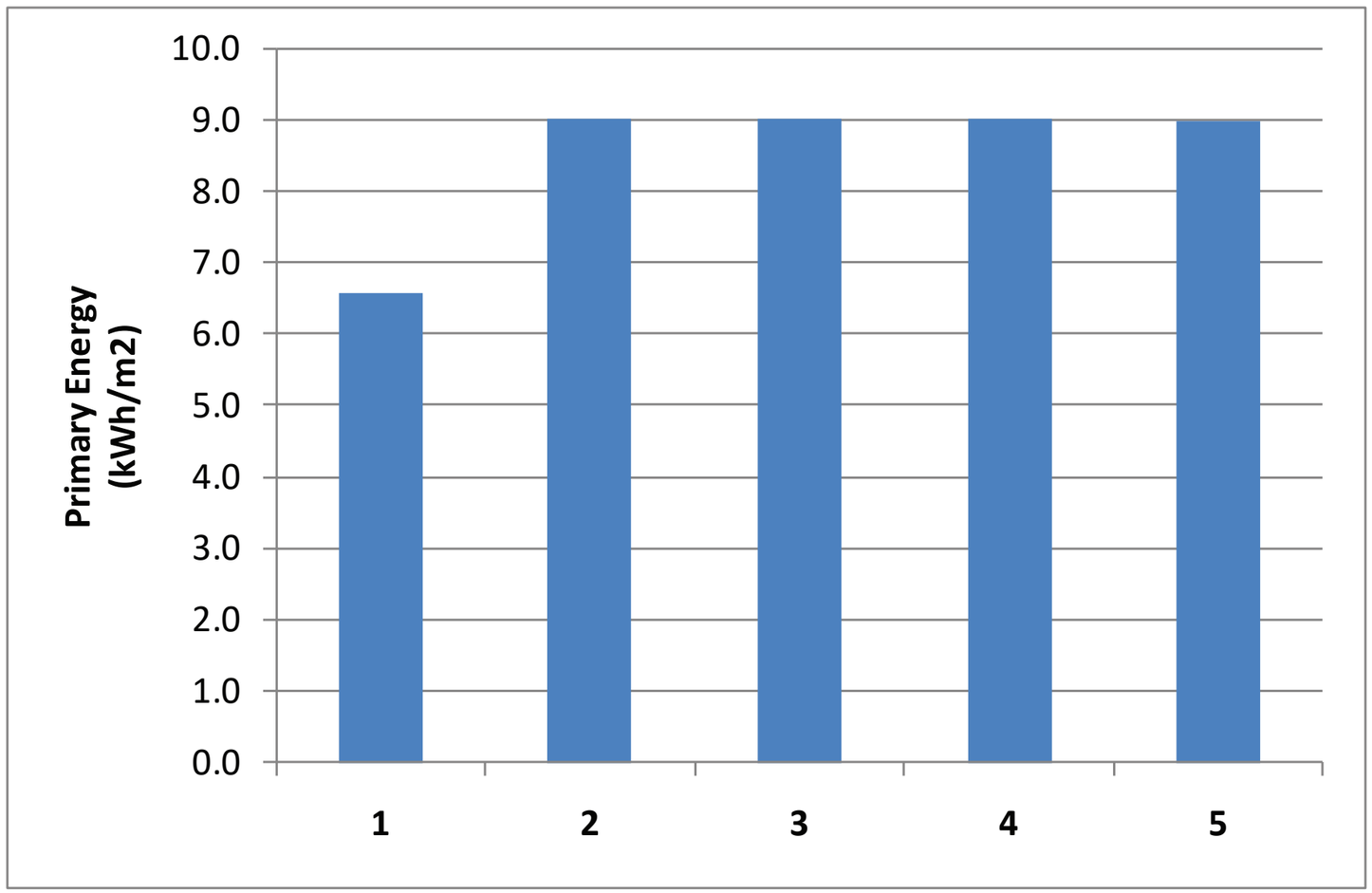
	design_no	1	2	3	4	5
Cooling Load (kWh/m2)	**level 01**	9.1	9.1	9.1	9.1	9.0
	level 02	9.1	9.0	9.0	9.0	9.1
	level 03	9.1	9.1	9.1	9.1	9.1
	total	9.1	9.1	9.1	9.0	9.1
Heating Load (kWh/m2)	**level 01**	22.7	22.7	22.8	22.8	22.9
	level 02	22.8	23.0	22.9	23.0	22.8
	level 03	22.8	22.8	22.8	22.8	22.8
	total	22.8	22.9	22.9	22.9	22.8
Lighting Load (kWh/m2)	**level 01**	9.0	9.0	8.8	8.8	8.0
	level 02	9.0	8.4	8.8	8.4	9.0
	level 03	9.0	9.0	9.0	9.0	9.0
	total	9.0	8.8	8.9	8.7	8.6
Energy Generated (kWh/m2)	**level 01**	16.1	16.1	15.8	15.8	14.6
	level 02	16.1	15.4	15.8	15.4	16.1
	level 03	16.1	16.1	16.1	16.1	16.1
	total	16.1	15.9	15.9	15.8	15.6
Final Energy (kWh/m2)	**level 01**	24.7	24.7	24.9	24.9	25.3
	level 02	24.7	25.0	25.0	25.0	24.7
	level 03	24.7	24.7	24.7	24.7	24.7
	total	24.7	24.8	24.9	24.9	24.9
Thermal Comfort (%)	**level 01**	99	99	99	99	99
	level 02	99	100	99	100	99
	level 3	99	99	99	99	99
	total	99	99	99	99	99

Comparison with BENG requirements

BENG 2:

Primary Energy < 40 kWh/m^2 for office buildings

Design	Heating Load (kWh/m2)	Cooling Load (kWh/m2)	Lighting Load (kWh/m2)	Fan & Pumps Electric (kWh/m2)	Energy Generated (kWh/m2)	Delivered Energy (kWh/m2)	Primary Energy (kWh/m2)
1	22.8	9.1	9.0	5.5	16.1	4.5	6.6
2	22.9	9.1	8.8	5.5	15.9	6.2	9.0
3	22.9	9.1	8.9	5.7	15.9	6.2	9.0
4	22.9	9.1	8.7	5.7	15.8	6.2	9.0
5	22.8	9.1	8.6	5.7	15.6	6.2	9.0

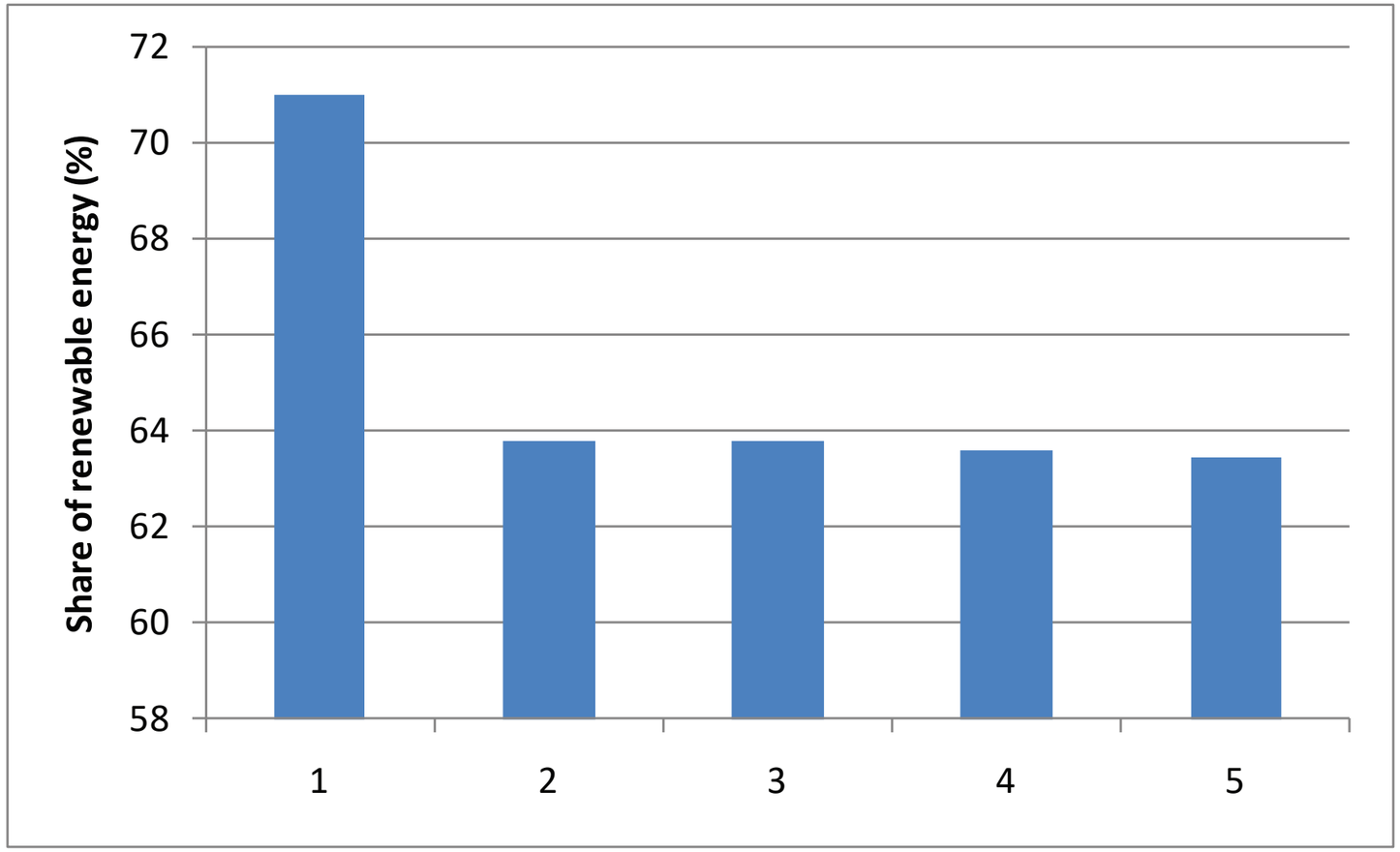


Comparison with BENG requirements

BENG 3:

share of renewable energy > 30% for office buildings

Design	Energy Generated (kWh/m2)	Primary Energy (kWh/m2)	Energy Generated / (Primary Energy+Energy Generated) *100 (%)
1	16.1	6.6	71
2	15.9	9.0	64
3	15.9	9.0	64
4	15.8	9.0	64
5	15.6	9.0	63



Improvement of energy performance according to benchmark

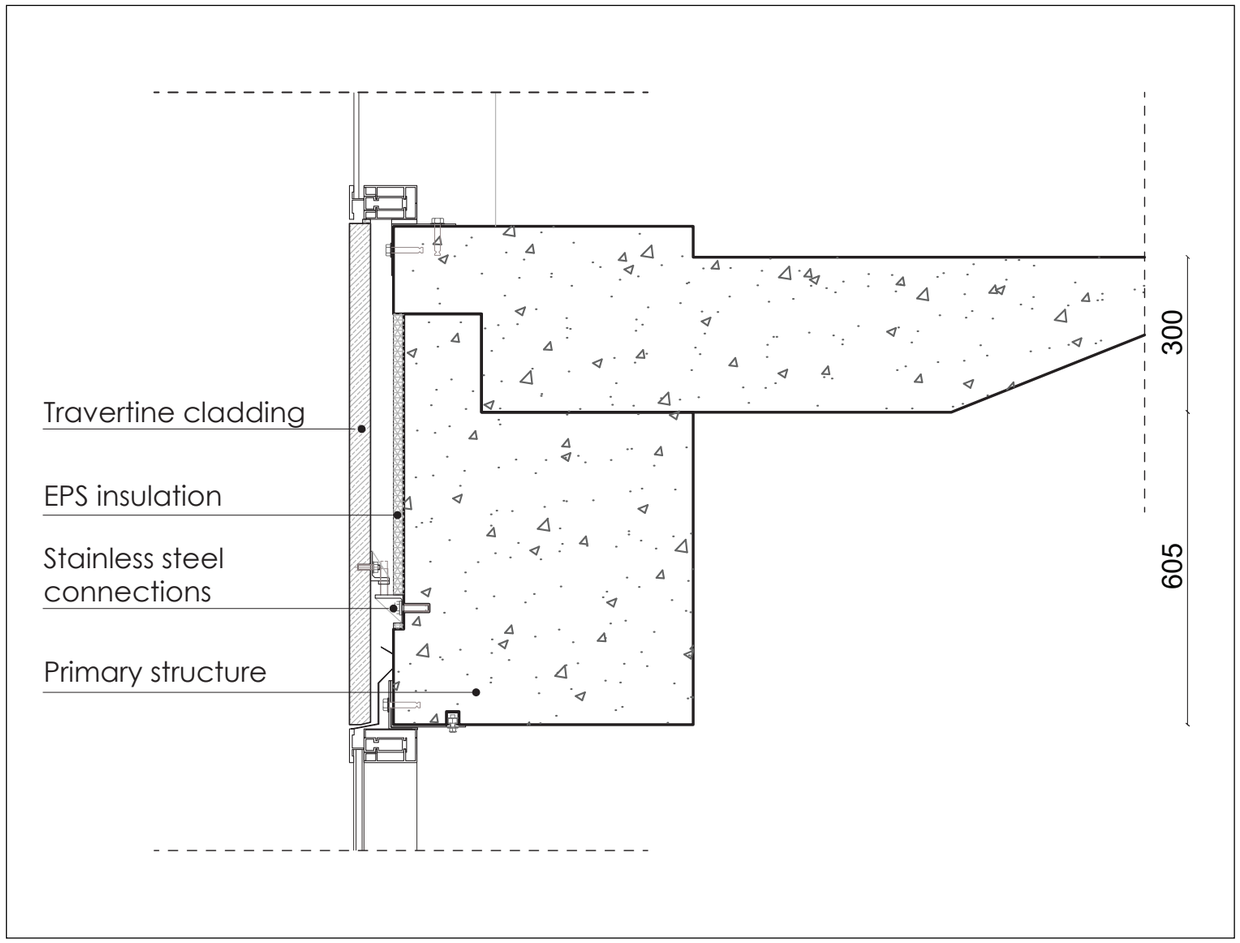
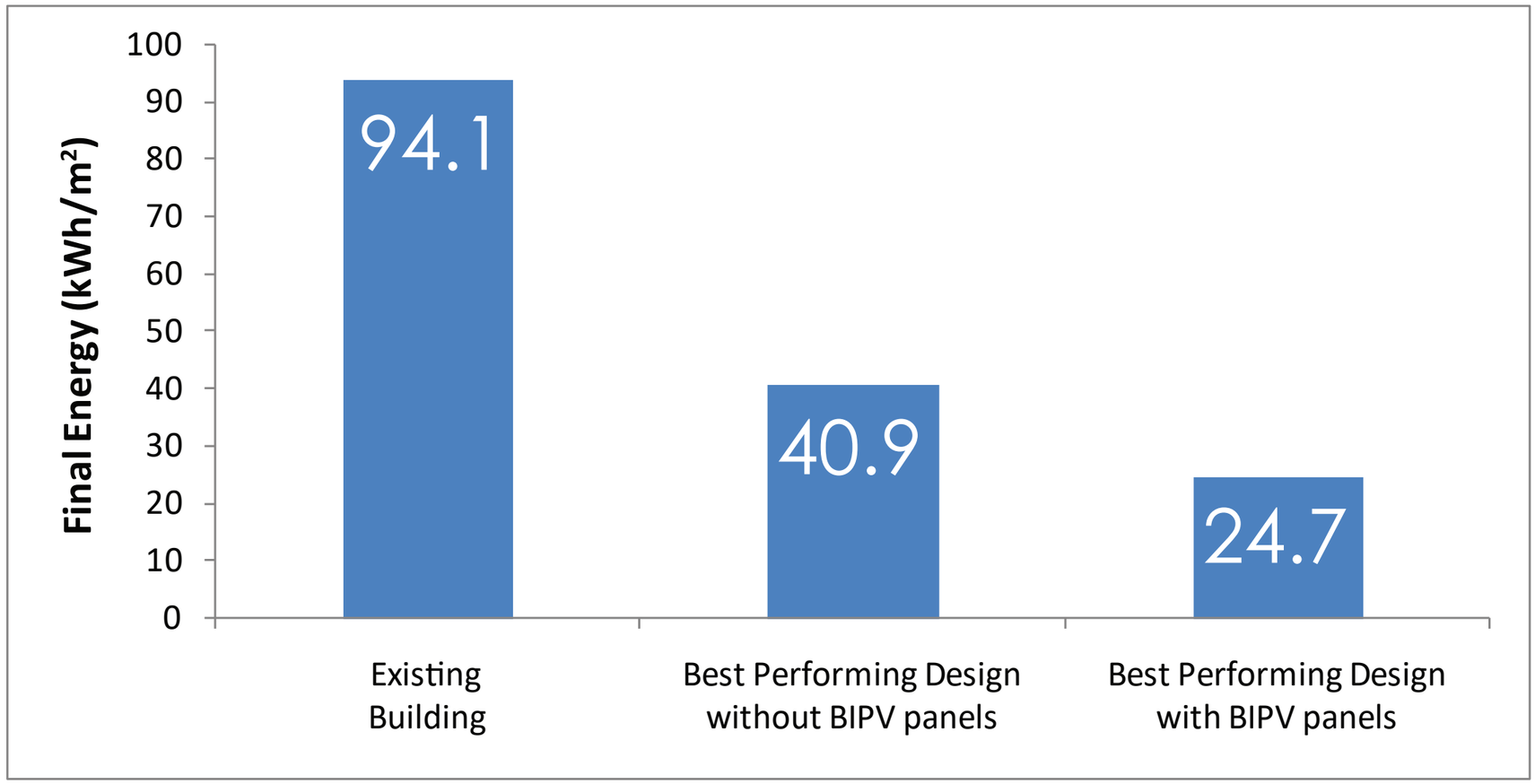


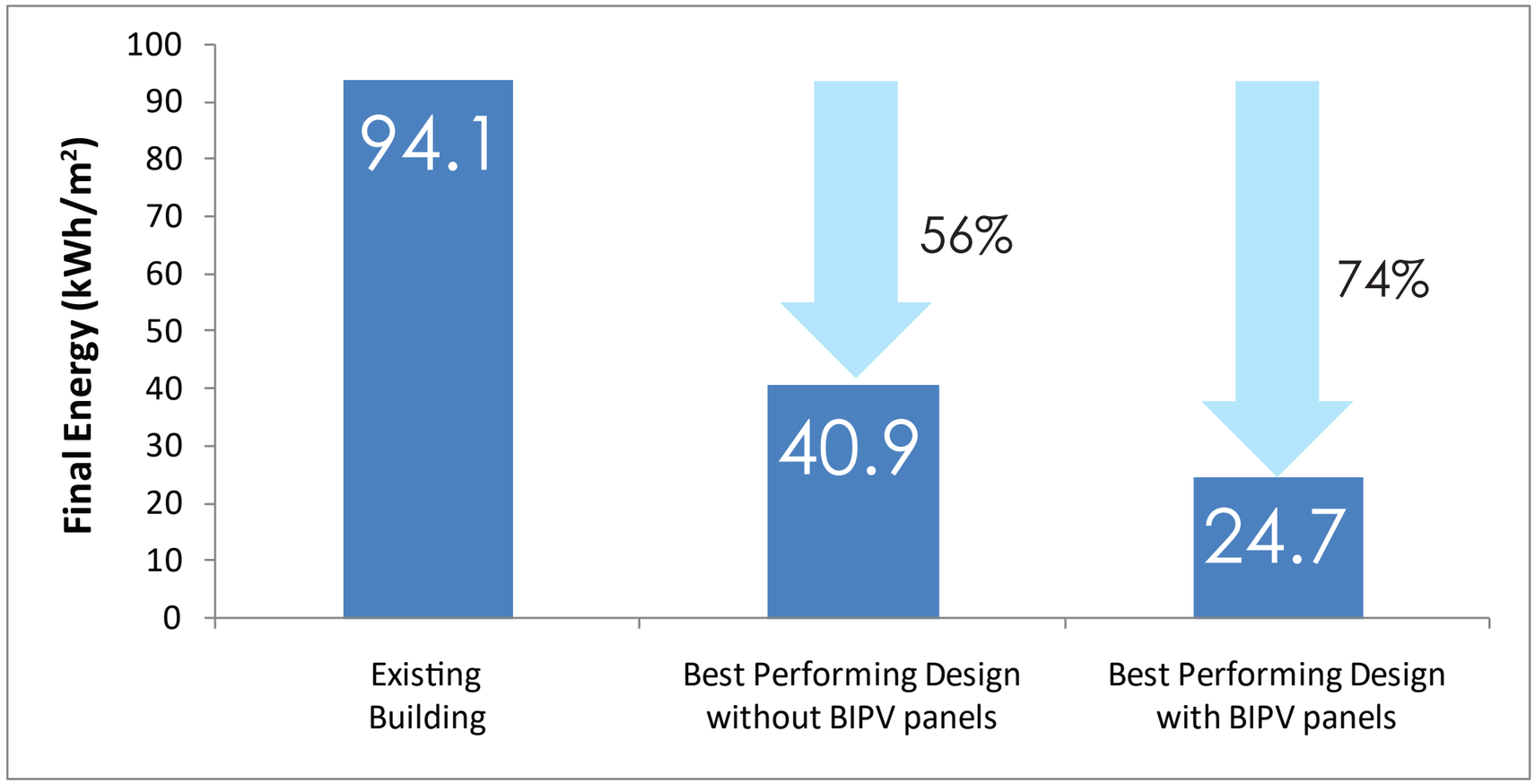
Figure: Vertical section of the façade of the existing building, Rotterdam Science tower, Rotterdam. Adapted from: (Avdic, Turkcan, Vargas, & Sakthivel, 2018).

Figure: North-east view of the Rotterdam Science tower (ErasmusMC, 2015).

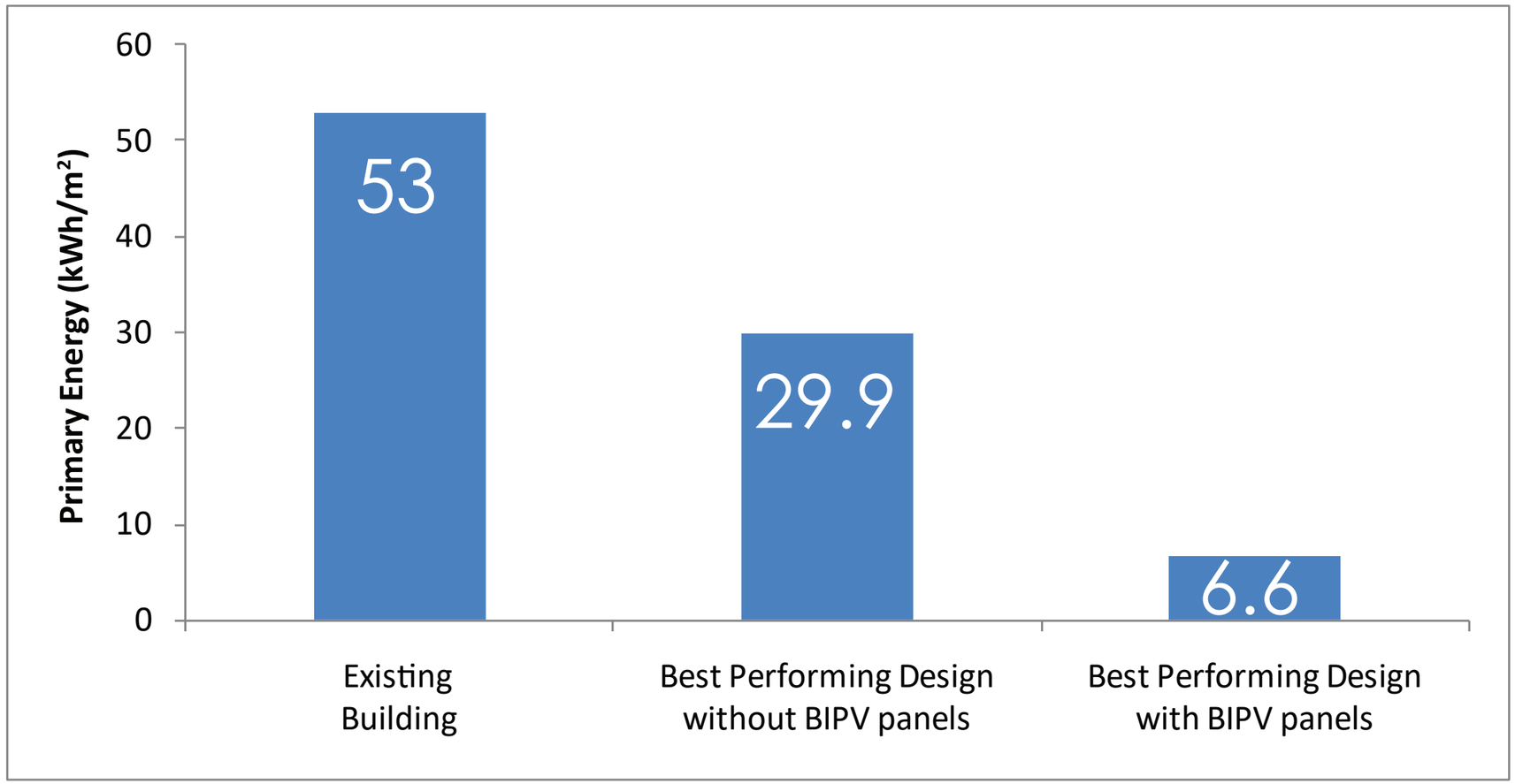
Improvement of energy performance according to benchmark



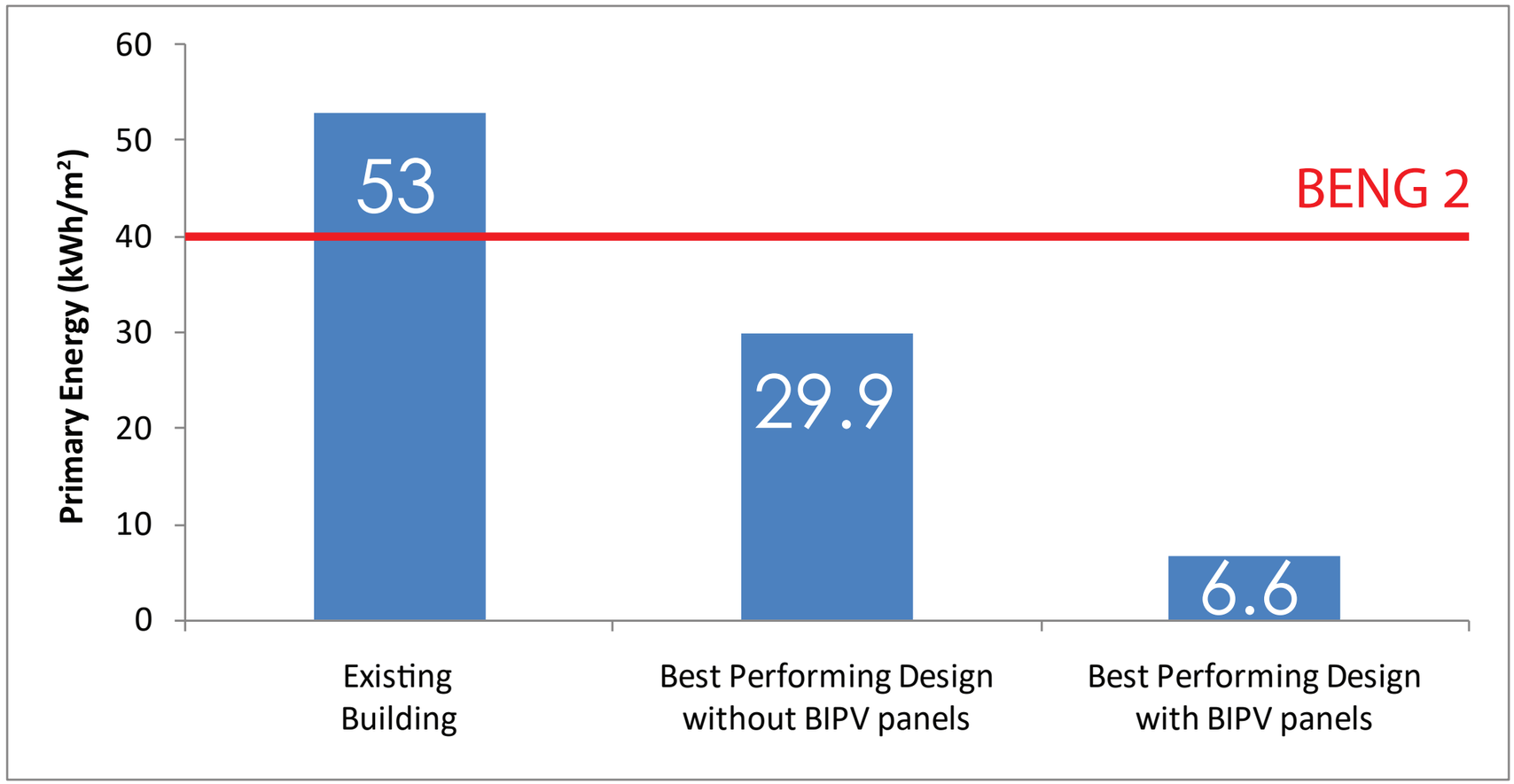
Improvement of energy performance according to benchmark



Improvement of energy performance according to benchmark

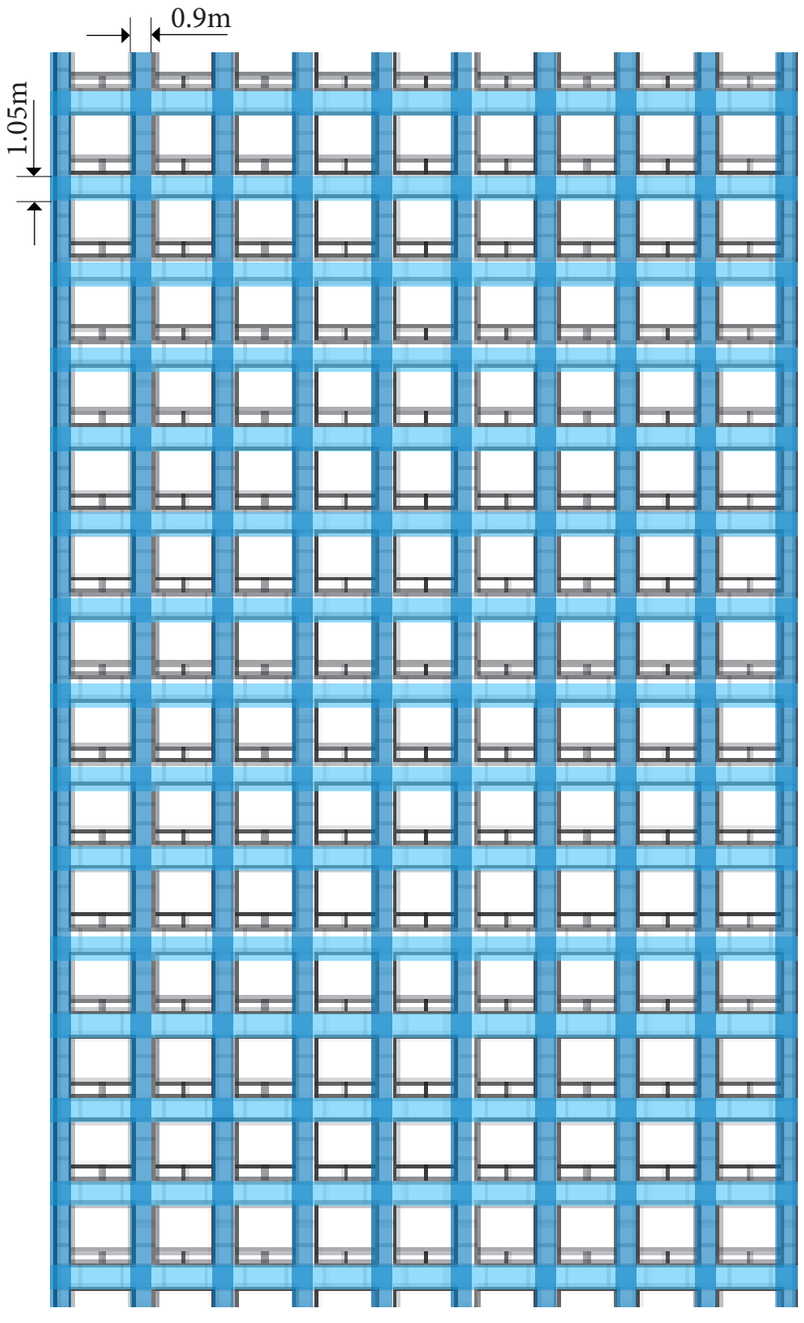


Improvement of energy performance according to benchmark



Facade design proposal

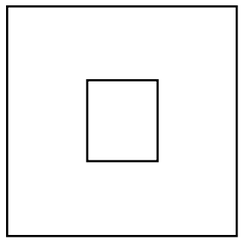
Existing building



Drawings: MOR (2018)

ErasmusMC. (2015). Retrieved from https://twitter.com/ErasmusMC

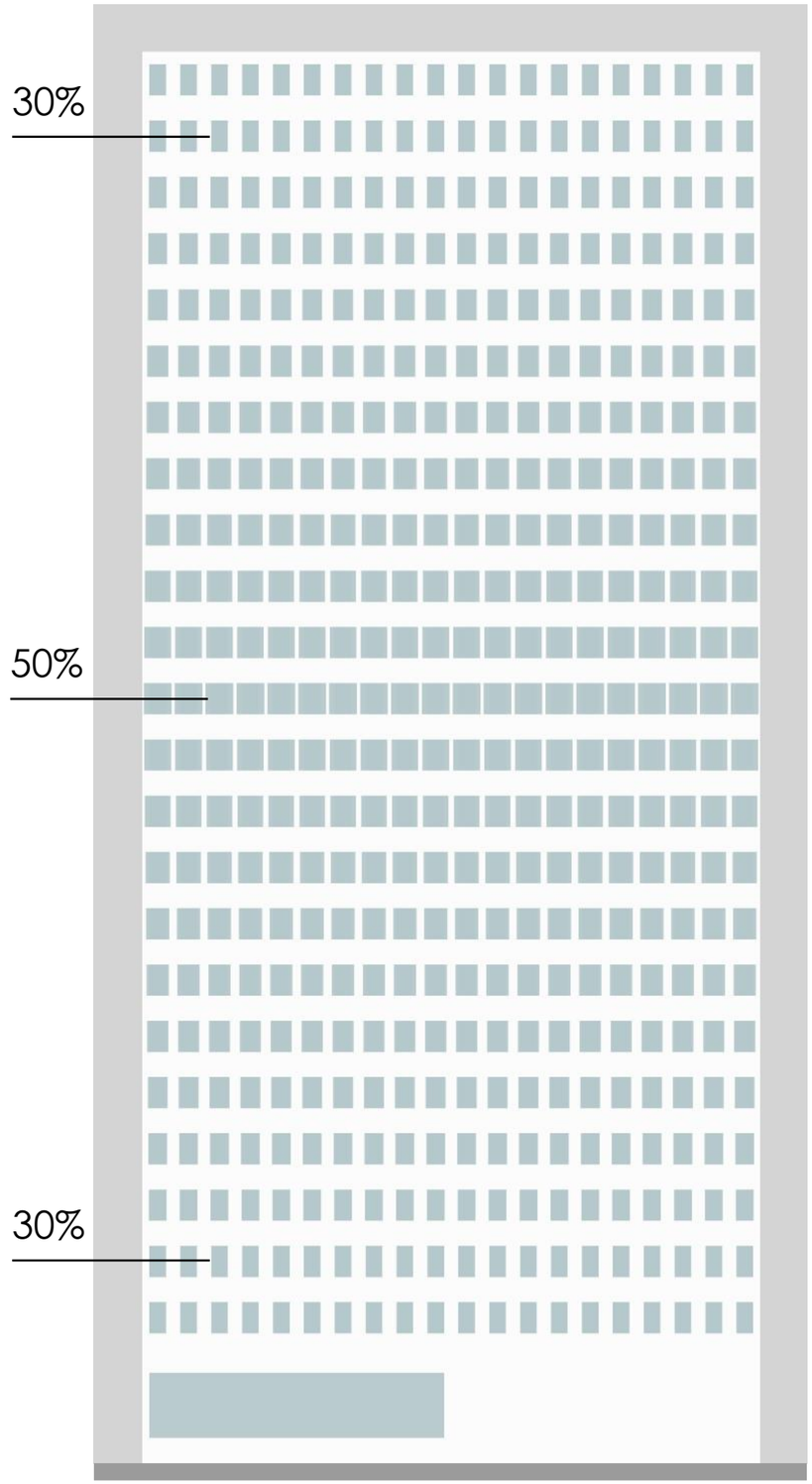
Facade design proposal



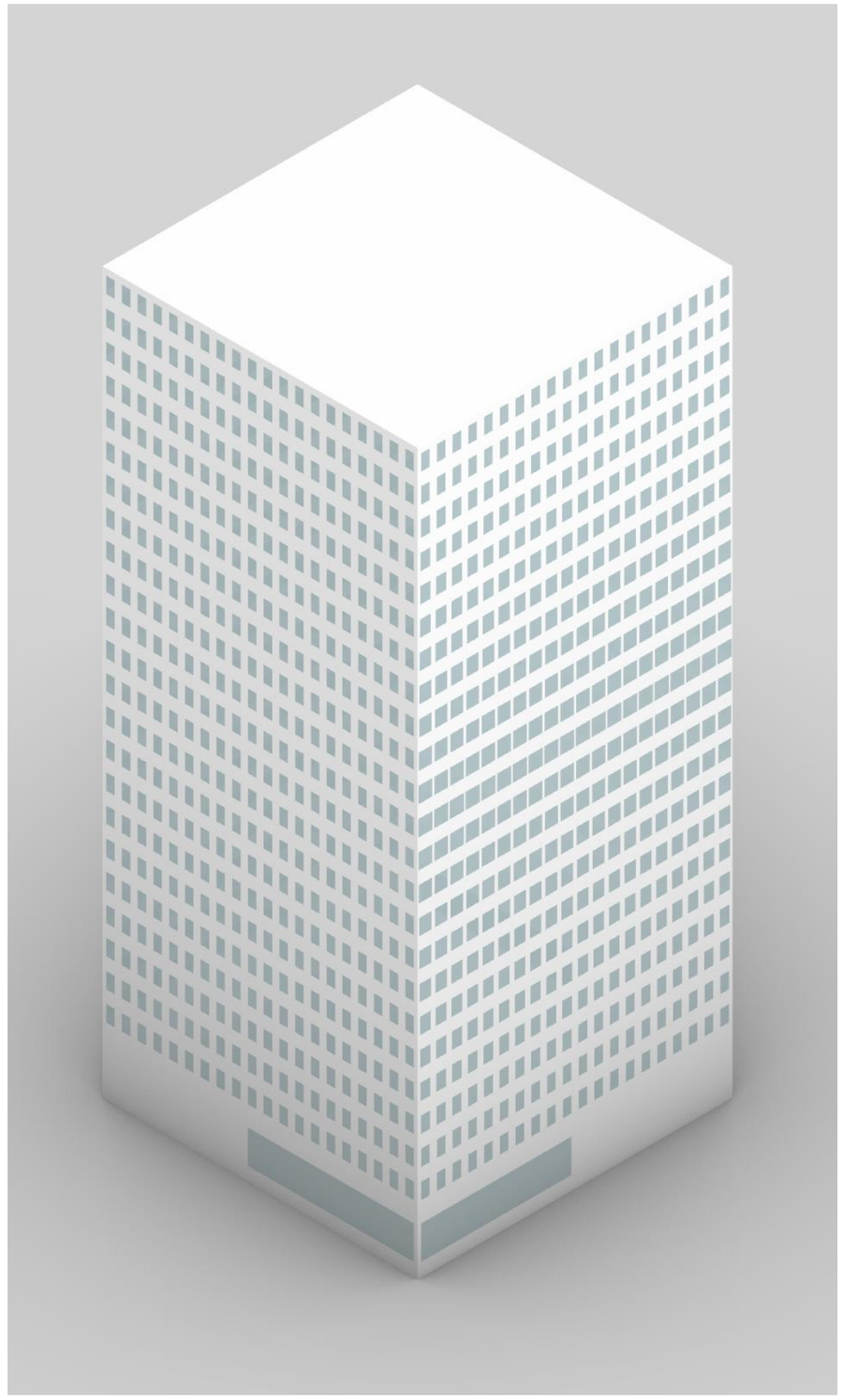
Design 1

Geometry no_5

Cooling Load (kWh/m2)	9.1
Heating Load (kWh/m2)	22.9
Lighting Load (kWh/m2)	8.8
Energy Generated (kWh/m2)	15.9
Final Energy (kWh/m2)	24.8
Thermal Comfort (%)	99

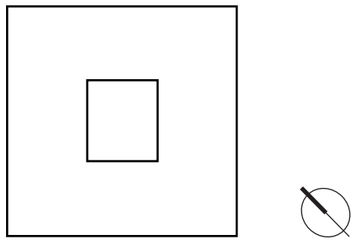


North - east elevation



Isometric view: East

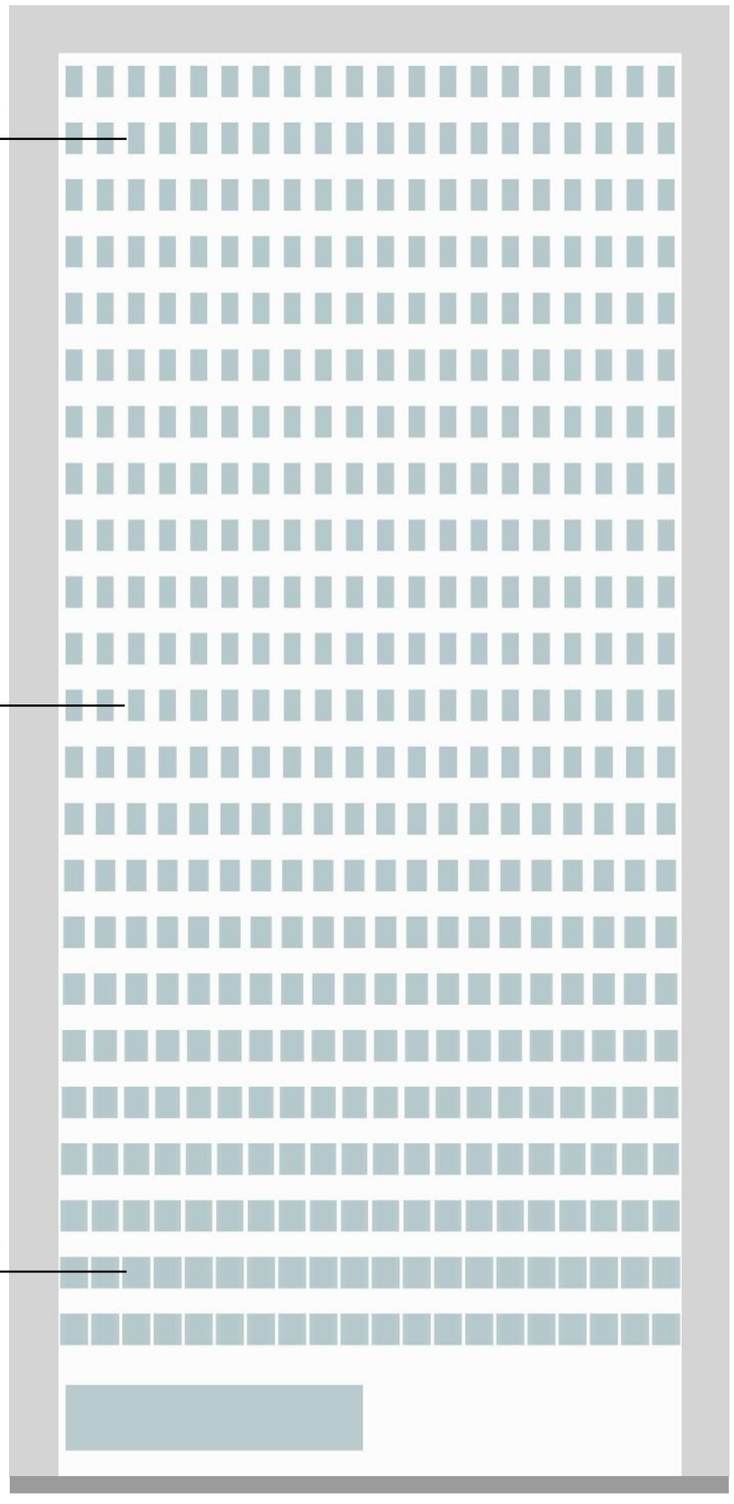
Facade design proposal



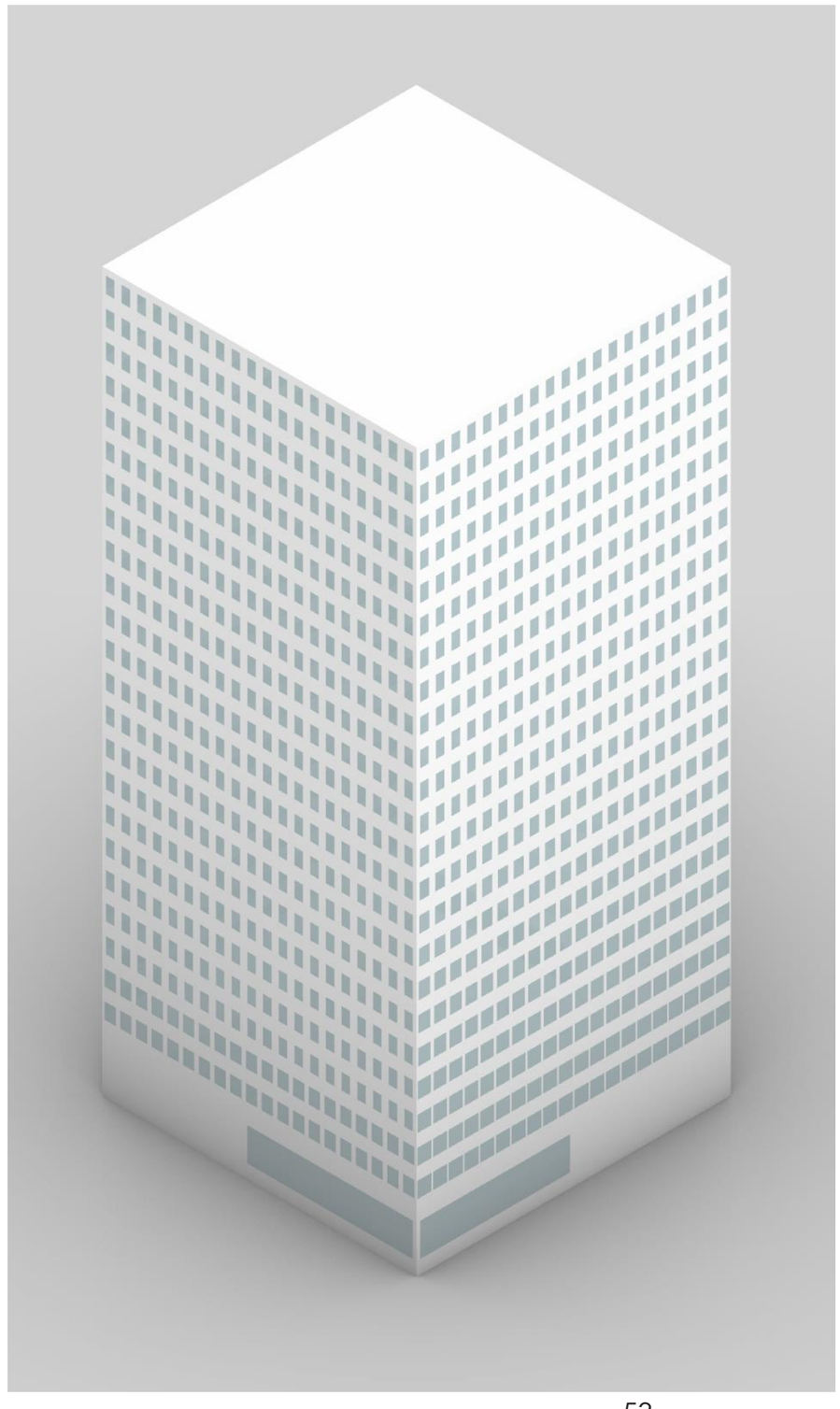
Design 2

Geometry no_5

Cooling Load (kWh/m2)	9.1
Heating Load (kWh/m2)	22.8
Lighting Load (kWh/m2)	8.6
Energy Generated (kWh/m2)	15.6
Final Energy (kWh/m2)	24.9
Thermal Comfort (%)	99

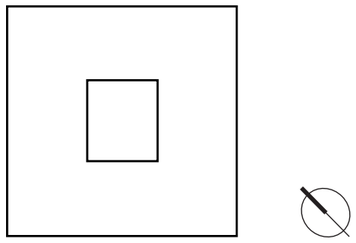


North - east elevation



Isometric view: East

Facade design proposal

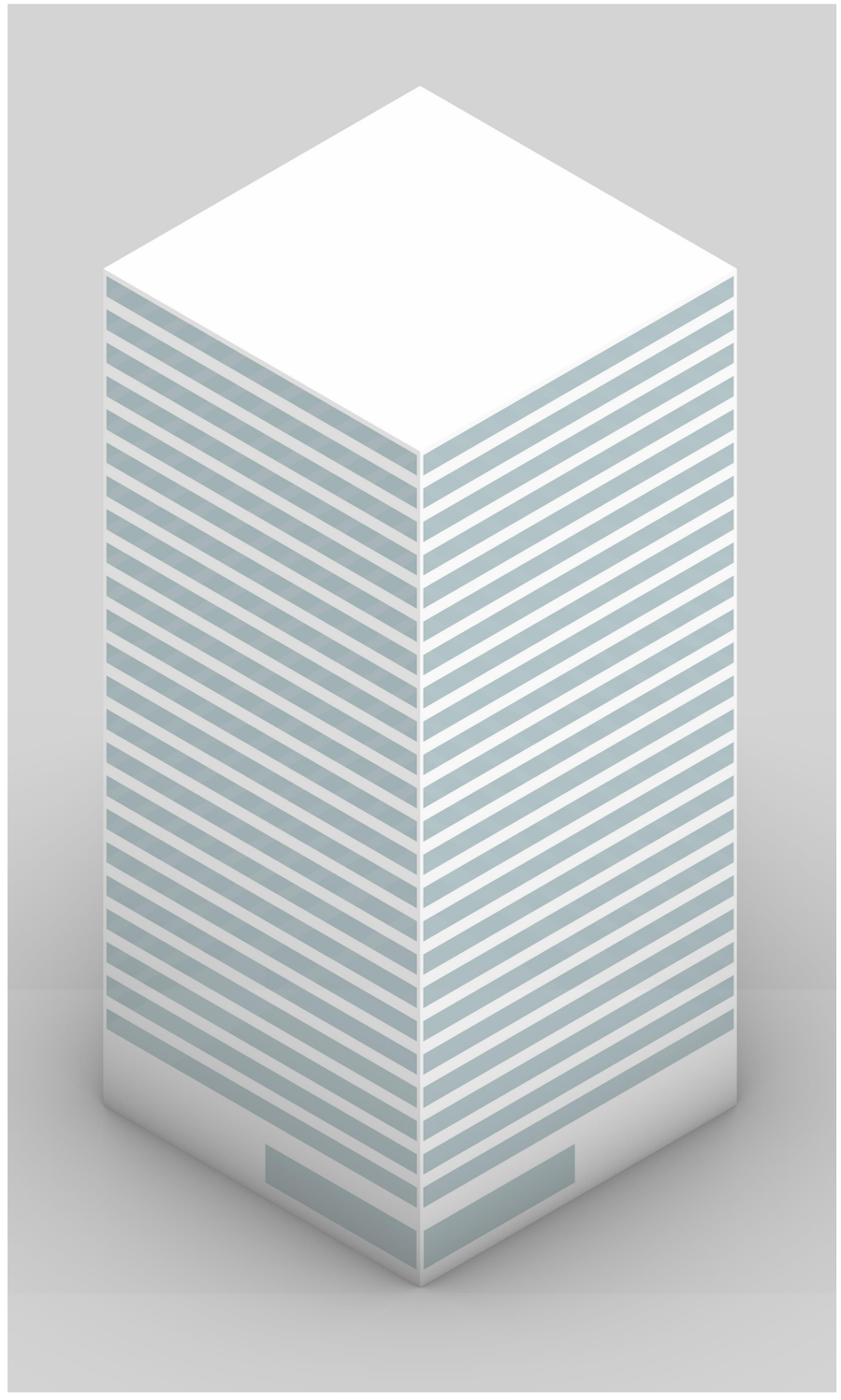


Design 3

Geometry no_5

Cooling Load (kWh/m2)	8.7
Heating Load (kWh/m2)	23.4
Lighting Load (kWh/m2)	6.4
Energy Generated (kWh/m2)	9.4
Final Energy (kWh/m2)	29.1
Thermal Comfort (%)	99

North - east elevation



Isometric view: East

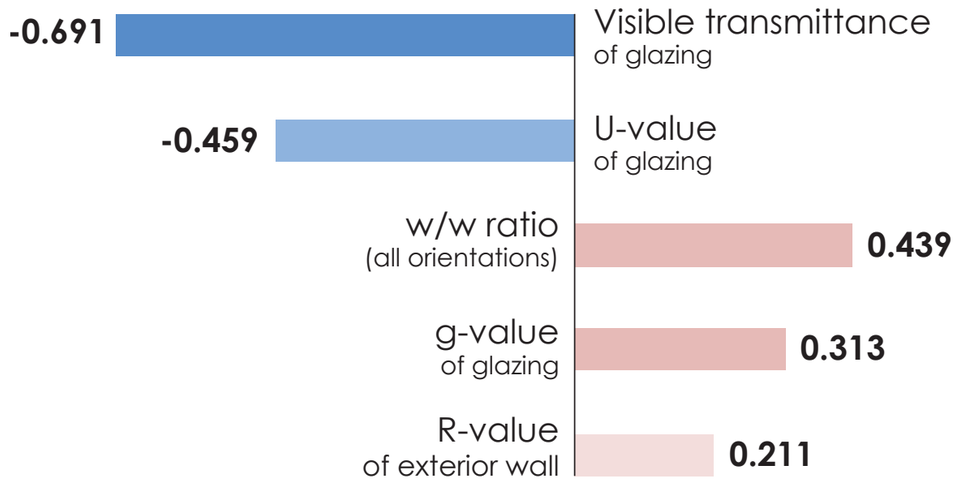
High-rise Office Building

Temperate Climate

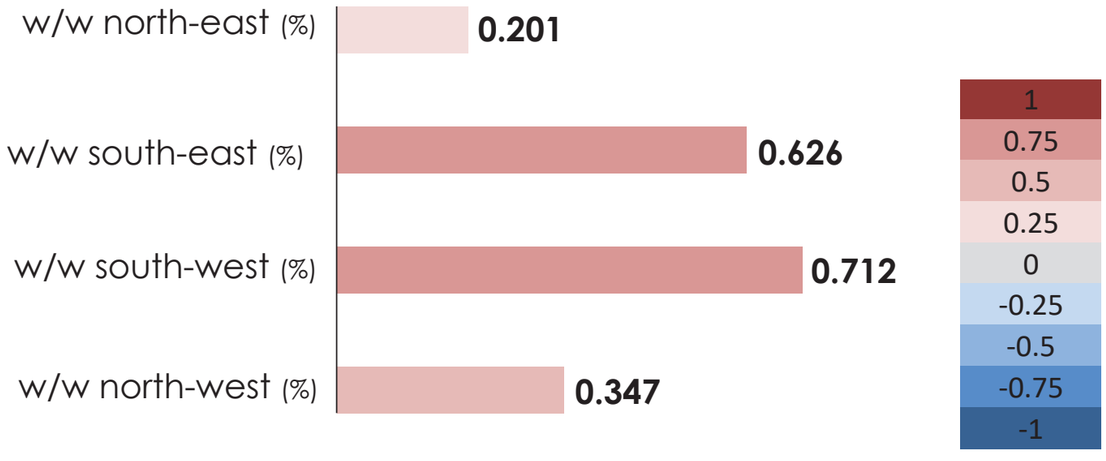
nZEB characteristics

Connection to the energy grid		On grid	●
		Off grid	
Renewable supply options		On site	●
		Off site	
Energy balance	Period	Annual	●
		Monthly	
	Type	Energy used / Energy Generated	●
		Energy from grid / Energy fed into the grid	
	Unit	Primary Energy	
		Final / Delivered Energy	●
Energy end uses	Building related		Cooling
			Heating
			Ventilation
			Lighting
	User related		Occupancy
			Equipment
	Embodied energy		Not considered

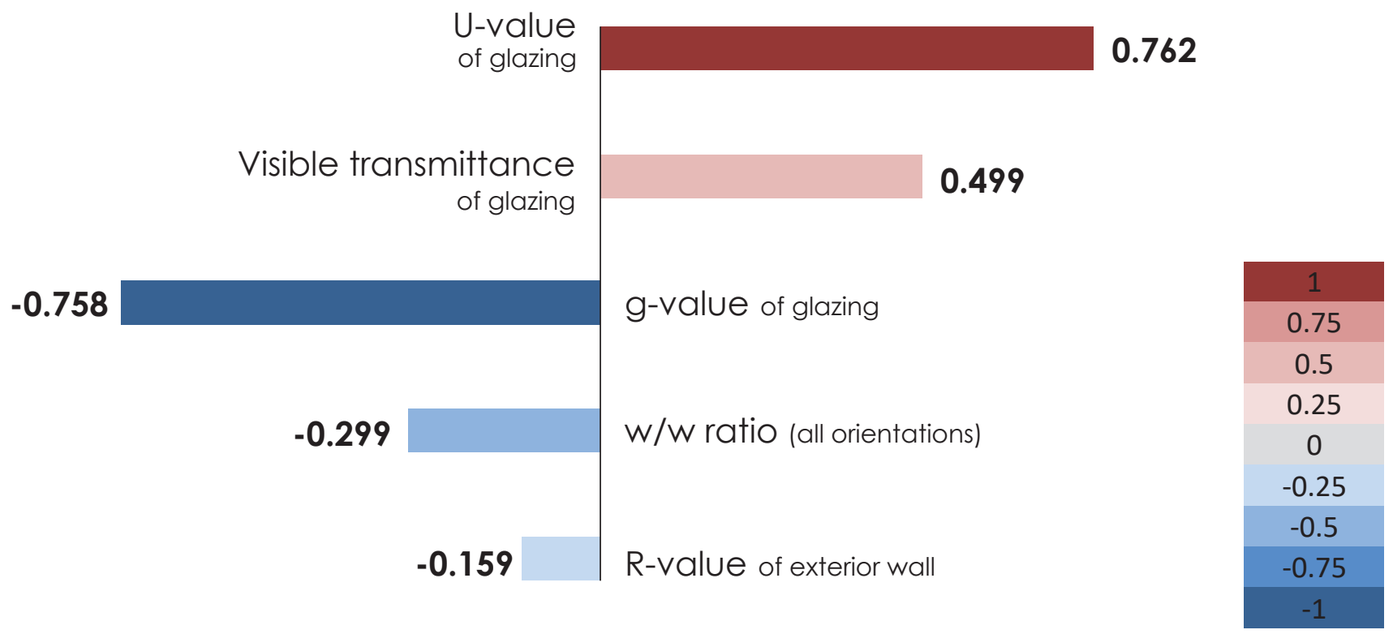
Pearson Correlation between Facade Parameters and Final Energy



Pearson Correlation between w/w ratios and Final Energy

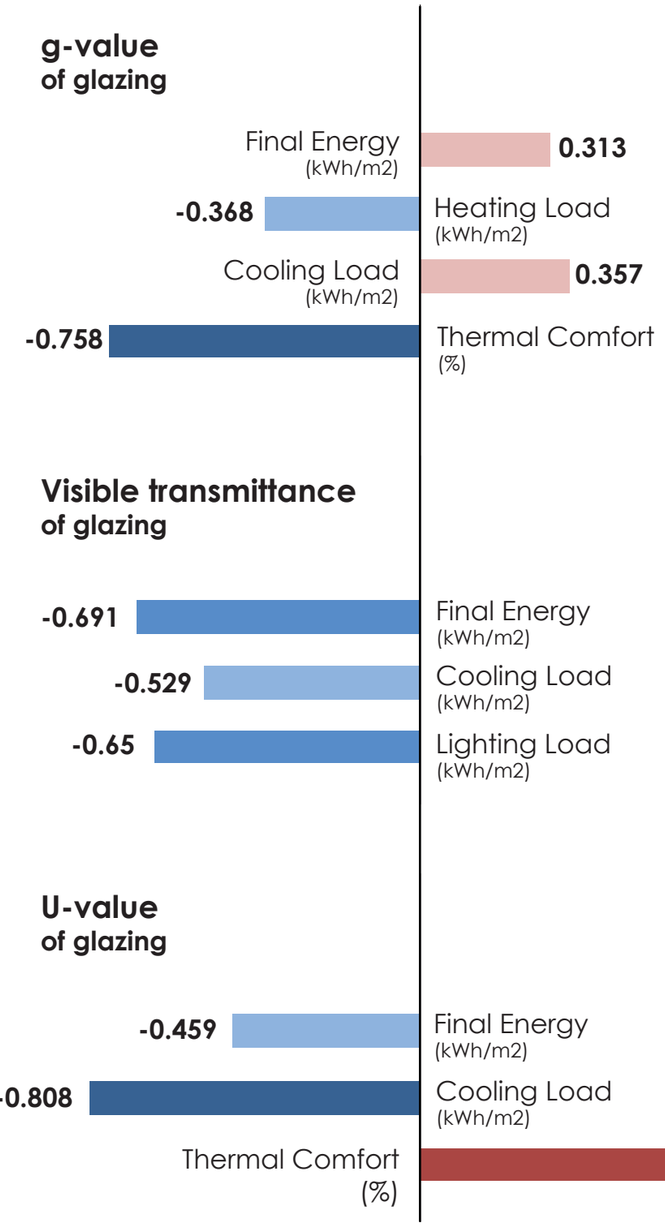


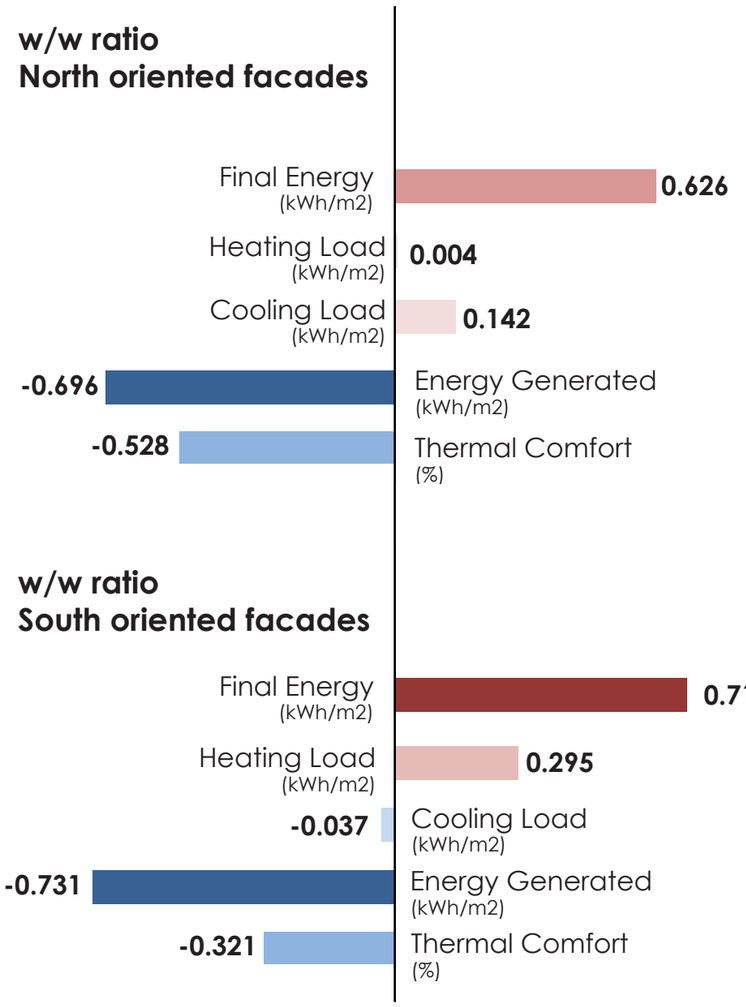
Pearson Correlation between
Facade Parameters and Thermal Comfort



Guidelines

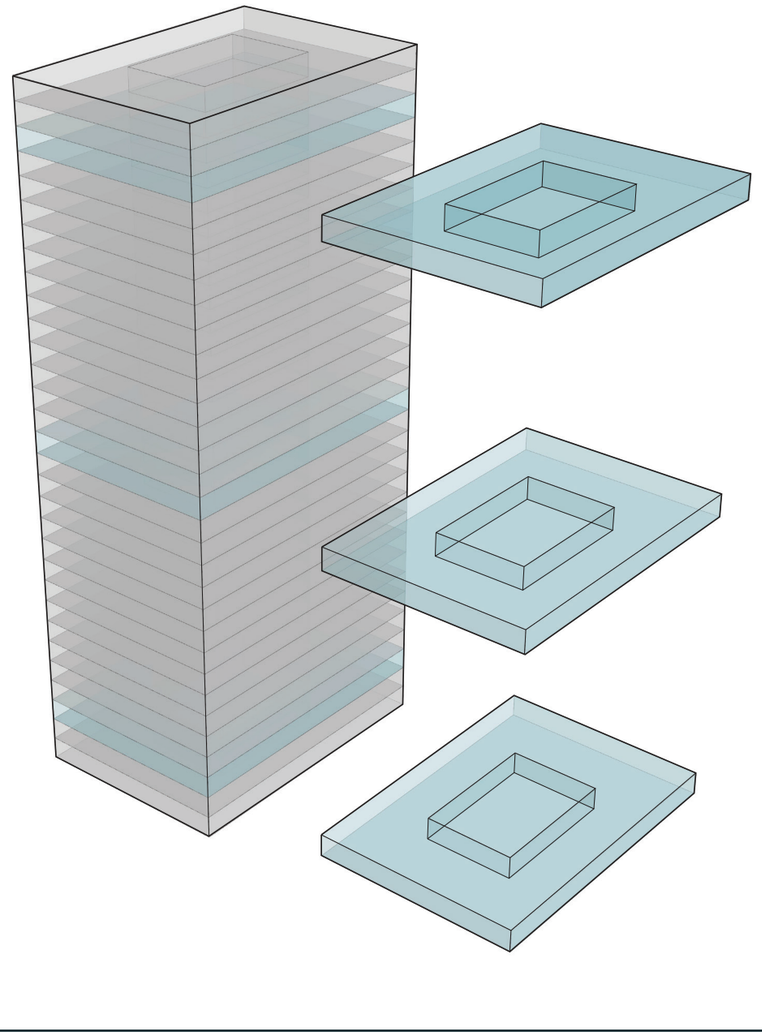
Most influential facade design parameters





Developed workflow

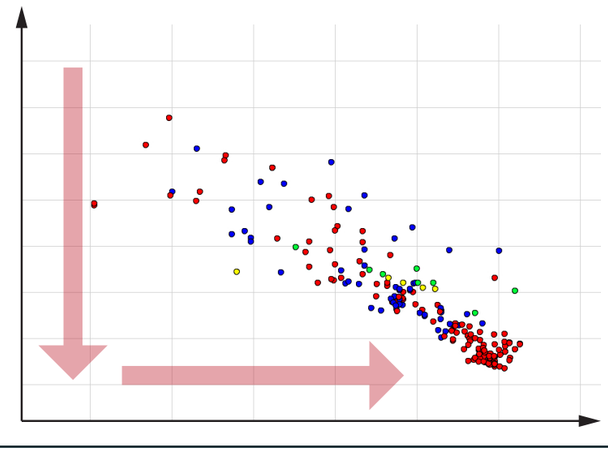
1 Parametric modeling



2 Performance evaluation

- Cooling load (kWh/m^2)
- Heating load(kWh/m^2)
- Lighting load (kWh/m^2)
- Energy Generated (kWh/m^2)
- Thermal comfort (%)

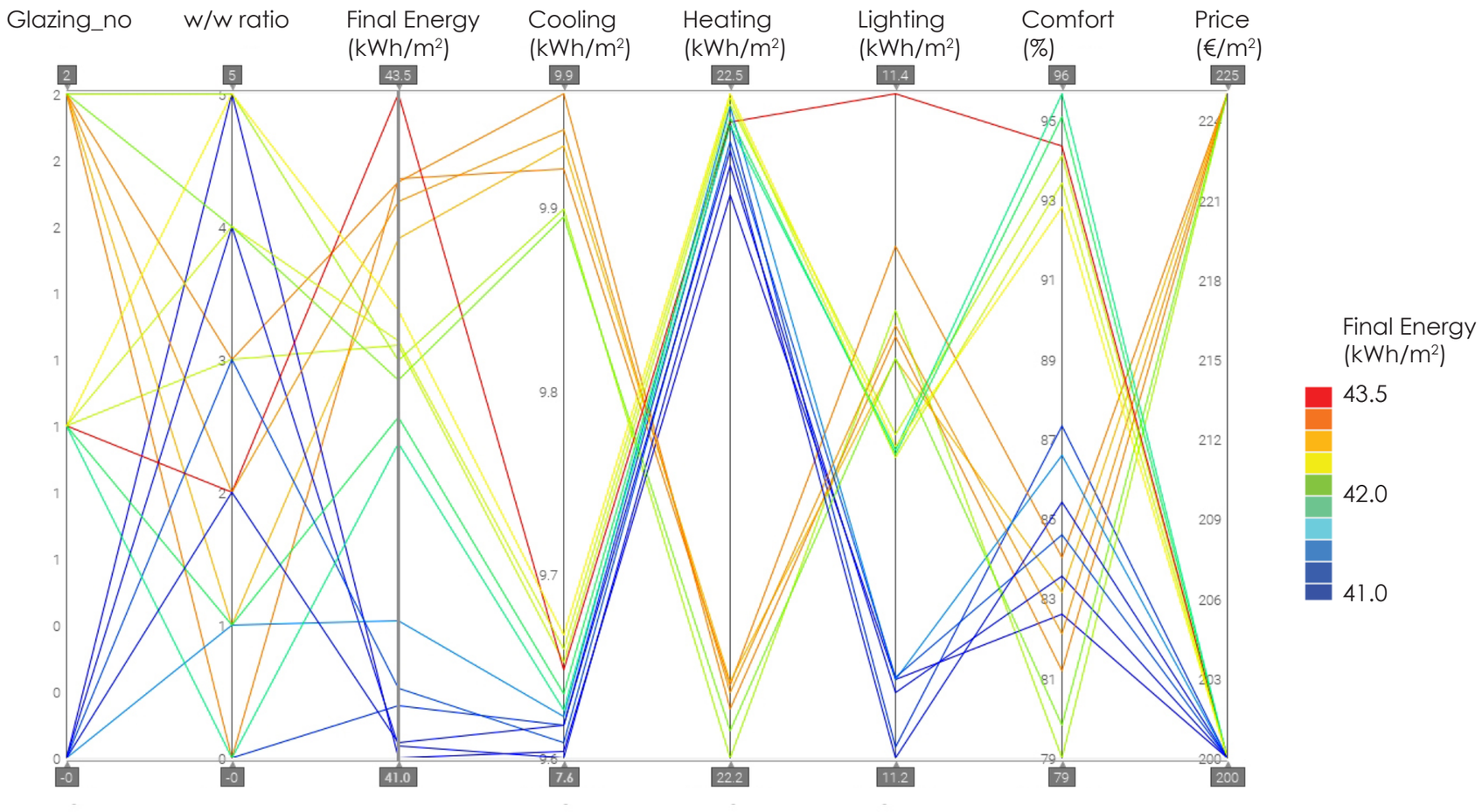
3 Optimization / design exploration



Potential use-cases of the developed workflow

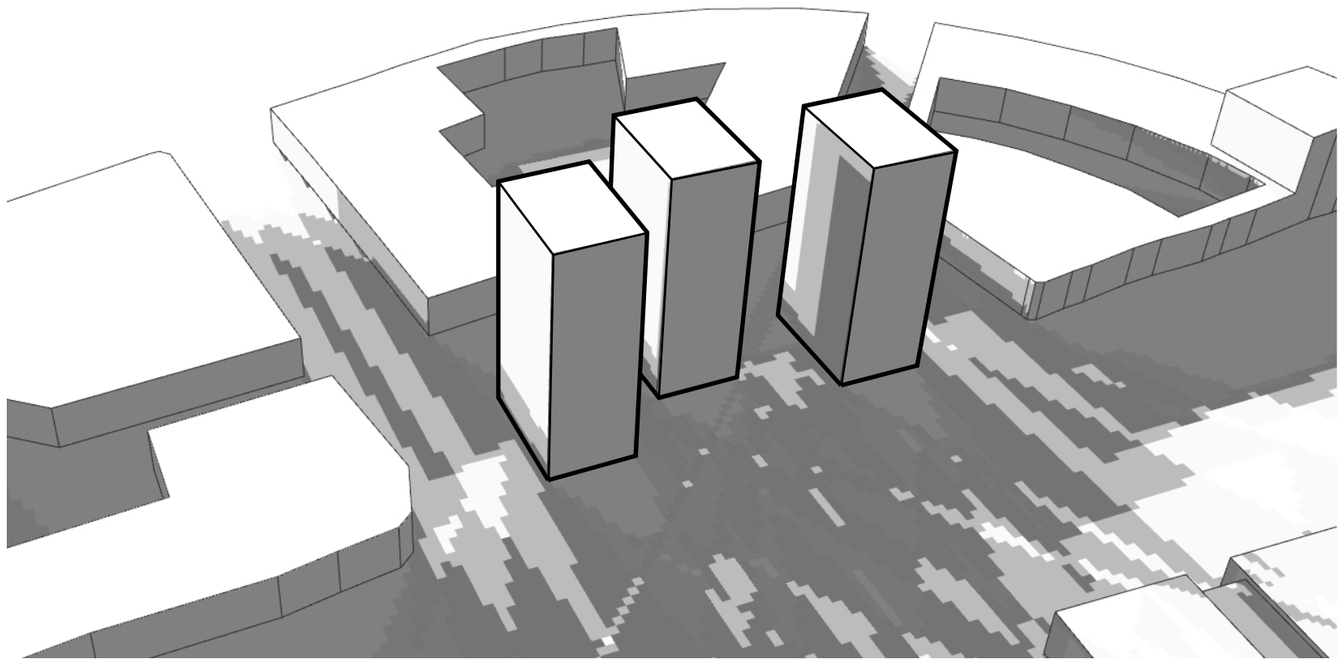
1. **Products of the market** with specific characteristics. **Cost** could be another parameter to be taken into account in the optimization.

Glazing_no	Name	U-value (W/m2-K)	g-value	VT-value	Cost (E/m2)
0	Dbl LoE (e2=.2) Clr 6mm/13mm Arg	1.689	0.531	0.721	200
1	Dbl LoE Spec Sel Clr 6mm/13mm Arg	1.338	0.345	0.682	200
2	Trp LoE (e5=.1) Clr 3mm/13mm Arg	1.058	0.458	0.698	225



Potential use-cases of the developed workflow

2. The script could be modified in order to include the **urban context** of the tested building. As a result, the optimal w/w ratio, the location and the tilt of the BIPV panels could be determined.



Conclusions

The best performing designs comply with the BENG requirements, showing that **the goal for nearly zero-energy high-rise office buidlings is feasible**.

The computational optimization of façade parameters led to **74% improvement of the final energy performance**.

The energy generation from the PVs mounted on the facade of the high-rise building **minimized the final energy by 40%.**

For **office high - rises**, a relatively high U-value and a low g-value for the glazing are suggested, in order to reach **high thermal comfort levels.**

The **guidelines** provide an indication to designers for the façade design of that kind of buildings. However, for an holistic approach towards a nZEB, one should also consider other design strategies.

Recommendations for further work

The definition in Honeybee could be modified, in order to include **dynamic interior shading**, in order to minimize the cooling load.

Research could be conducted for the **optimization of the HVAC system**, taking into account the energy breakdown of high-rise buildings.

It is suggested to include the **urban context** in the definition. Therefore, the optimal w/w ratios, the location and orientation of the BIPV panels according to context could be explored.

It is recommended to compare the obtained optimization results with those of a **brute-force approach**, in order to check if the results can be further improved.

Thank you !