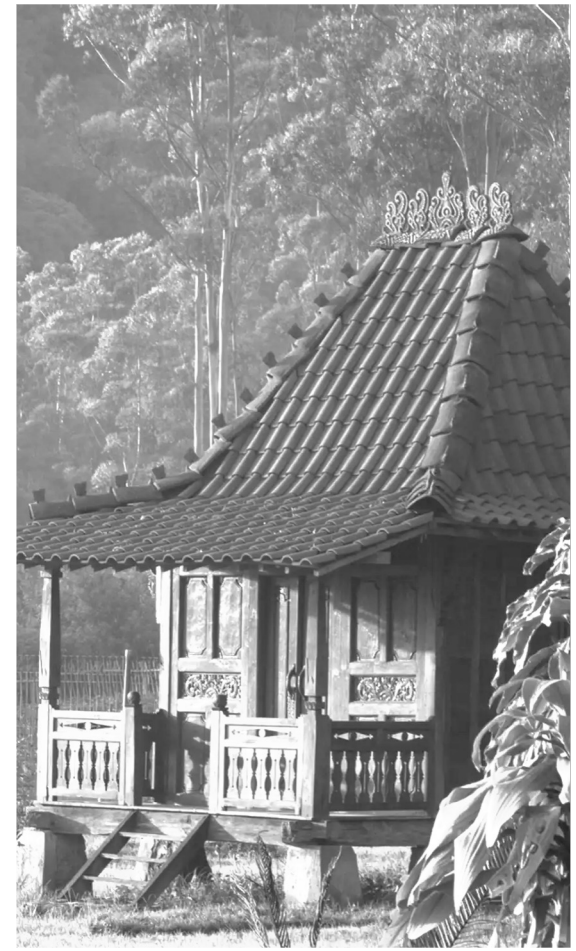
Hello!

Source: nature.org



Pulse Building – TU Delft

”It’s cold especially near the glass. Surprisingly, the areas far from the glass are also cold, even inside the classroom is cold.”

Aprisia, Indonesian.

”Pulse gets cold during the winter, especially seating on the last floor near the glass.”

Mohammed, Ethiopian.

”It's always cold, I have to wear a sweater always. But it's good in summers that it’s cold.”

Gargi, Indian.

”I usually stay at the study area, it is cold during winter. Inside the classroom also cold”

Liu, Chinese.

Comparative Analysis of Energy Saving and Thermal Comfort in Full-Glass Façade Building:

System Modifications, Retrofitting, and Their Combination

Alya Farah Taufiqoh

Regina Bokel (1st mentor)

Telesilla Bristogianni (2nd mentor)

Chujie Lu (3rd mentor)

Dirk Dubbeling (External delegate)

TU Delft Delft University of Technology

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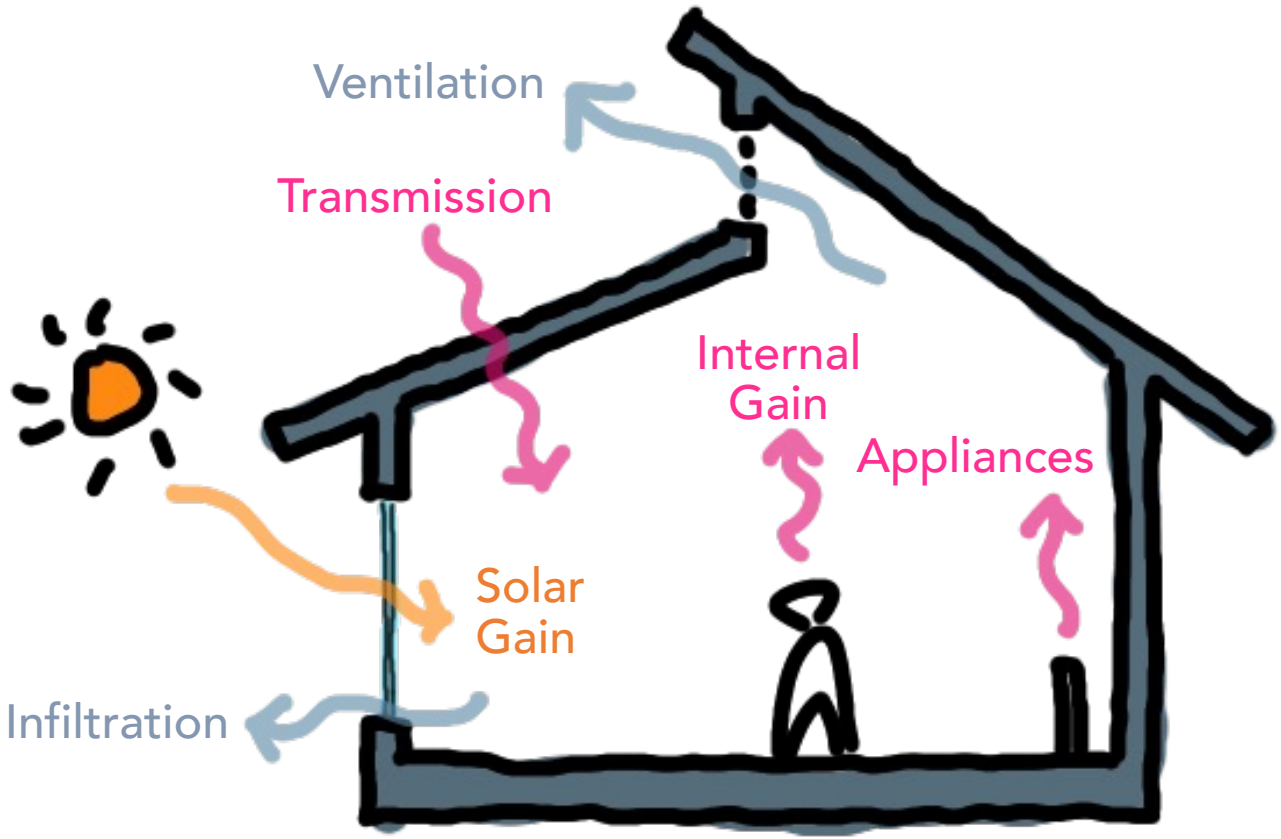
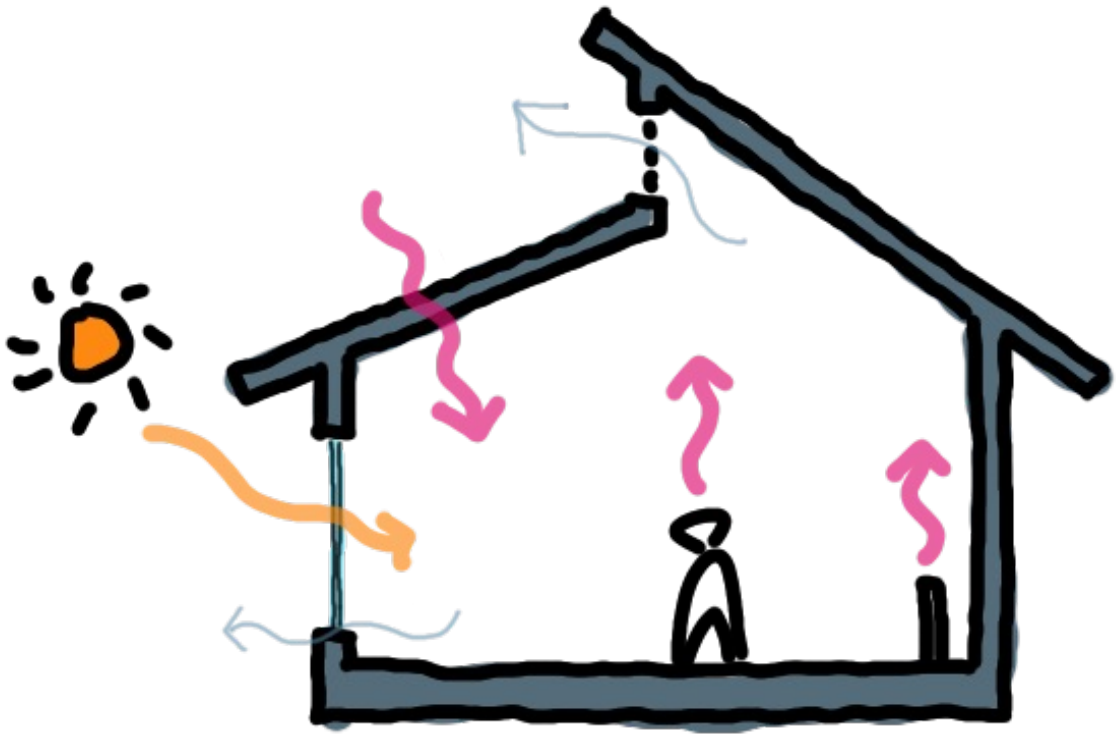
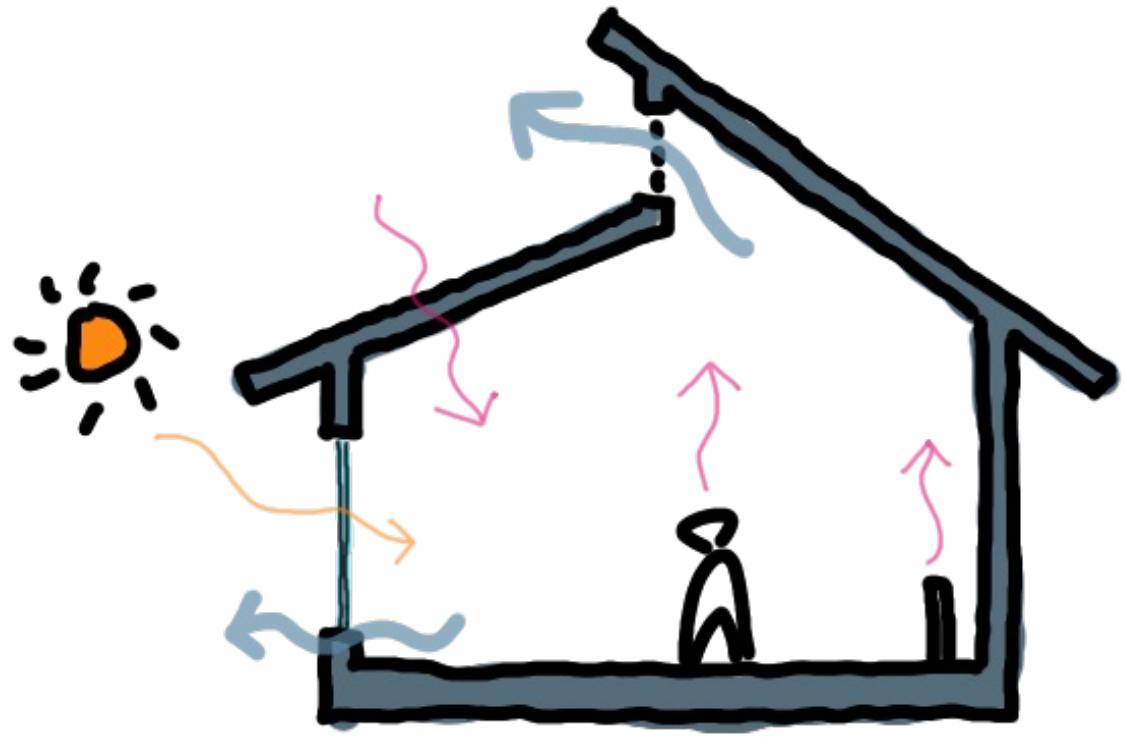


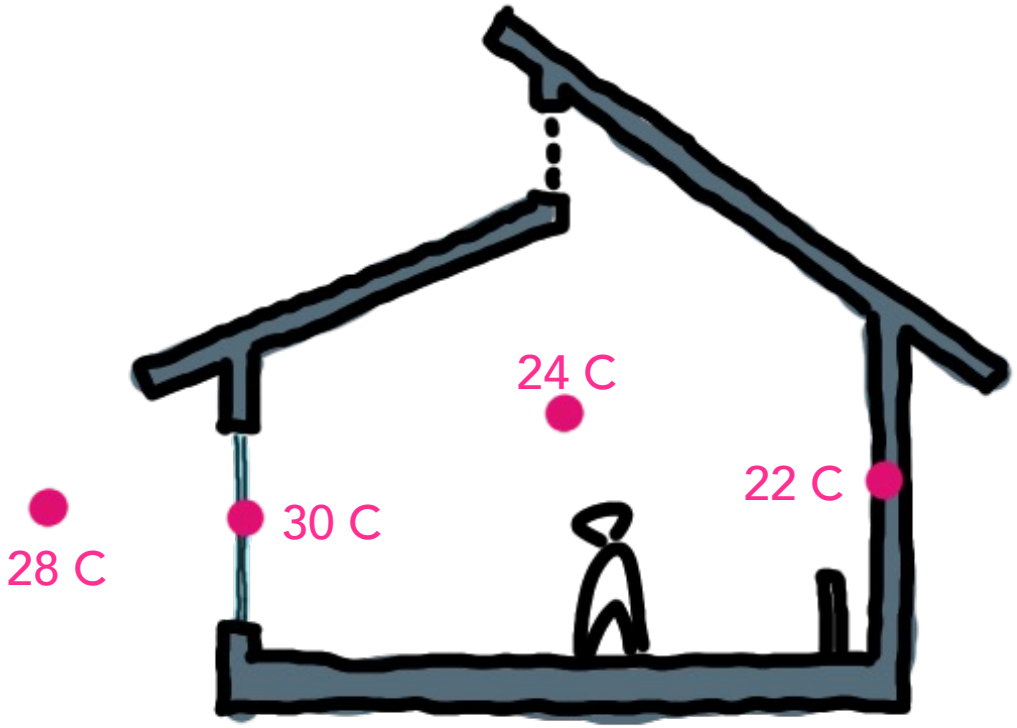
Energy in = Energy out



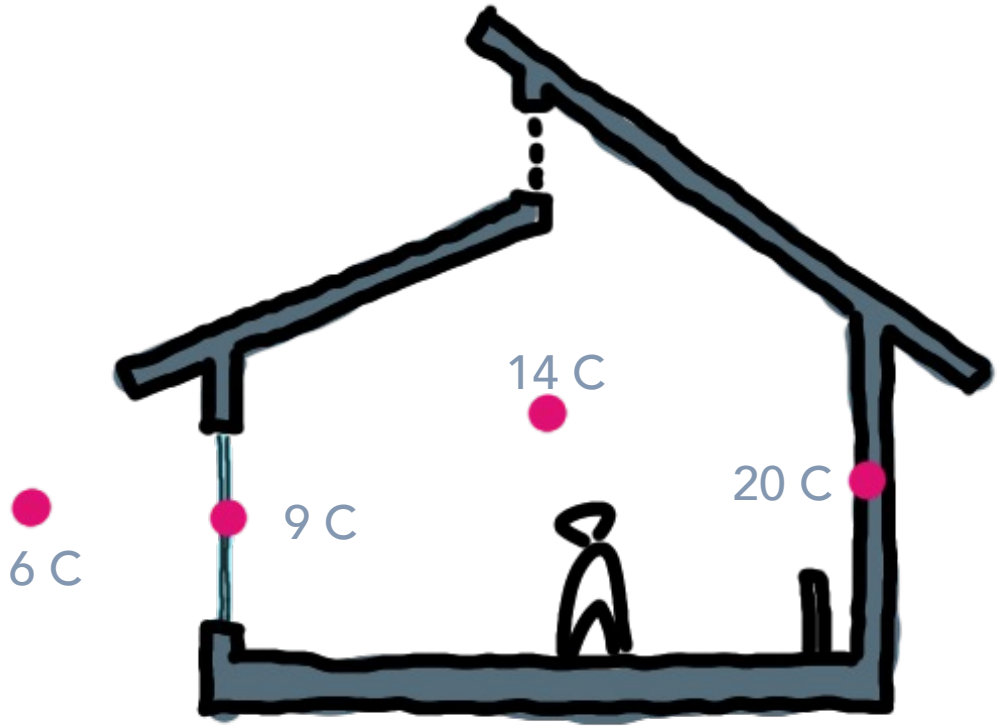
Too much heat!



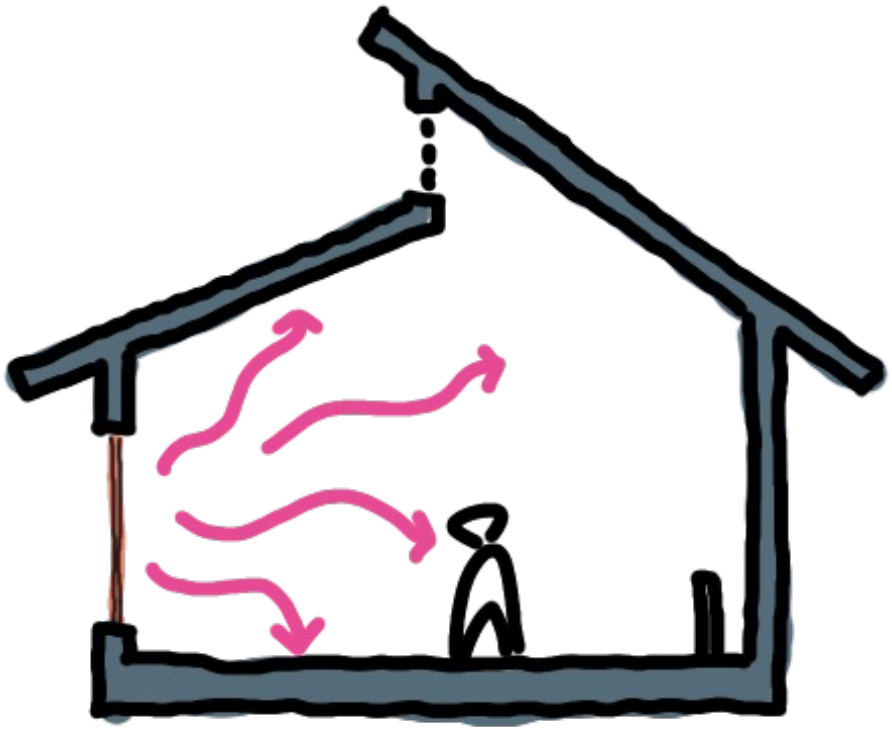
Too cold!



Summer

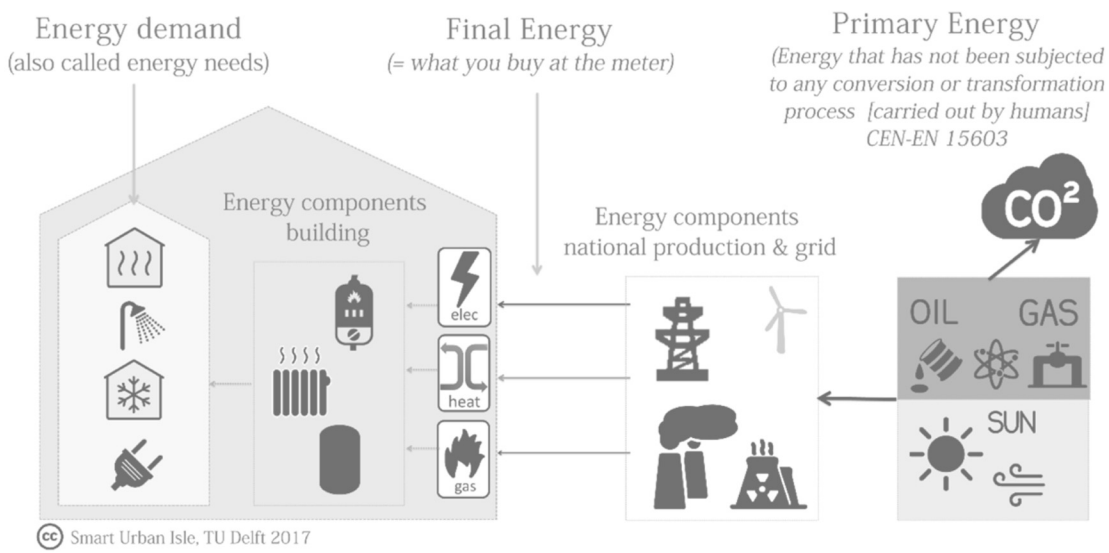


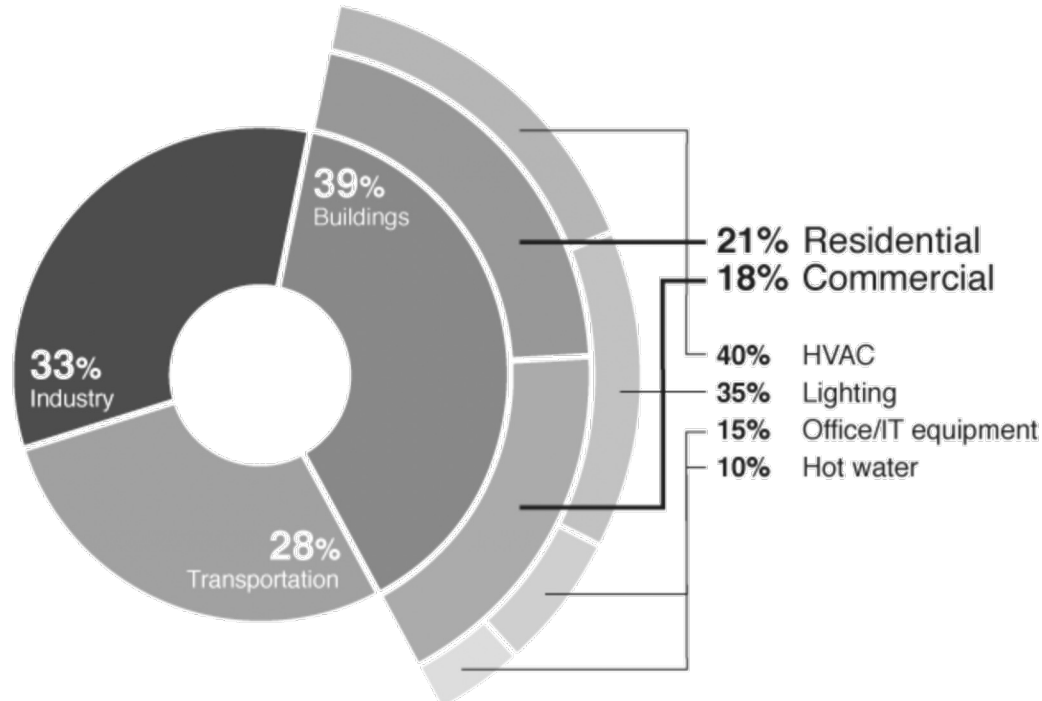
Winter



Radiating Heat
Room becomes warm

Absorbing Heat
Room becomes cold


Energy demand
(also called energy needs)
Final Energy
(= what you buy at the meter)
Primary Energy
(Energy that has not been subjected to any conversion or transformation process [carried out by humans] CEN-EN 15603
Energy components building
Energy components national production & grid
elec
heat
gas
CO²
OIL
GAS
SUN
Smart Urban Isle, TU Delft 2017


39% Buildings
33% Industry
28% Transportation
21% Residential
18% Commercial
40% HVAC
35% Lighting
15% Office/IT equipment
10% Hot water

Retrofitting

Modifying/adding something on the glass to reduce the heat transfer

Smart Control

Optimizing energy saving and thermal comfort

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/scs

A Critical Review of Façade Retrofit Measures for Minimizing Heating and Cooling Demand in Existing Buildings

Soad Sarihi, Fatemeh Mehdizadeh Saradj *, Mohsen Faizi

Department of architecture, Iran university of science and technology, Narmak Street, Tehran, 1684613114, Tehran, Iran

ARTICLE INFO

Keywords:
Façade Retrofit
Energy Conservation Measures
Energy Modulation Measures
Existing Buildings
Cooling
Heating

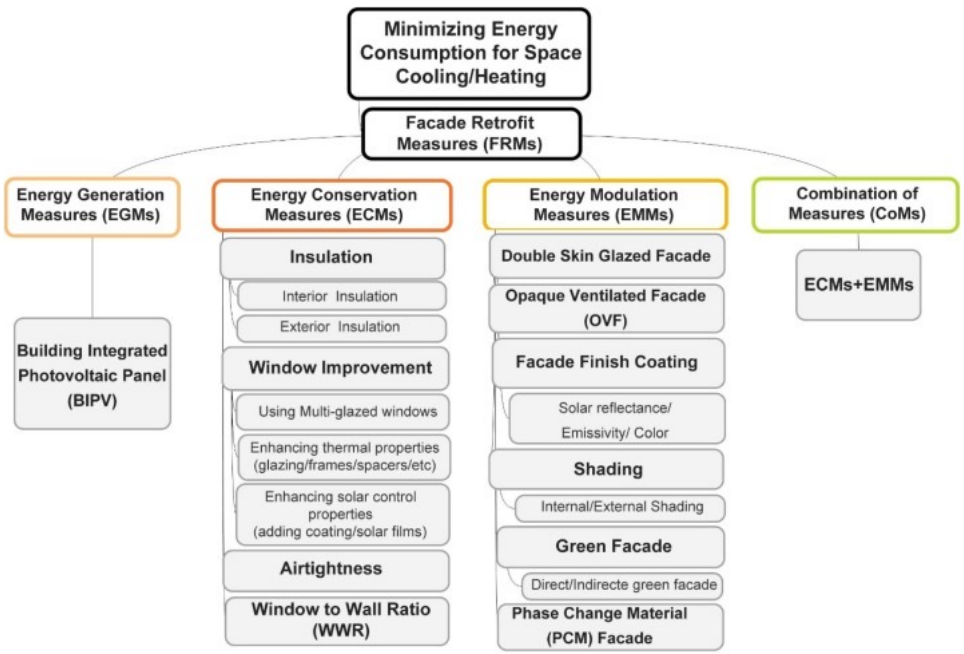
ABSTRACT

The building industry is currently experiencing a myriad of challenges, including low energy performance in existing buildings. Since the façade considerably contributes to heating and cooling in buildings, façade retrofit is presumed as an effective solution to minimize cooling and heating demand in existing buildings.

In-depth scrutiny in façade retrofit actions reveals different Façade Retrofit Measures (FRMs) that aim to minimize cooling and heating demand in existing buildings. They include Energy Conservation Measures (ECMs), which prevent excessive heat transmittance, and Energy Modulation Measures (EMMs), which modulate energy consumption through passive heating and cooling strategies. A Combination of Measures (CoMs) is also the state-of-the-art in the face of retrofit actions.

In this paper, a further analysis elaborates on the effectiveness of each measure in Cooling-Dominated (CD) and Heating-Dominated (HD) climates. This analysis showed that façade retrofit could reduce energy consumption for heating and cooling by up to 50% through architectural interventions.

The study findings also revealed that ECMs effectively minimize energy consumption in a heating-dominated climate by lowering conductive and convective heat transfer. However, EMMs are more crucial in reducing energy consumption in a cooling-dominated climate by controlling radiative heat transfer.



Challenges and opportunities of machine learning control in building operations

Liang Zhang[1] (✉), Zhelun Chen[2], Xiangyu Zhang[3], Amanda Pertzborn[4], Xin Jin[3]

1. The University of Arizona, 1209 E 2nd St, Tucson, AZ, USA
2. Drexel University, 3141 Chestnut St, Philadelphia, PA, USA
3. National Renewable Energy Laboratory, 15013 Denver W Pkwy, Golden, CO, USA
4. National Institute of Standards and Technology, 100 Bureau Dr, Gaithersburg, MD, USA

Abstract

Machine learning control (MLC) is a highly flexible and adaptable method that enables the design, modeling, tuning, and maintenance of building controllers to be more accurate, automated, flexible, and adaptable. The research topic of MLC in building energy systems is developing rapidly, but to our knowledge, no review has been published that specifically and systematically focuses on MLC for building energy systems. This paper provides a systematic review of MLC in building energy systems. We review technical papers in two major categories of applications of machine learning in building control: (1) building system and component modeling for control, and (2) control process learning. We identify MLC topics that have been well-studied and those that need further research in the field of building operation control. We also identify the gaps between the present and future application of MLC and predict future trends and opportunities.

Keywords

machine learning;
building operation control;
building energy system;
reinforcement learning

Article History

Received: 23 September 2022
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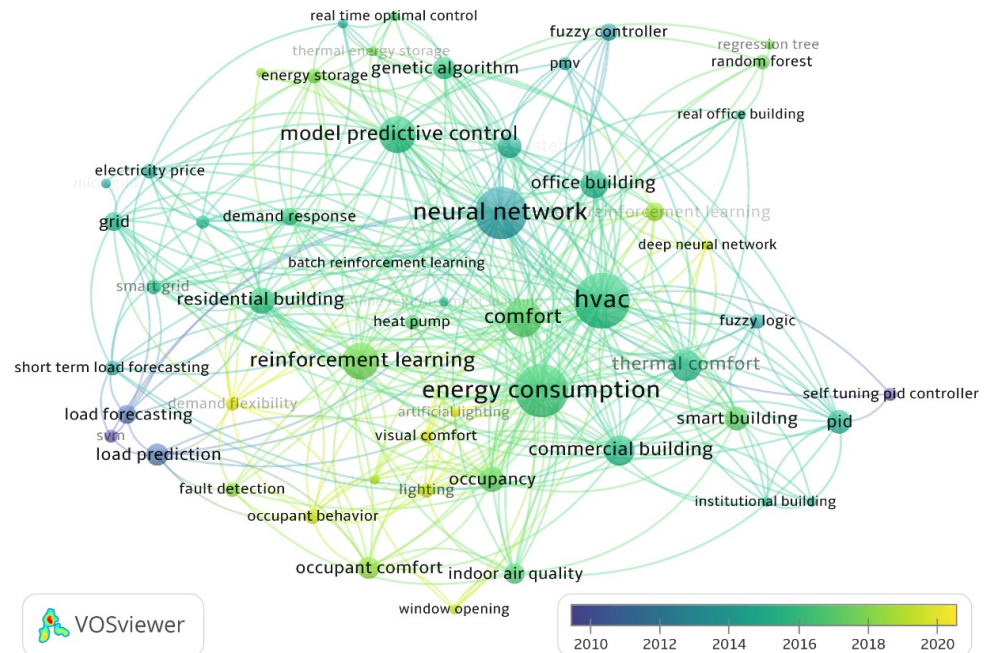


What is the optimal strategy for reducing energy demand and maintaining thermal comfort in glass façade buildings: **modifying the existing building system**, **implementing retrofitting strategies**, or employing **a combination of both** approaches?

What is the optimal strategy for reducing energy demand and maintaining thermal comfort in glass façade buildings: modifying the existing building system, implementing retrofitting strategies, or employing a combination of both approaches?

Smart Control (MPC)

How can a model be developed for model prediction, and what is the problem formulation for the control?

How does the integration of MPC affect energy efficiency and occupant comfort?

Retrofitting

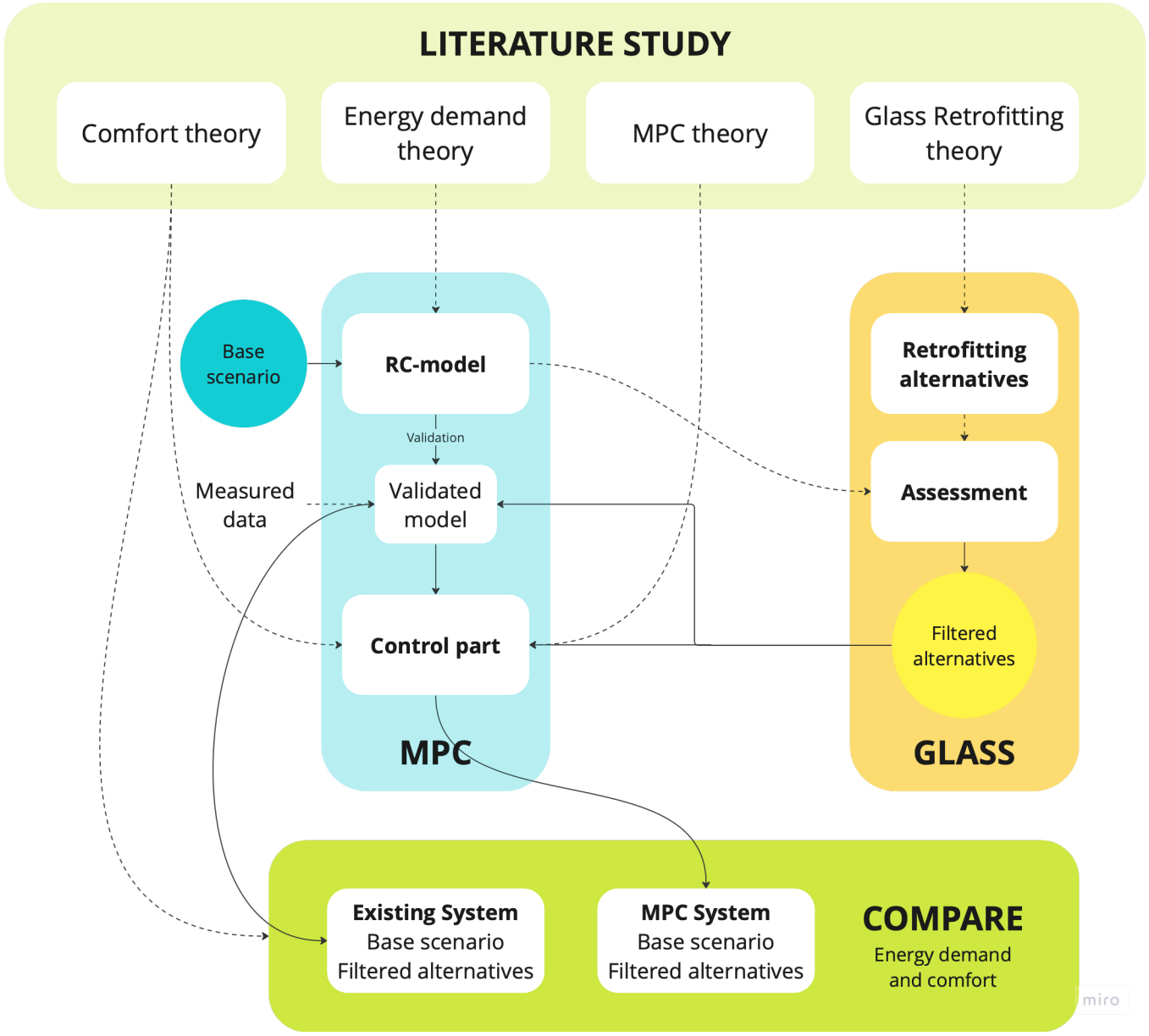
What are the retrofitting options that doesn't influence the glass façade look?

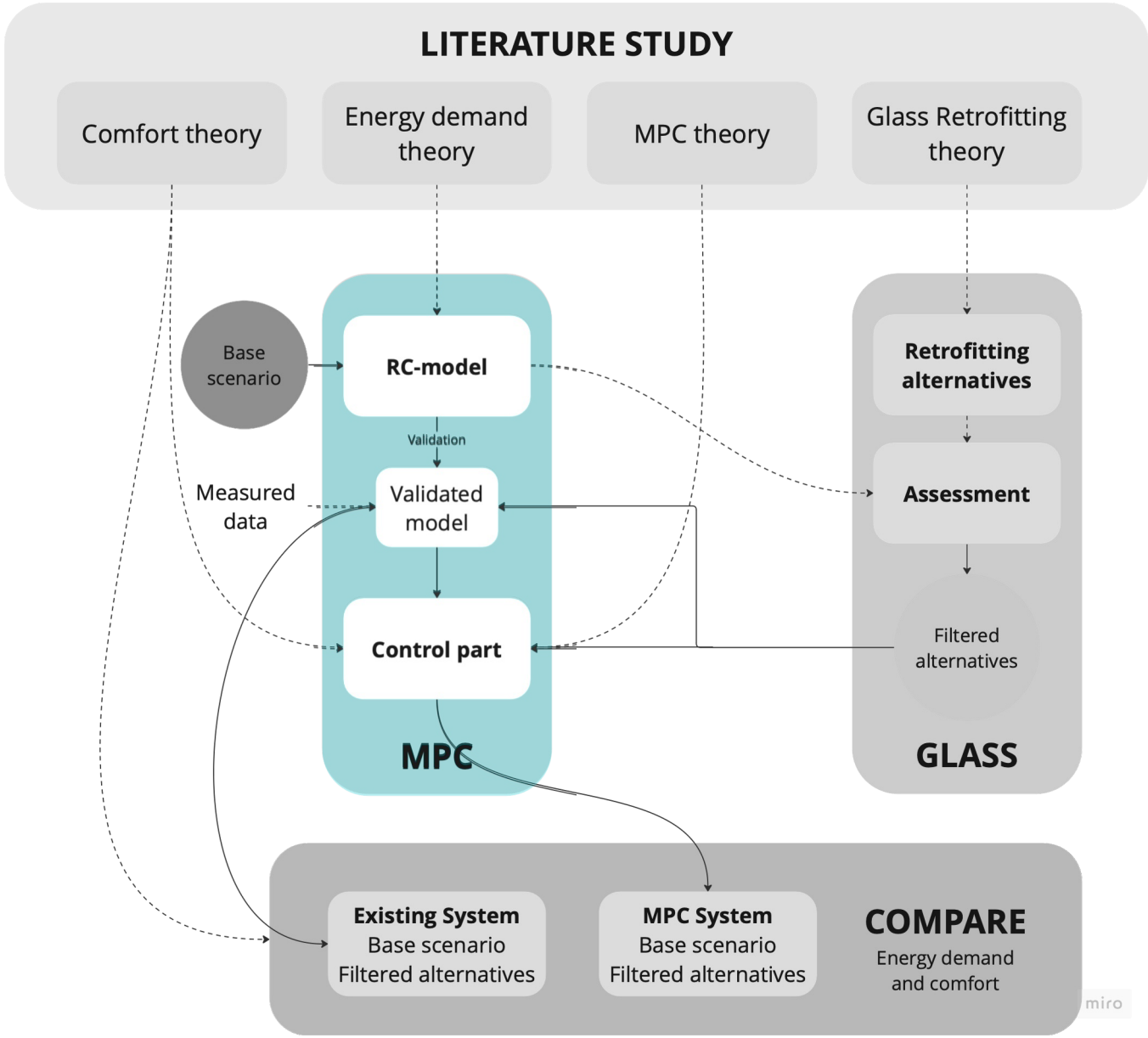
How do they impact energy consumption and thermal comfort?

MPC + Retrofitting

What are the comparative advantages and disadvantages (in relation to energy demand and thermal comfort) of modifying building systems vs implementing retrofitting strategies?

What is the effectiveness of combining building system modifications with retrofitting strategies in achieving optimal energy savings and comfort levels?


LITERATURE STUDY
Comfort theory
Energy demand theory
MPC theory
Glass Retrofitting theory
Base scenario
RC-model
Validation
Measured data
Validated model
Control part
MPC
Retrofitting alternatives
Assessment
Filtered alternatives
GLASS
Existing System
Base scenario
Filtered alternatives
MPC System
Base scenario
Filtered alternatives
COMPARE
Energy demand and comfort
miro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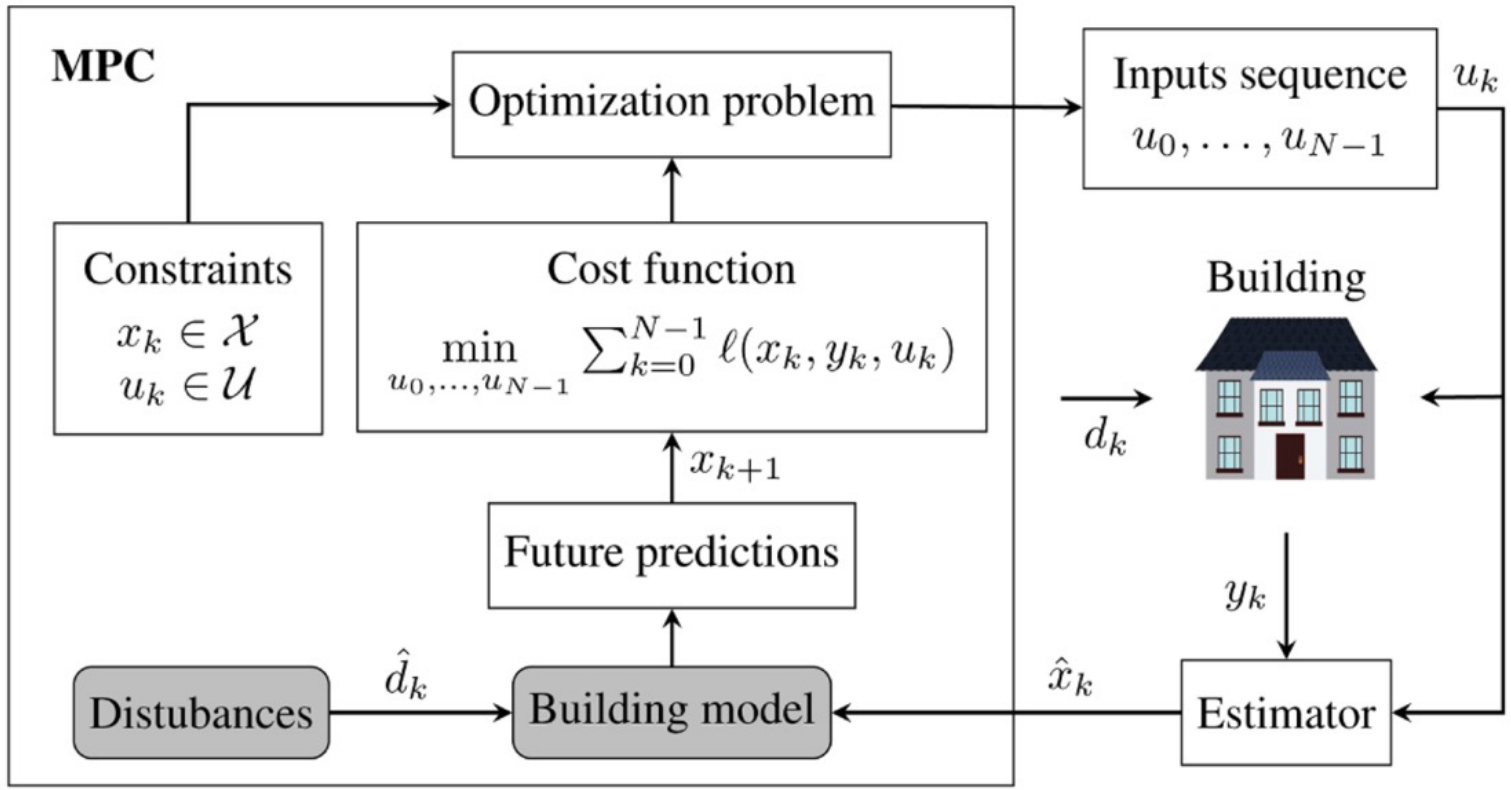
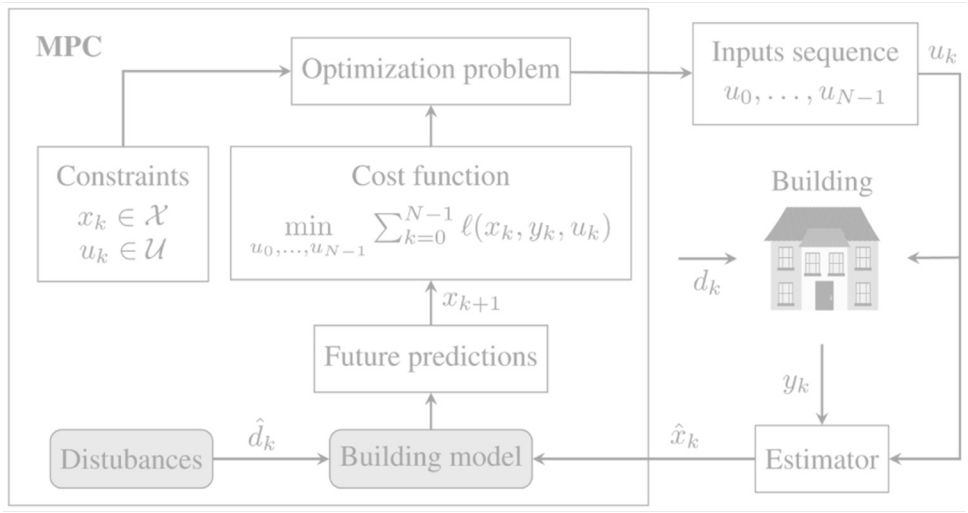

MPC
Optimization problem
Inputs sequence
$u_0, \ldots, u_{N-1}$
u_k
Constraints
$x_k \in \mathcal{X}$
$u_k \in \mathcal{U}$
Cost function
$\min_{u_0,\ldots,u_{N-1}} \sum_{k=0}^{N-1} \ell(x_k, y_k, u_k)$
Building
d_k
x_{k+1}
Future predictions
y_k
$\hat{d}_k$
$\hat{x}_k$
Distubances
Building model
Estimator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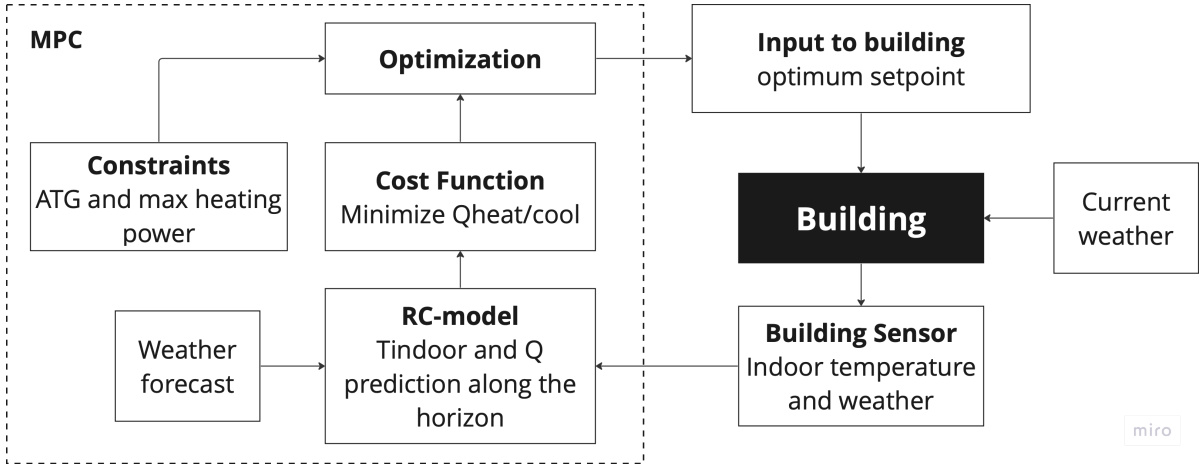
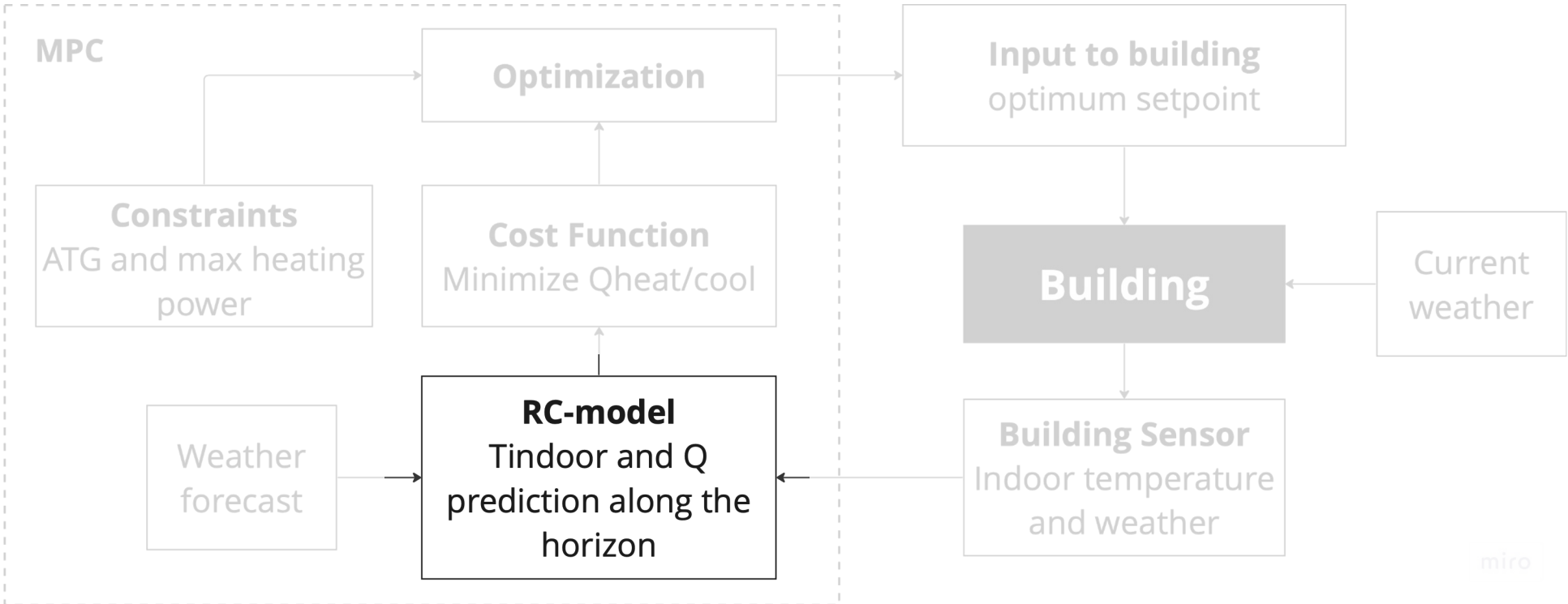

MPC
Optimization
Input to building
optimum setpoint
Constraints
ATG and max heating power
Cost Function
Minimize Qheat/cool
Building
Current weather
Weather forecast
RC-model
Tindoor and Q prediction along the horizon
Building Sensor
Indoor temperature and weather
miro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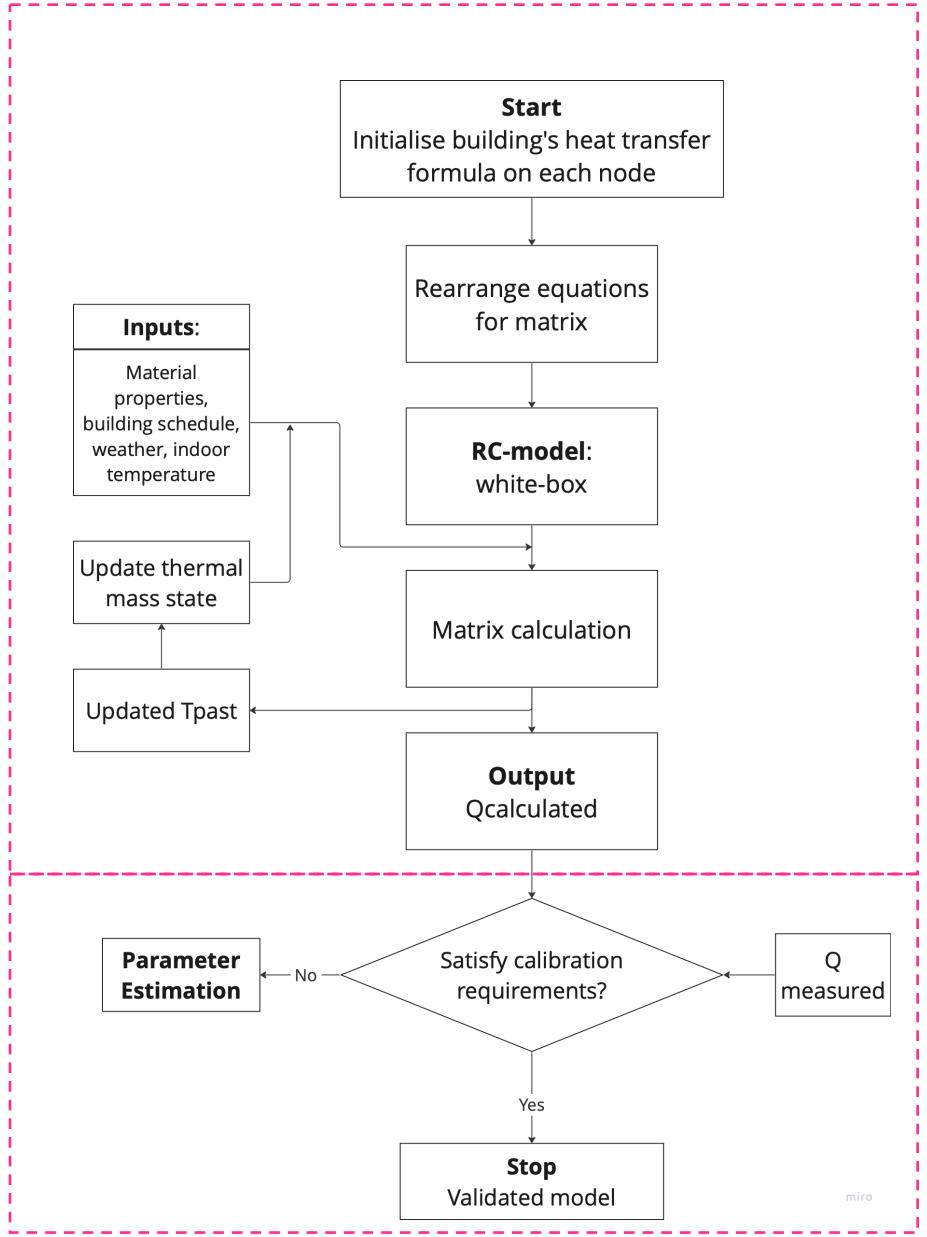
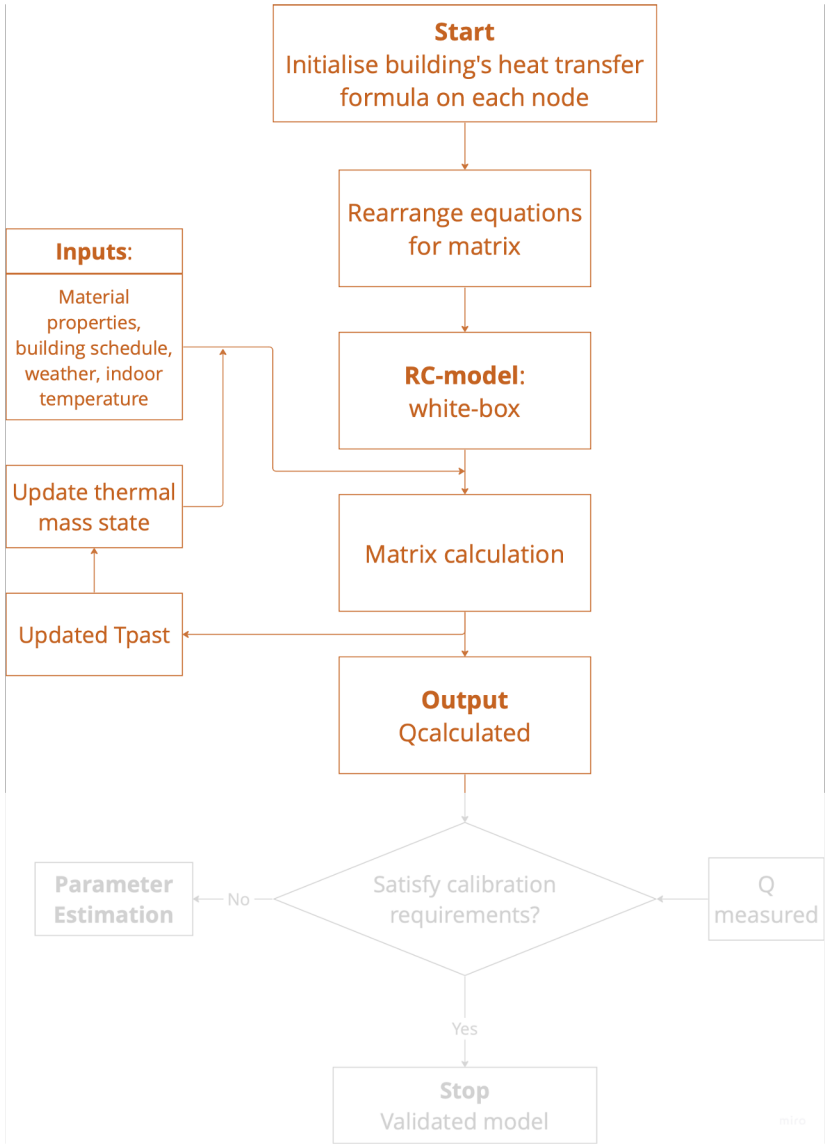
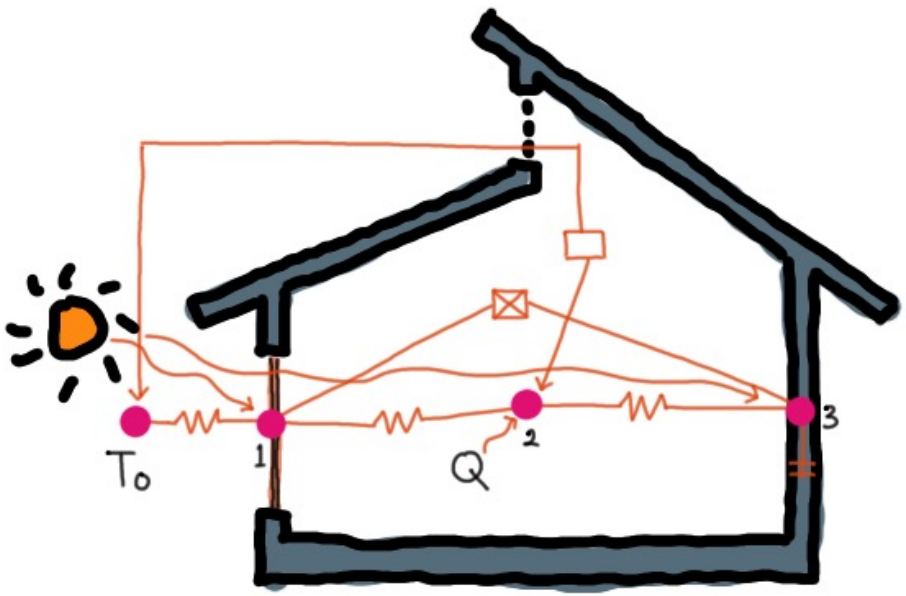


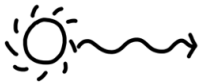
Prediction calculation

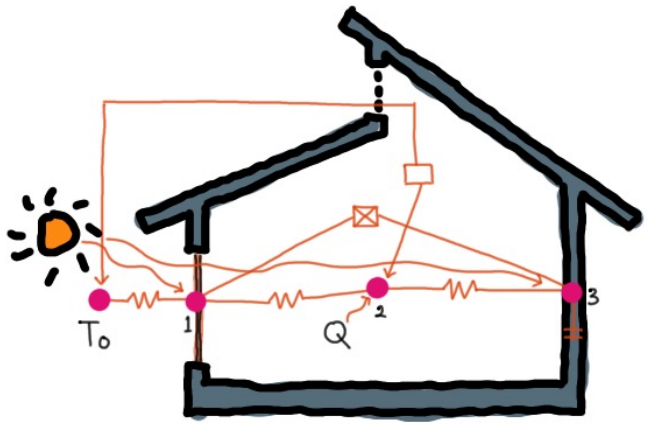
Calculation validation


Start
Initialise building's heat transfer formula on each node
Rearrange equations for matrix
Inputs:
Material properties, building schedule, weather, indoor temperature
RC-model: white-box
Update thermal mass state
Matrix calculation
Updated Tpast
Output
Qcalculated
Parameter Estimation
No
Satisfy calibration requirements?
Q measured
Yes
Stop
Validated model



Simple room example

Symbols	*Description*	*Equations*
	Absorbed solar radiation	$A_1 \times A_{gl} \times Q_z$
	Heating	Q_{heat}
	Advection	$\rho_{air} \times V_{air} \times C_{p_{air}} \times \Delta T$
	Convection	$\propto_{conv} \times A_s \times \Delta T$
	Radiation	$\propto_{rad} \times F \times A_s \times \Delta T$
	Conduction and accumulation using response factor method	$A_s\left(\sum_{i=0}^{N} X_i \times {T_s}^{t-i}\right)$ $N = 50 \times d_s$ $X_0 = {}^{2}/_{\pi}\sqrt{\frac{k \times \rho \times C_{p_s}}{3600}}$ $X_n = -X_0\left(2\sqrt{n} - \sqrt{n+1} - \sqrt{n-1}\right); n > 0$ $X_{n_{cor}} = X_n - \frac{Error}{N-1}; n > 2$ $Error = \sum_{n=0}^{N} X_n$



Simple room example

Node 1

$$\propto_{conv_o}.A_{gl}.(T_o - T_1) + \propto_{conv_i}.A_{gl}.(T_2 - T_1) + \propto_{rad}.A_{gl}.F_{13}(T_3 - T_1) + A_1.A_{gl}.Q_z = 0$$

Node 2

$$\propto_{conv_i}.A_{gl}.(T_1 - T_2) + \propto_{conv_i}.A_w.(T_3 - T_2) + \rho_{air}.V_{air}.C_{p_{air}}.(T_o - T_2) + Q_{heat} = 0$$

Node 3

$$\propto_{conv_i}.A_w.(T_2 - T_3) + \propto_{rad}.A_w.F_{31}(T_1 - T_3) + D_1.A_{gl}.Q_z = A_w\left(X_0.T_3 + X_1.T_3^{(t-1)} + X_2.T_3^{(t-2)} + X_3.T_3^{(t-3)} + .. + X_n.T_3^{(t-n)}\right)$$

Equation

$$\mathrm{T} = \mathrm{M}^{-1}\mathrm{B}$$

T

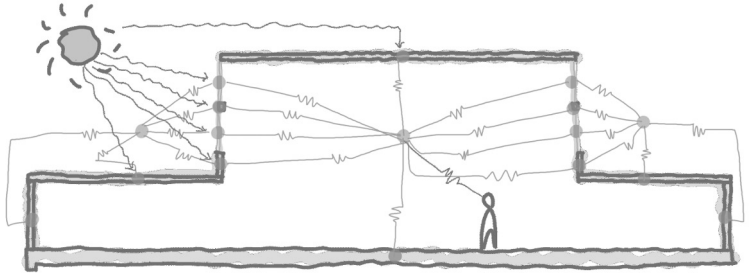
$$\begin{bmatrix} T_1 \\ Q_{heat} \\ T_3 \end{bmatrix}$$

M

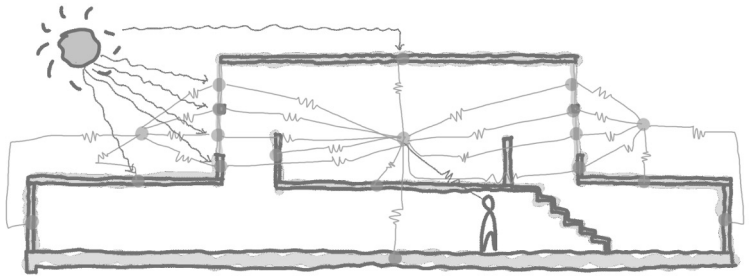
$$\begin{bmatrix} -A_{gl}.\left(\propto_{conv_o}. - \propto_{conv_i}. - \propto_{rad}.F_{13}\right) & 0 & \propto_{rad}.A_{gl}.F_{13} \\ \propto_{conv_i}.A_{gl} & 1 & \propto_{conv_i}.A_w \\ \propto_{rad}.A_w.F_{31} & 0 & -A_w.\left(\propto_{conv_i} + \propto_{rad}.F_{31} + X_0\right) \end{bmatrix}$$

B

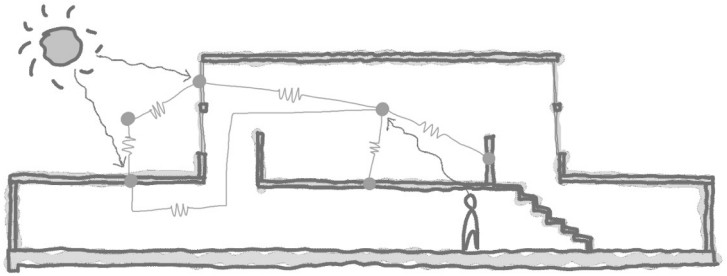
$$\begin{bmatrix} -A_1.A_{gl}.Q_z - \propto_{conv_o}.A_{gl}.T_0 - \propto_{conv_i}.A_{gl}.T_2 \\ \left(\propto_{conv_i}.A_{gl} + \propto_{conv_i}.A_w + \rho_{air}.V_{air}.C_{p_{air}}\right).T_2 - \rho_{air}.V_{air}.C_{p_{air}}.T_o \\ -D_1.A_{gl}.Q_z + A_w\left(X_1.T_3^{(t-1)} + X_2.T_3^{(t-2)} + X_3.T_3^{(t-3)} + .. + X_n.T_3^{(t-n)}\right) - \propto_{conv_i}.A_w.T_2 \end{bmatrix}$$



Version 1

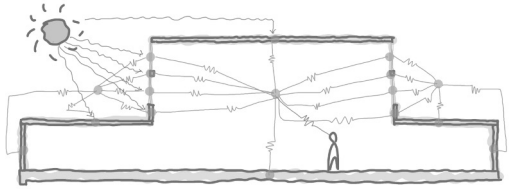


Version 2



Version 3

version 1

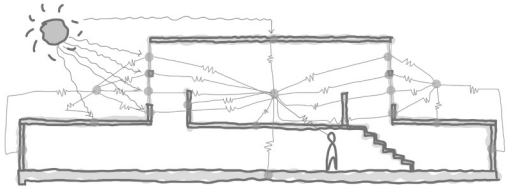


Envelope only

20 nodes

20 x 20 matrix

version 2

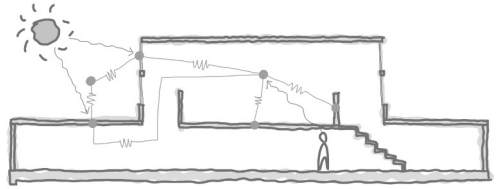


Envelope and inner mass

22 nodes

22 x 22 matrix

version 3

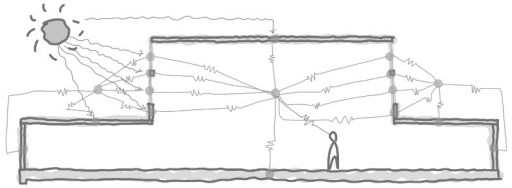


Lumped envelope
and inner mass

5 nodes

5 x 5 matrix

version 1



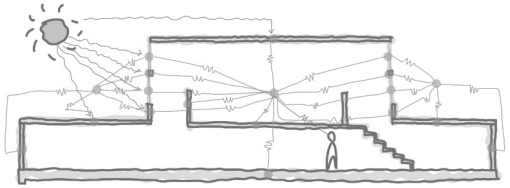
CV(RMSE)
0.28 0.66

MBE
0.23 0.33

Execution Time
3660s 3789s

Winter Summer

version 2



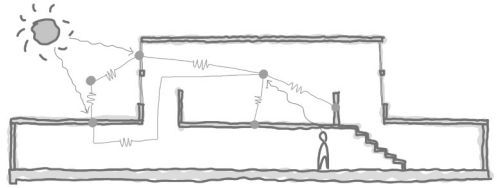
CV(RMSE)
0.18 0.57

MBE
0.02 0.03

Execution Time
4403s 4263s

Winter Summer

version 3



CV(RMSE)
0.17 0.56

MBE
0.01 0.01

Execution Time
50s 51s

Winter Summer

CV(RMSE) should be <30% and MBE should be <10% for hourly calibration.

version 1

CV(RMSE)
0.28 0.66

MBE
0.23 0.33

Execution Time
3660s 3789s

Winter Summer

version 2

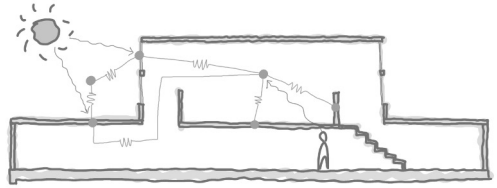
CV(RMSE)
0.18 0.57

MBE
0.02 0.03

Execution Time
4403s 4263s

Winter Summer

version 3



CV(RMSE)
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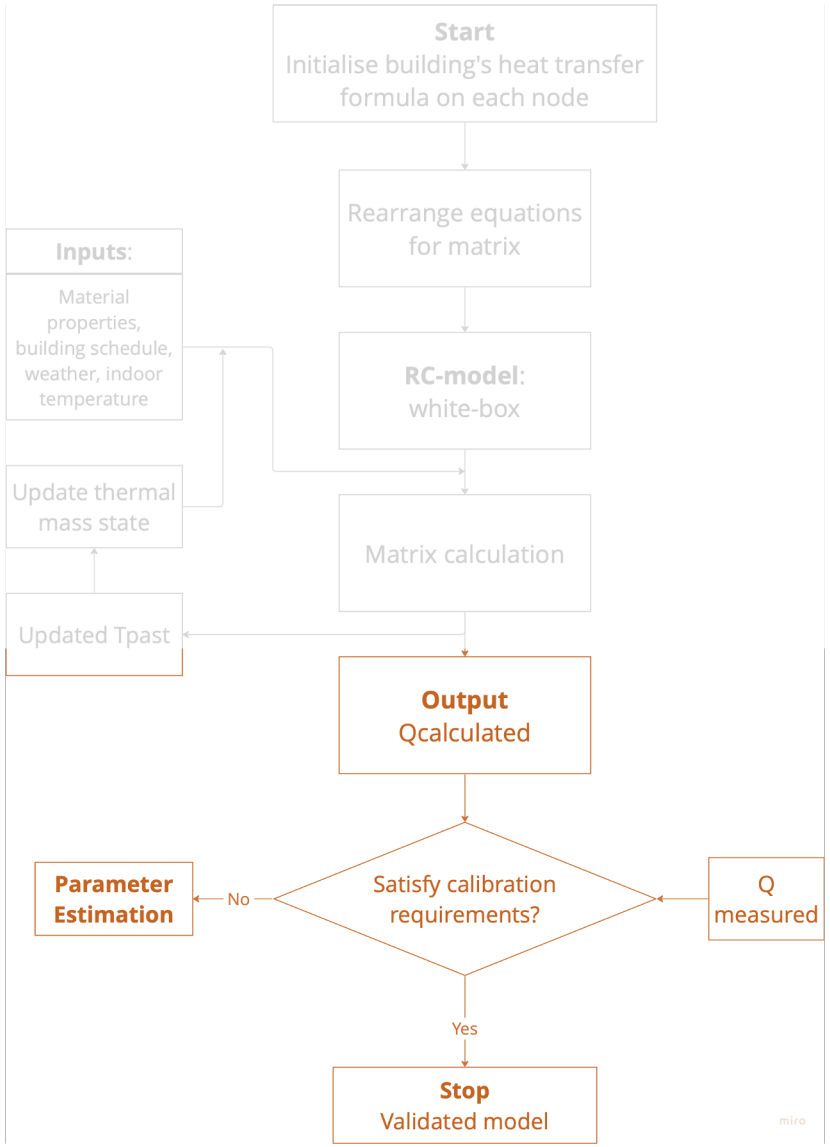
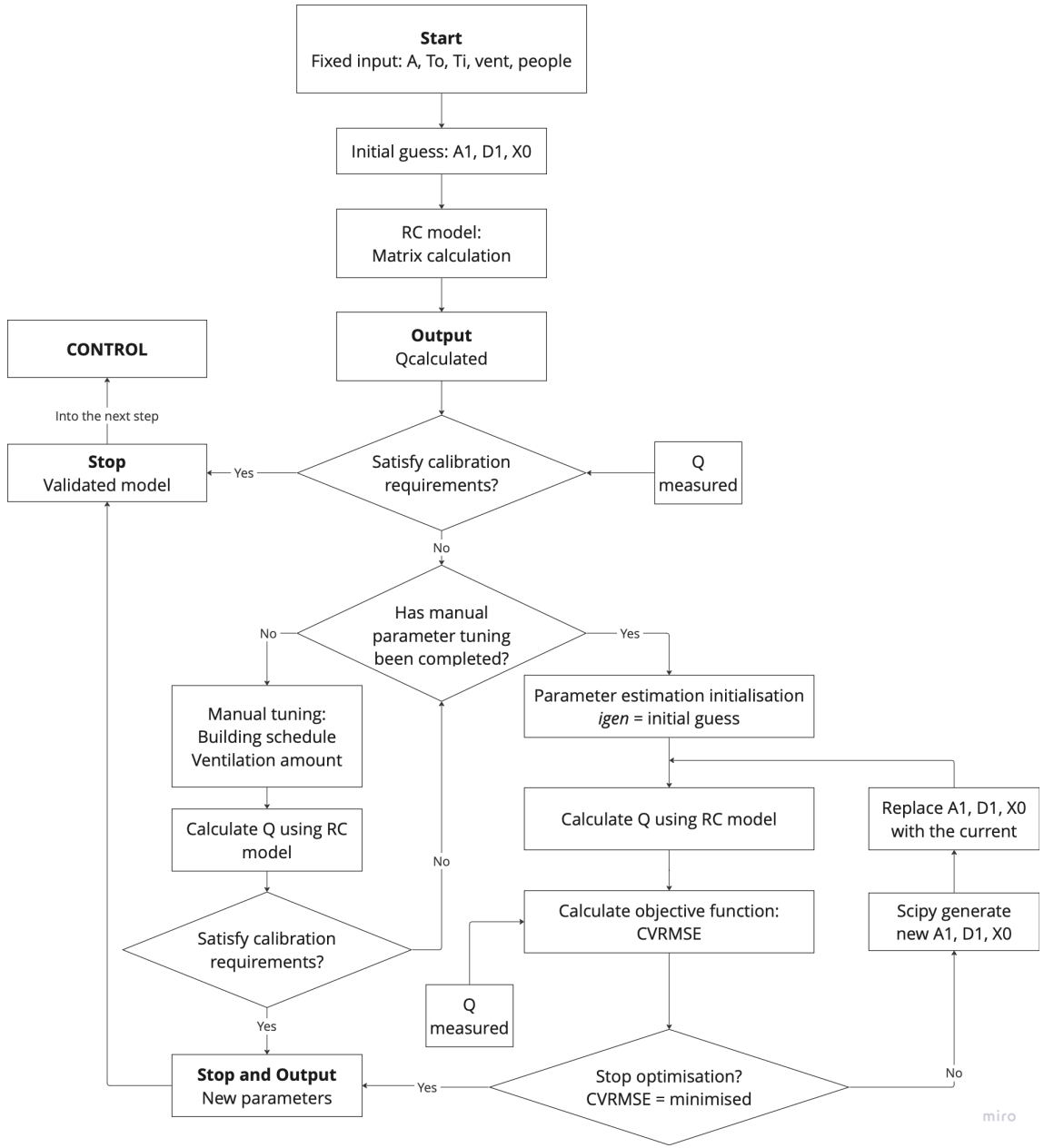
MBE
0.01 0.01

Execution Time
50s 51s

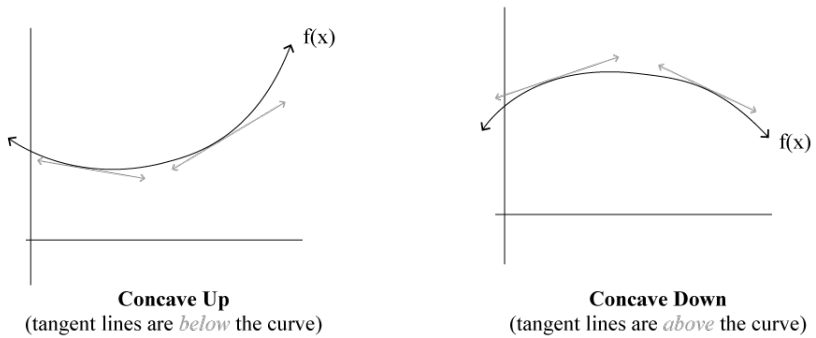
Winter Summer

CV(RMSE) should be <30% and MBE should be <10% for hourly calibration.


Start
Initialise building's heat transfer formula on each node
Rearrange equations for matrix
Inputs:
Material properties, building schedule, weather, indoor temperature
RC-model: white-box
Update thermal mass state
Matrix calculation
Updated Tpast
Output
Qcalculated
Parameter Estimation
No
Satisfy calibration requirements?
Q measured
Yes
Stop
Validated model
miro

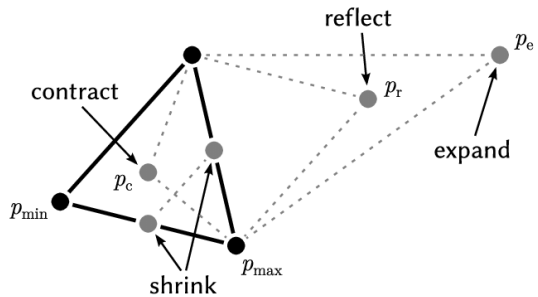

Start
Fixed input: A, To, Ti, vent, people
Initial guess: A1, D1, X0
RC model:
Matrix calculation
Output
Qcalculated
CONTROL
Into the next step
Stop
Validated model
Yes
Satisfy calibration requirements?
Q measured
No
Has manual parameter tuning been completed?
No
Yes
Manual tuning:
Building schedule
Ventilation amount
Calculate Q using RC model
Satisfy calibration requirements?
No
Yes
Stop and Output
New parameters
Parameter estimation initialisation
igen = initial guess
Calculate Q using RC model
Calculate objective function:
CVRMSE
Q measured
Stop optimisation?
CVRMSE = minimised
Yes
Scipy generate new A1, D1, X0
Replace A1, D1, X0 with the current
No
miro

Derivative based algorithm



L-BFGS-B *and* SLSQP

Non-derivative based algorithm



Nelder-Mead

attempt 1

Parameters
Sun absorption of glass and opaque

Results
Parameter values and CV(RMSE) did not change

attempt 2

Parameters
Sun absorption of glass and opaque (different starting values)

Results
Parameter values changed but CV(RMSE) did not change

attempt 3

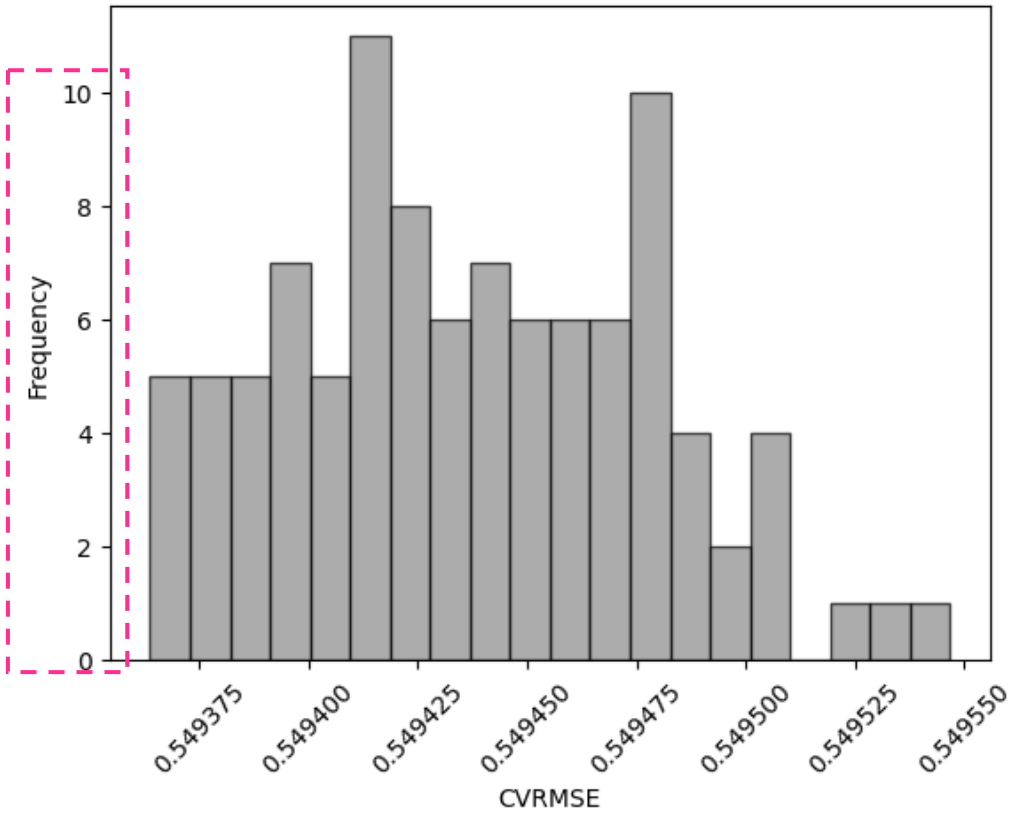
Parameters
Sun absorption of glass and opaque + thermal mass of inner surface

Results
CV(RMSE) still not changed

The algorithms were sensitive with decimal starting point,
but why did the CV(RMSE) stay the same?

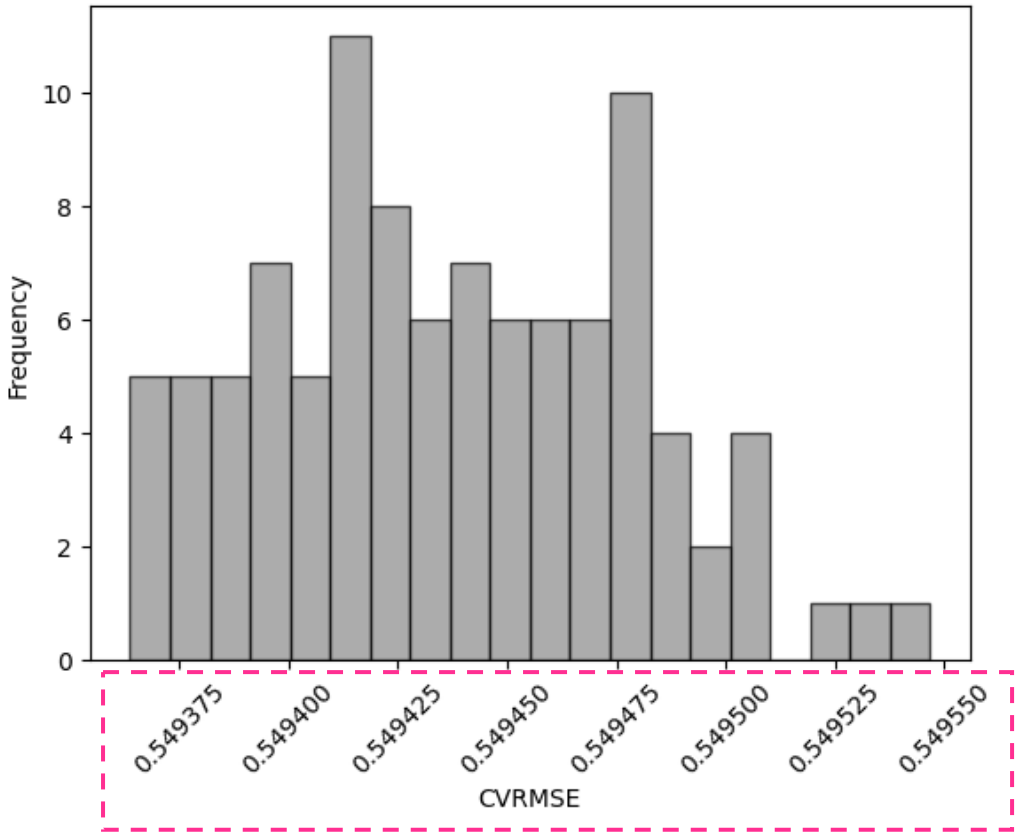
attempt 4

100 set of parameters
(randomly picked from 3rd attempt)



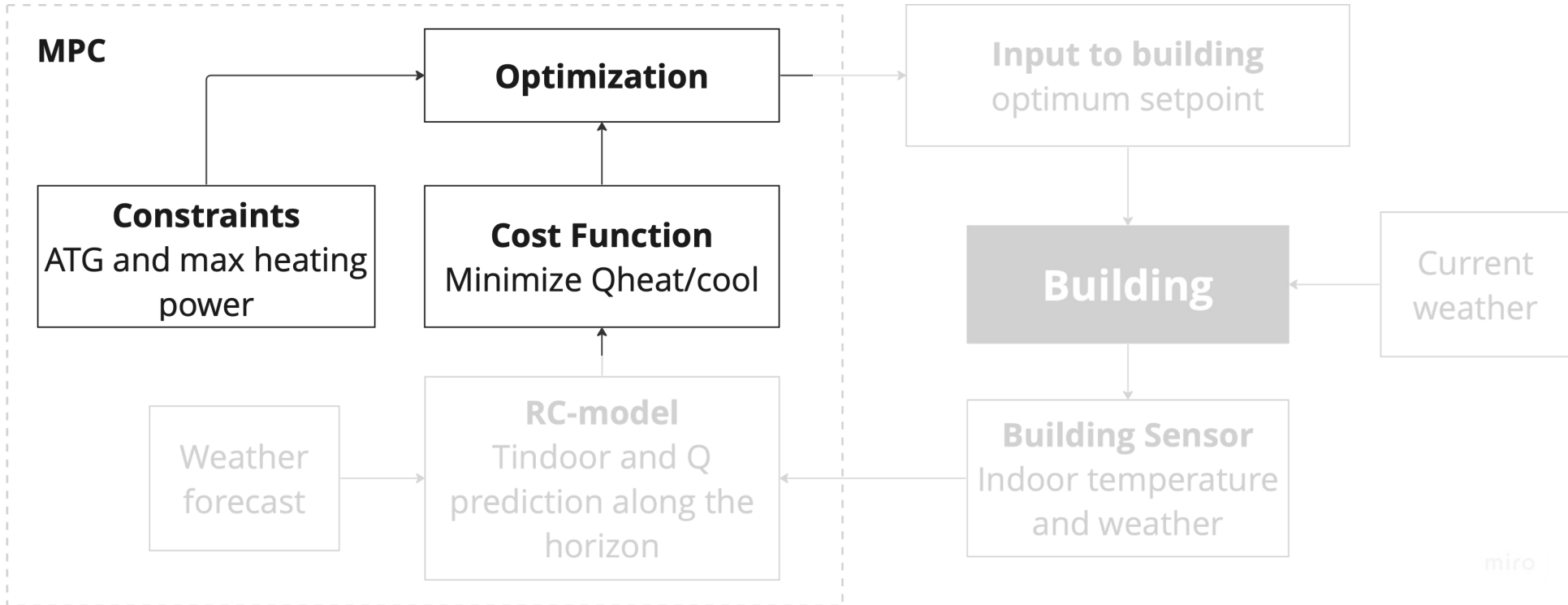
Monte-Carlo simulation

attempt 4

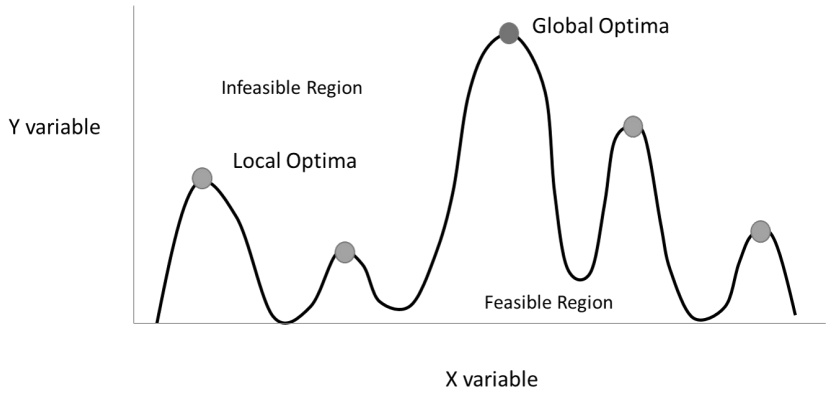


Distribution of the CVRMSE is narrow

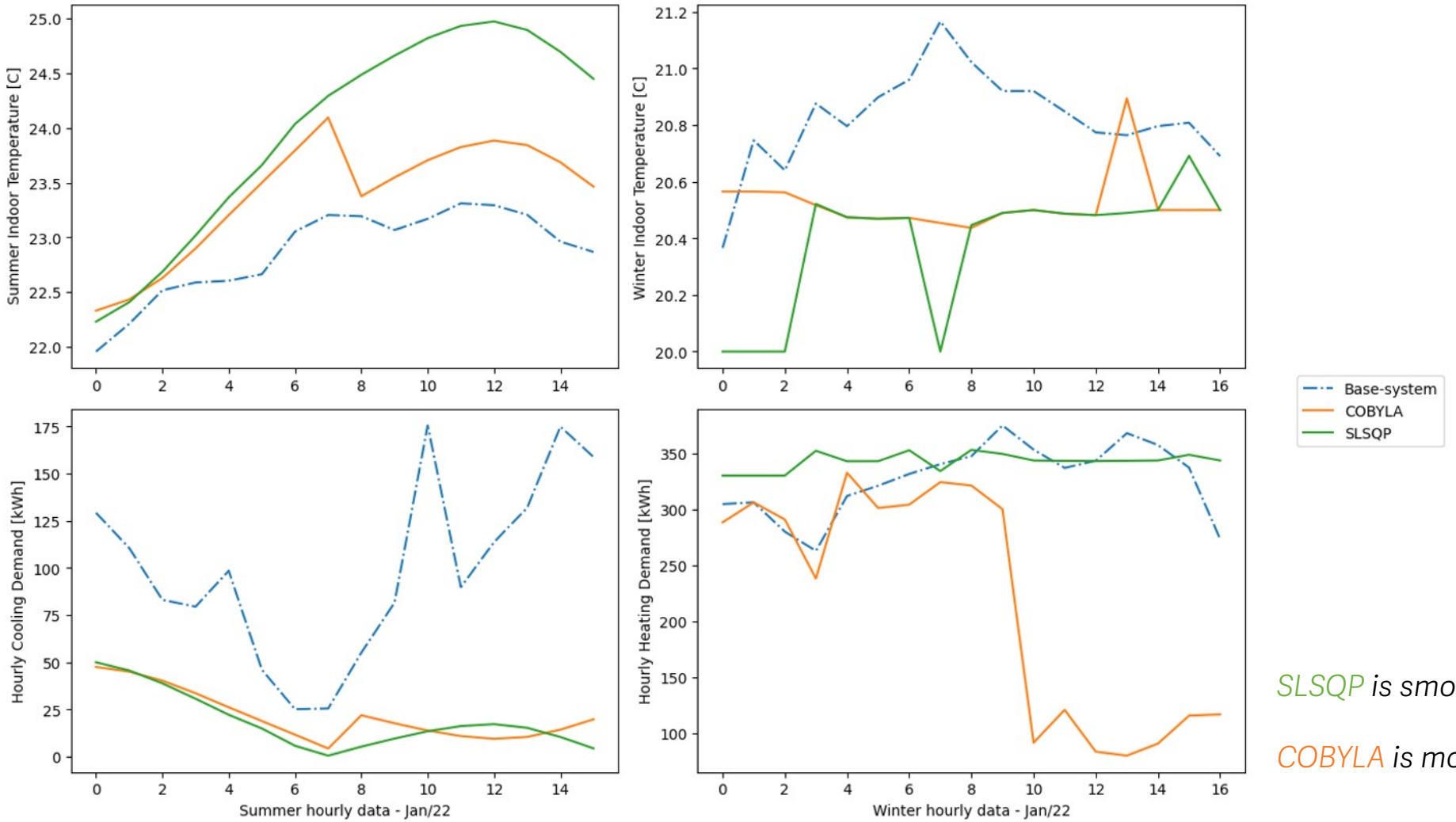
Monte-Carlo simulation


MPC
Optimization
Input to building
optimum setpoint
Constraints
ATG and max heating power
Cost Function
Minimize Qheat/cool
Building
Current weather
RC-model
Tindoor and Q prediction along the horizon
Weather forecast
Building Sensor
Indoor temperature and weather
miro

Local Optimum Algorithm



COBYLA *and* SLSQP

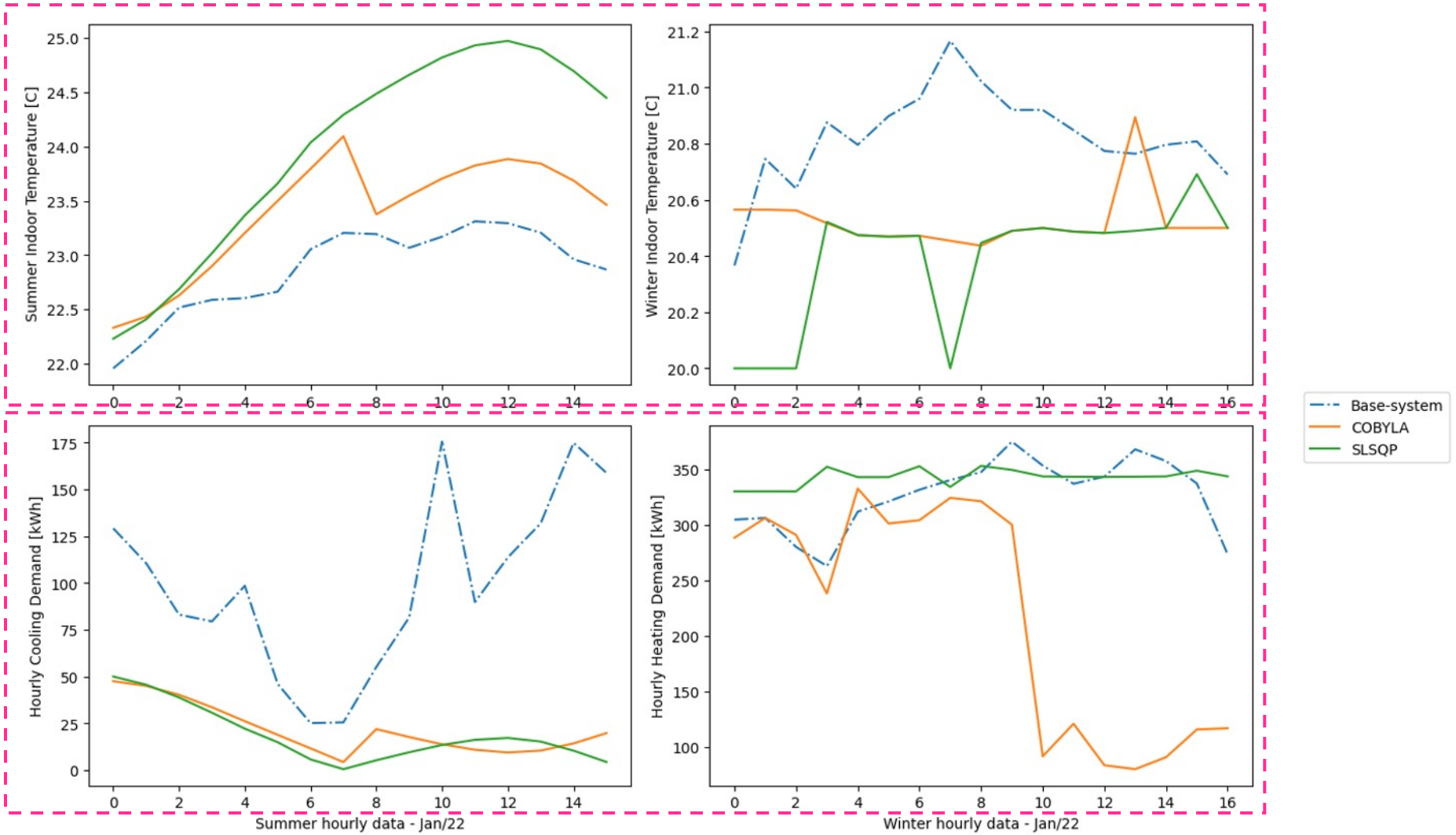


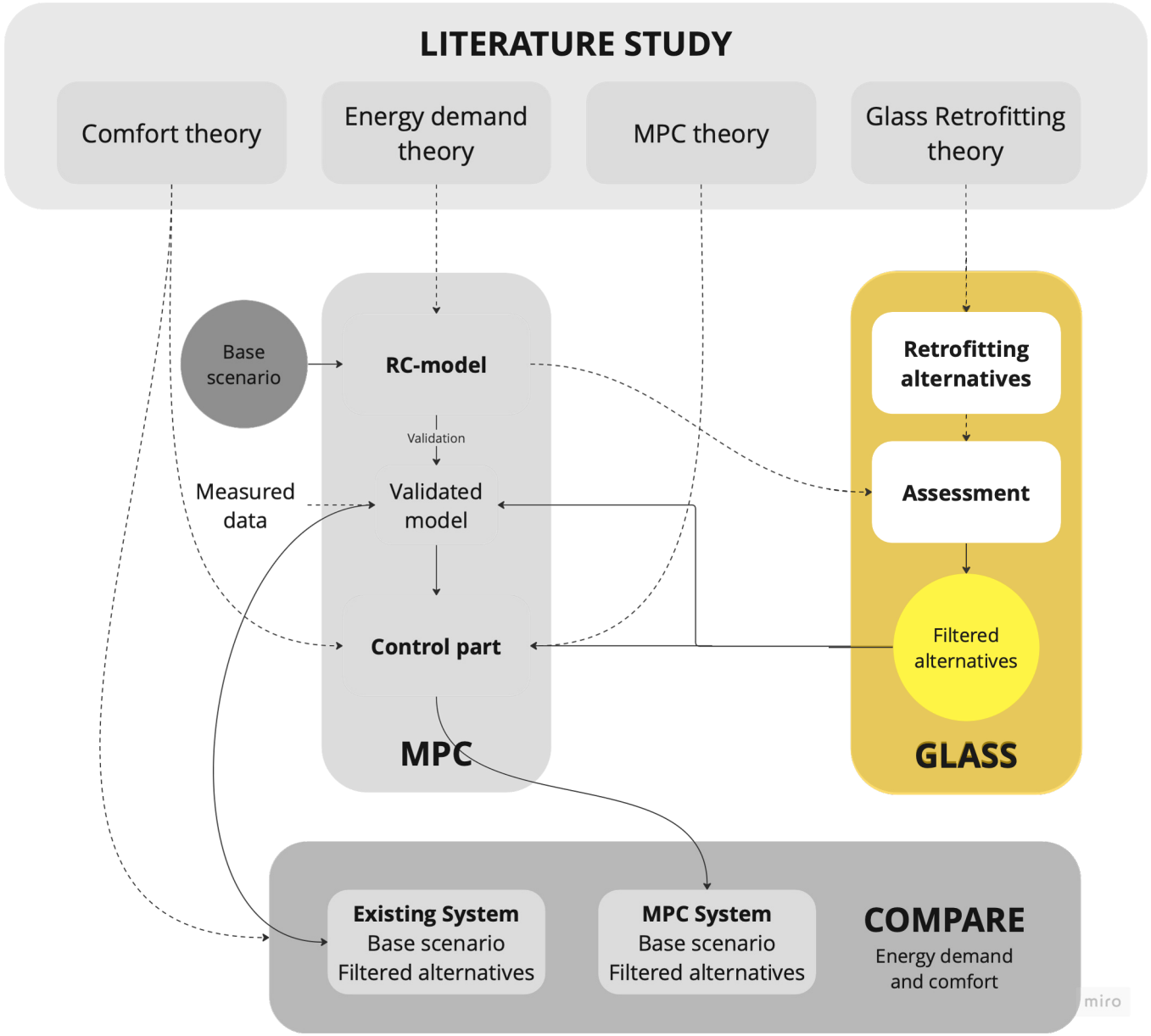
SLSQP is smoother

COBYLA is more aggresive

Indoor temperature

Energy demand




LITERATURE STUDY
Comfort theory
Energy demand theory
MPC theory
Glass Retrofitting theory
Base scenario
RC-model
Validation
Measured data
Validated model
Control part
MPC
Retrofitting alternatives
Assessment
Filtered alternatives
GLASS
Existing System
Base scenario
Filtered alternatives
MPC System
Base scenario
Filtered alternatives
COMPARE
Energy demand and comfort
miro

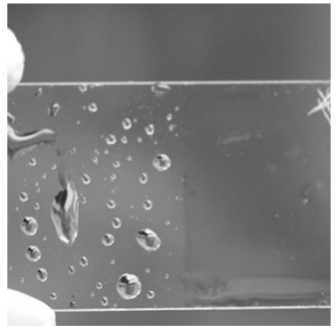
Change composition

Add shading

Change glass

Add enamels

Add films

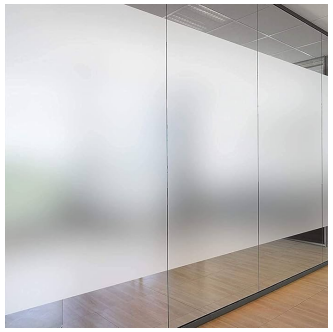


Add coatings

Add paints

Add PCM

Add Curtains



Add films

Add Curtains

Installed in uncontrolled-env

Keep the existing glass in place

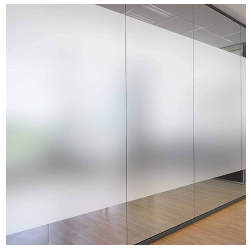
Quick installation time

No special maintenance

No additional structure

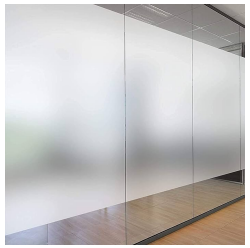
Keep the façade look

System 1



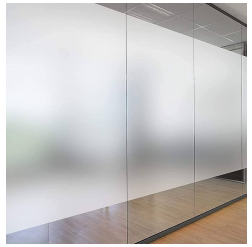
Low-E film

System 2



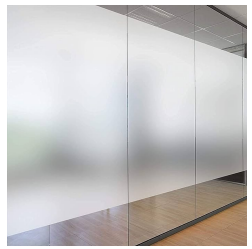
Insulating film

System 3



Solar control film (inside)

System 4



Solar control film (outside)

System 5

Curtain 0% openness

System 6

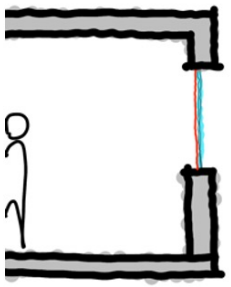
Curtain 28% openness

System 7

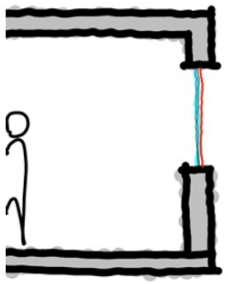
Curtain 54% openness

System 8

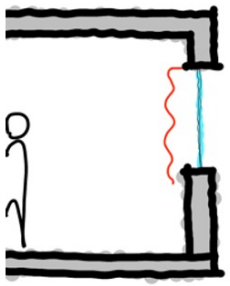
Air pocket curtain



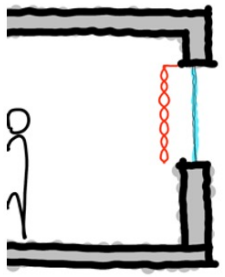
System 1-3



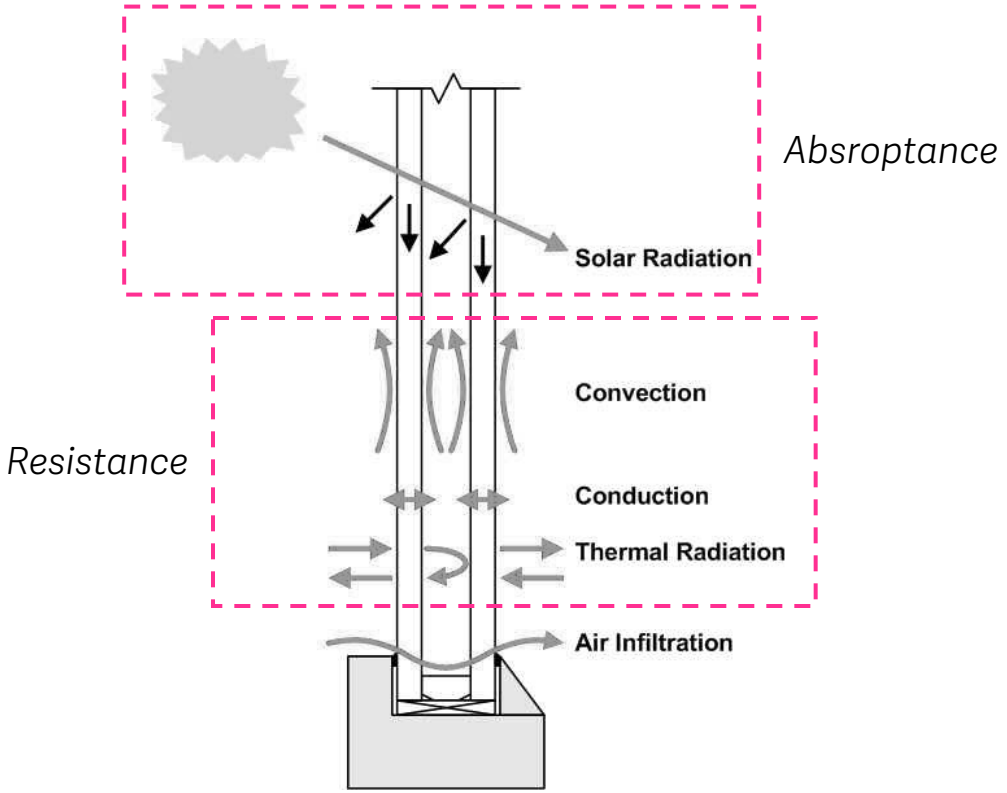
System 4



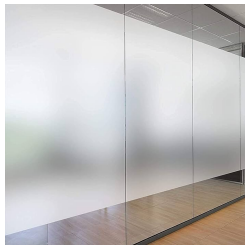
System 5-7



System 8

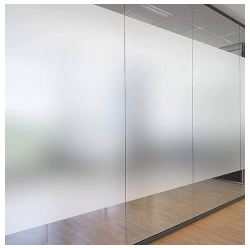

Absroptance
Solar Radiation
Resistance
Convection
Conduction
Thermal Radiation
Air Infiltration

System 1



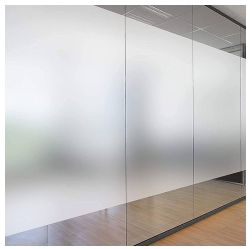
Low-E film

System 2



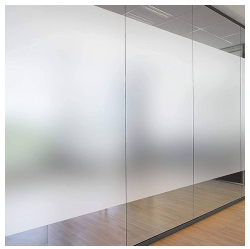
Insulating film

System 3



Solar control film (inside)

System 4



Solar control film (outside)

System	R strategy [m^2K/W]	R total [m^2K/W]	U-value total [W/m^2K]	SHGC total
Base	-	0.606	1.65	0.4
1	-	0.82	1.22	0.29
2	0.23	0.84	1.19	0.28
3	0.007	0.613	1.63	0.328
4	0.0004	0.6064	1.65	0.236

System 5

Curtain
0% openness

System 6

Curtain
28% openness

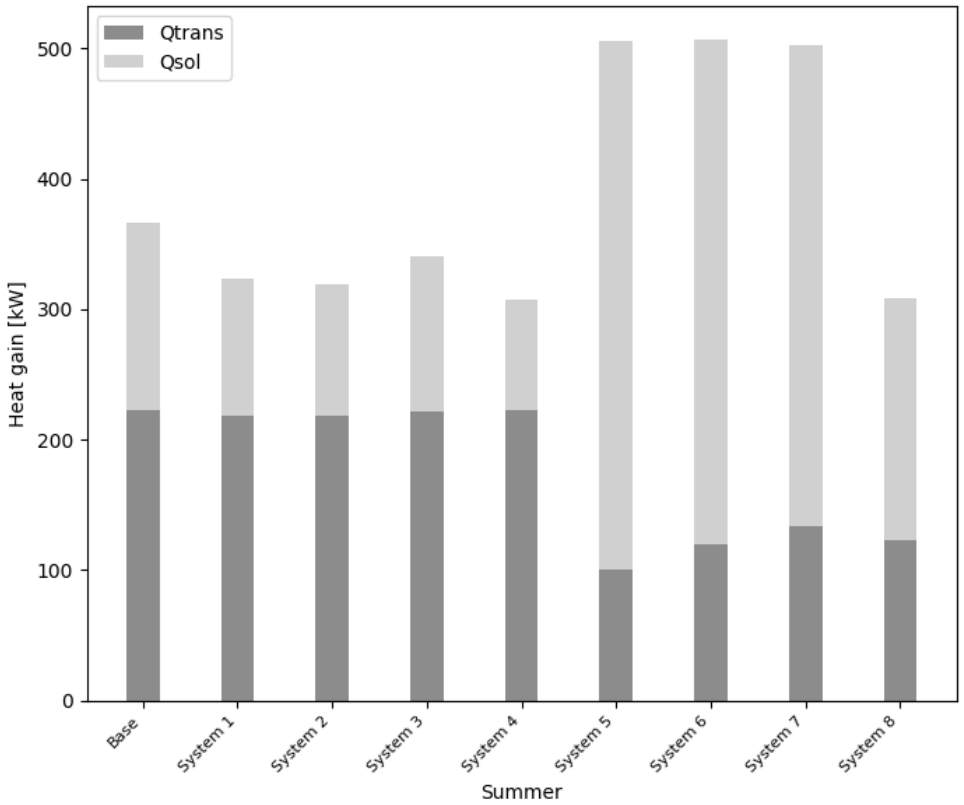
System 7

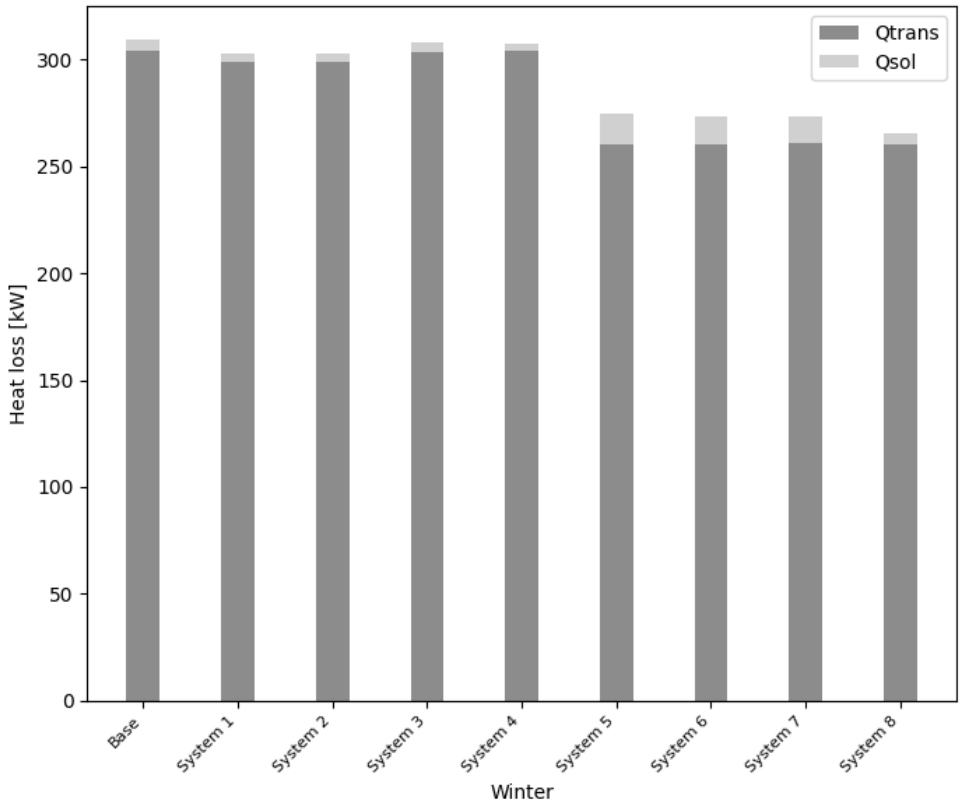
Curtain
54% openness

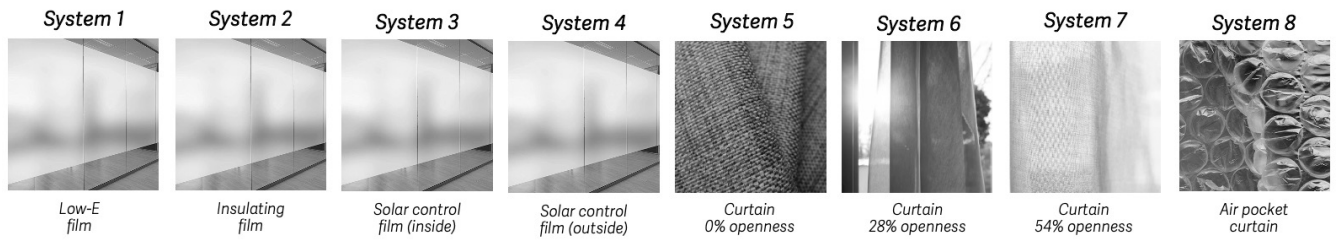
System 8

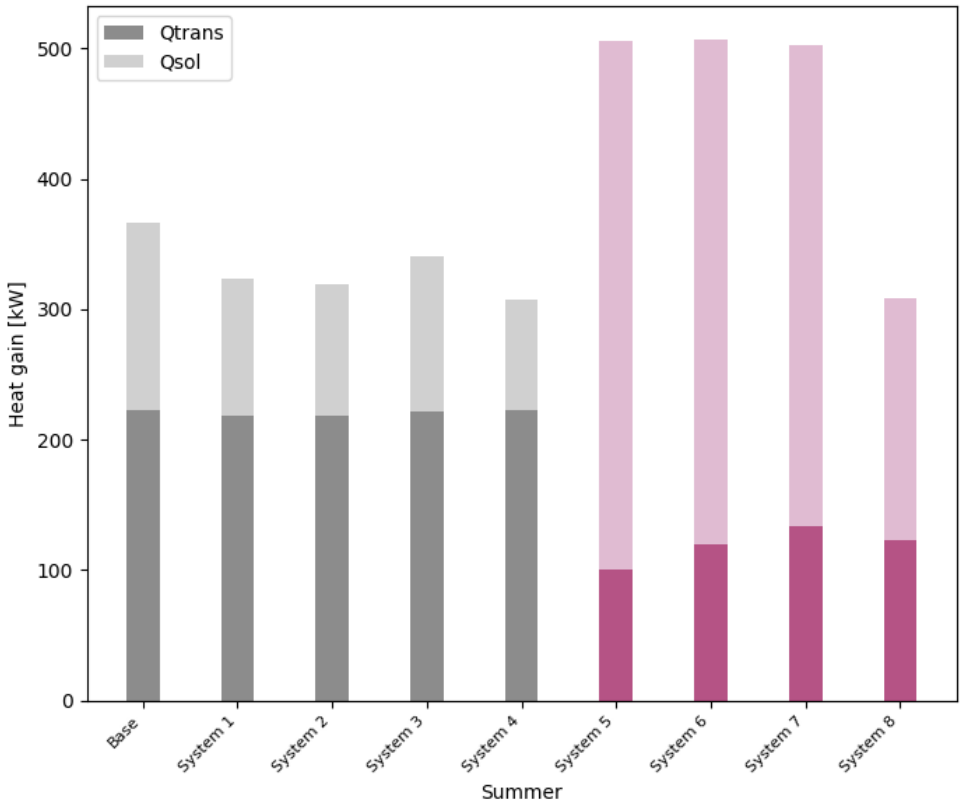
Air pocket
curtain

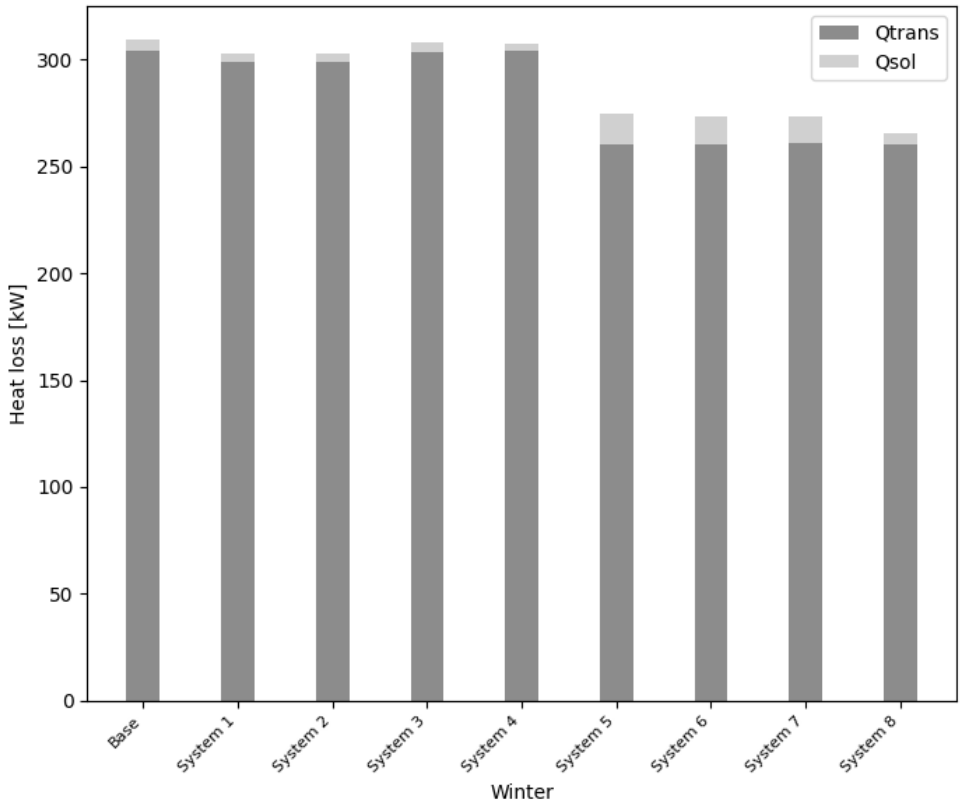
	Retrofitting Strategies			Window Glass		
System	Thickness [m]	U-value [W/m^{2}K]	Absorption	R [m^{2}K/W]	U-value [W/m^{2}K]	SHGC
5	0.003	0.01	0.44	0.606	1.65	0.4
6	0.003	0.3	0.36	0.606	1.65	0.4
7	0.001	0.54	0.3	0.606	1.65	0.4
8	0.127	0.35	0.1	0.606	1.65	0.4

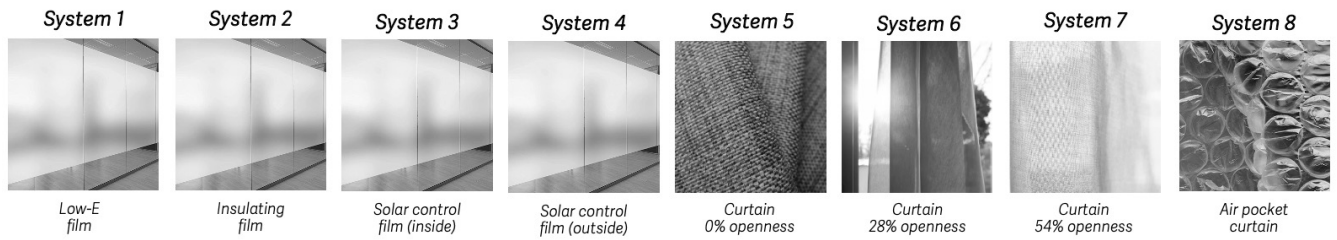

Qtrans
Qsol
Heat gain [kW]
0
100
200
300
400
500
Base
System 1
System 2
System 3
System 4
System 5
System 6
System 7
System 8
Summer


Qtrans
Qsol
Heat loss [kW]
0
50
100
150
200
250
300
Base
System 1
System 2
System 3
System 4
System 5
System 6
System 7
System 8
Winter


System 1
Low-E film
System 2
Insulating film
System 3
Solar control film (inside)
System 4
Solar control film (outside)
System 5
Curtain 0% openness
System 6
Curtain 28% openness
System 7
Curtain 54% openness
System 8
Air pocket curtain


Qtrans
Qsol
Heat gain [kW]
0
100
200
300
400
500
Base
System 1
System 2
System 3
System 4
System 5
System 6
System 7
System 8
Summer


Qtrans
Qsol
Heat loss [kW]
0
50
100
150
200
250
300
Base
System 1
System 2
System 3
System 4
System 5
System 6
System 7
System 8
Winter


System 1
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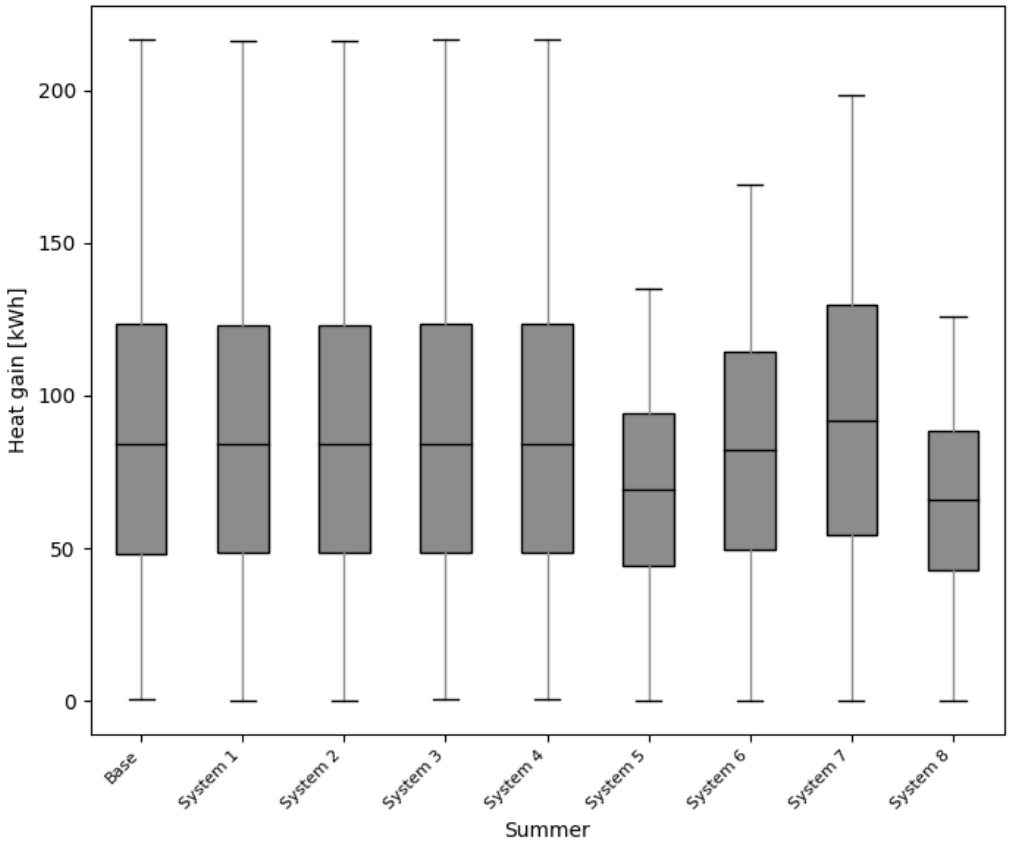
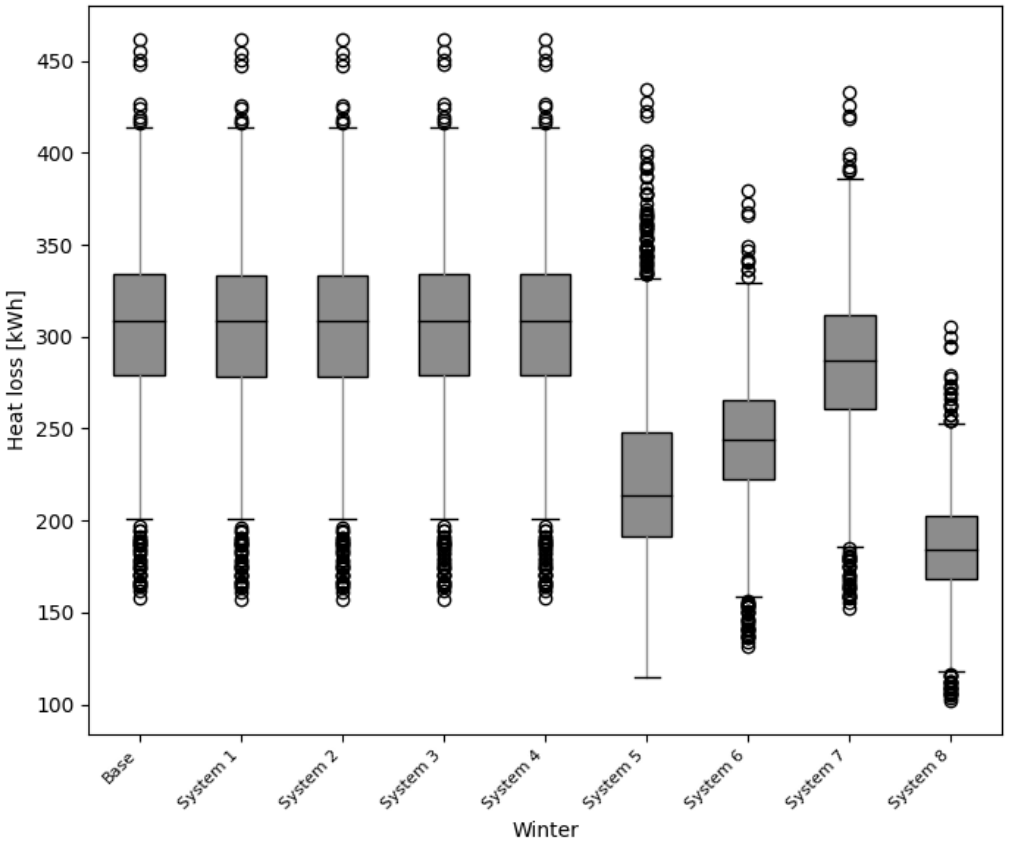
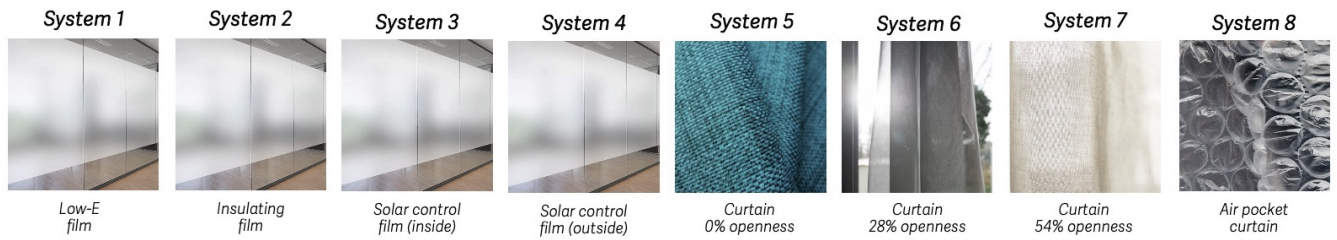
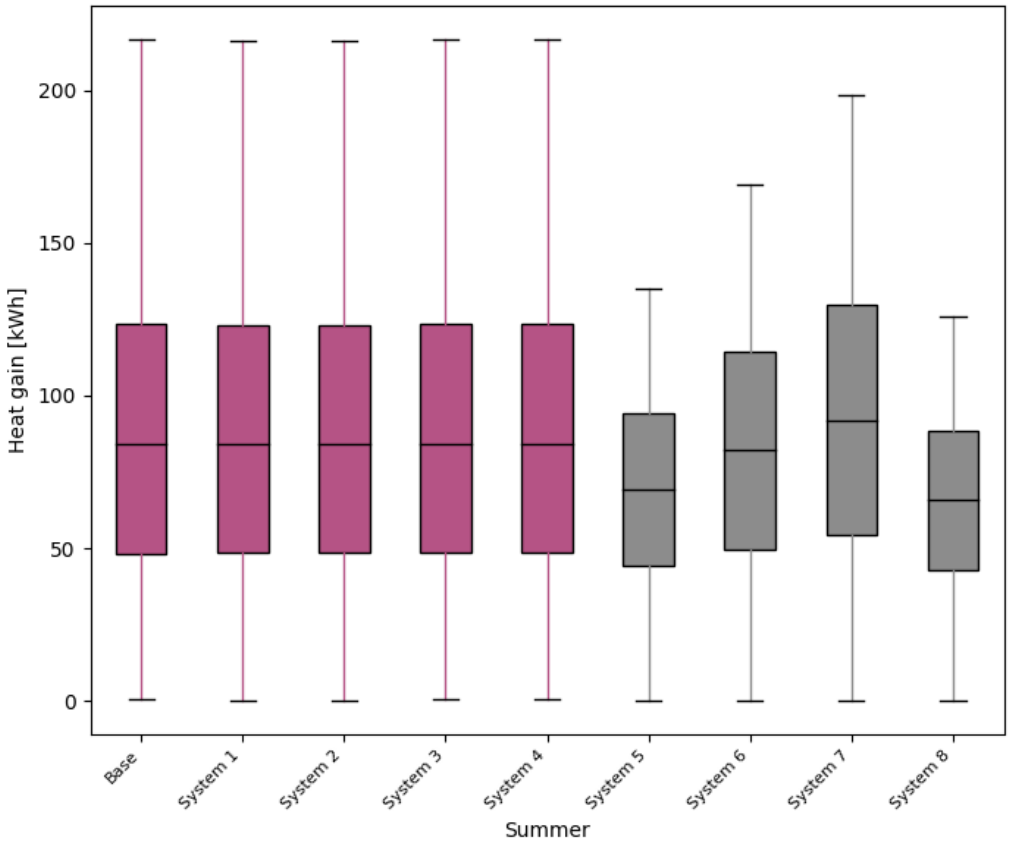
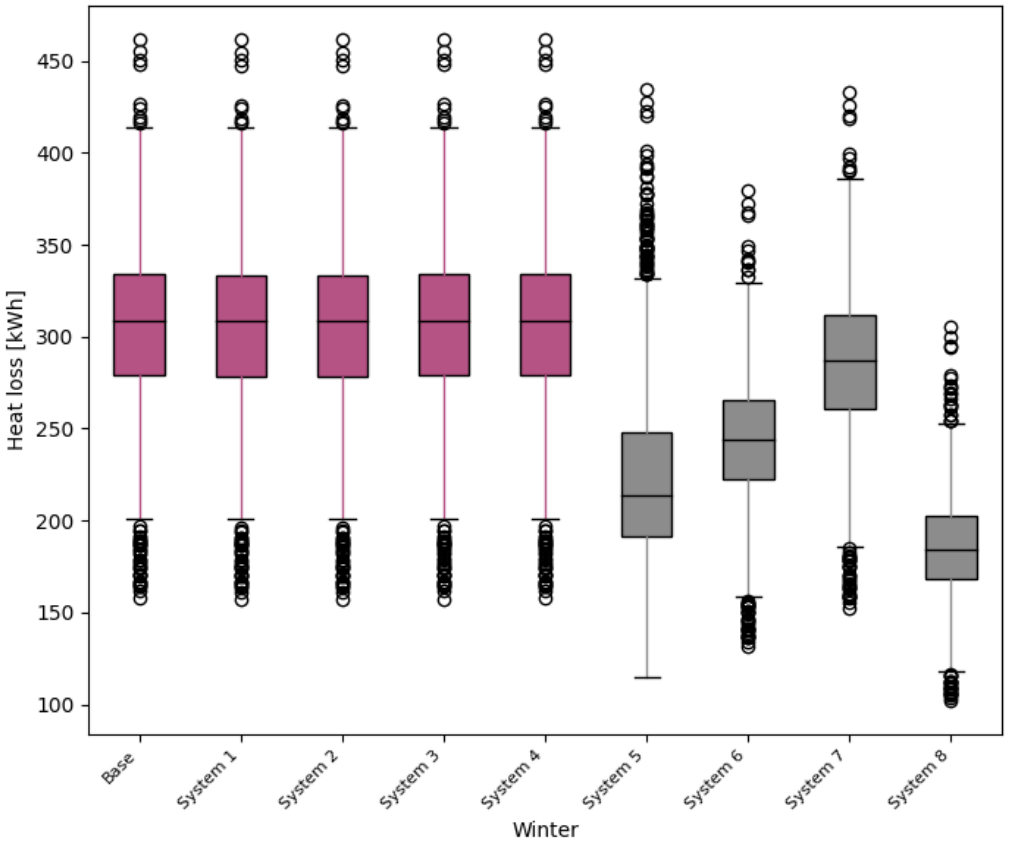
Solar control film (outside)
System 5
Curtain 0% openness
System 6
Curtain 28% openness
System 7
Curtain 54% openness
System 8
Air pocket curtain

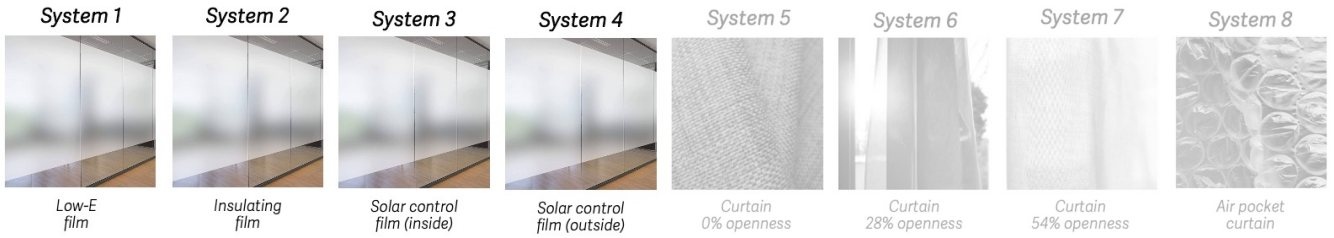

Heat gain [kWh]
0
50
100
150
200
Base
System 1
System 2
System 3
System 4
System 5
System 6
System 7
System 8
Summer


Heat loss [kWh]
100
150
200
250
300
350
400
450
Base
System 1
System 2
System 3
System 4
System 5
System 6
System 7
System 8
Winter


System 1
Low-E film
System 2
Insulating film
System 3
Solar control film (inside)
System 4
Solar control film (outside)
System 5
Curtain 0% openness
System 6
Curtain 28% openness
System 7
Curtain 54% openness
System 8
Air pocket curtain


Heat gain [kWh]
0
50
100
150
200
Base
System 1
System 2
System 3
System 4
System 5
System 6
System 7
System 8
Summer


Heat loss [kWh]
100
150
200
250
300
350
400
450
Base
System 1
System 2
System 3
System 4
System 5
System 6
System 7
System 8
Winter


System 1
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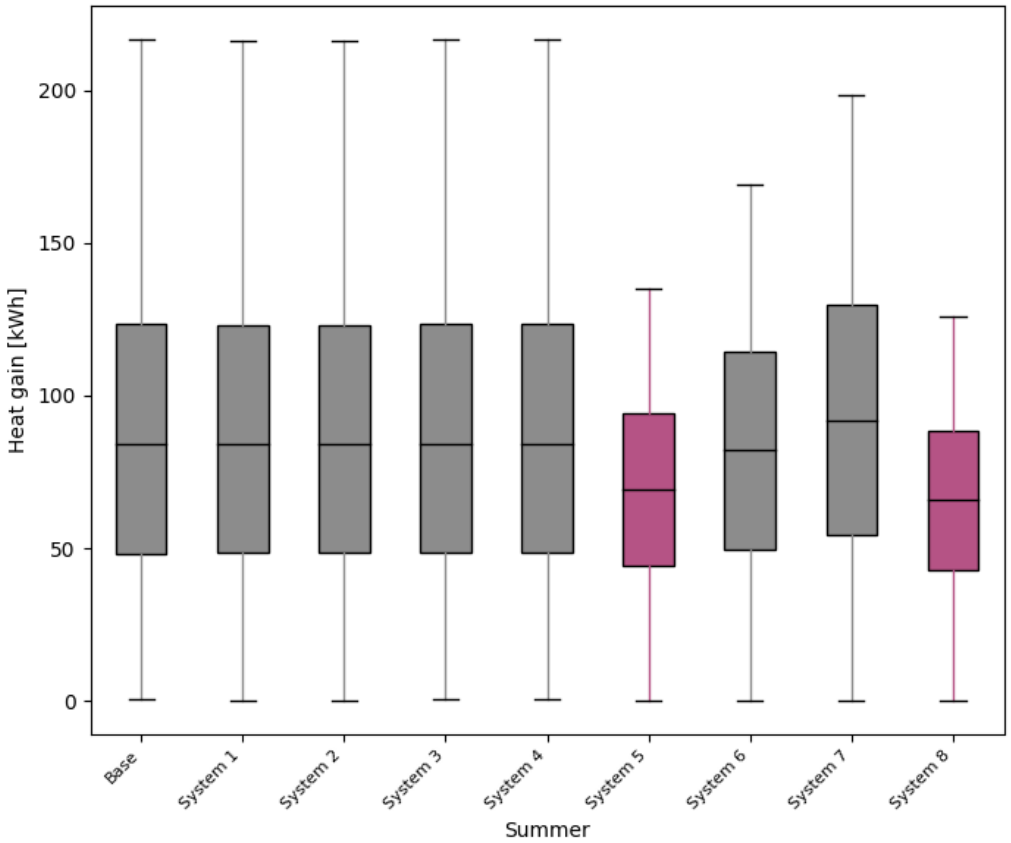
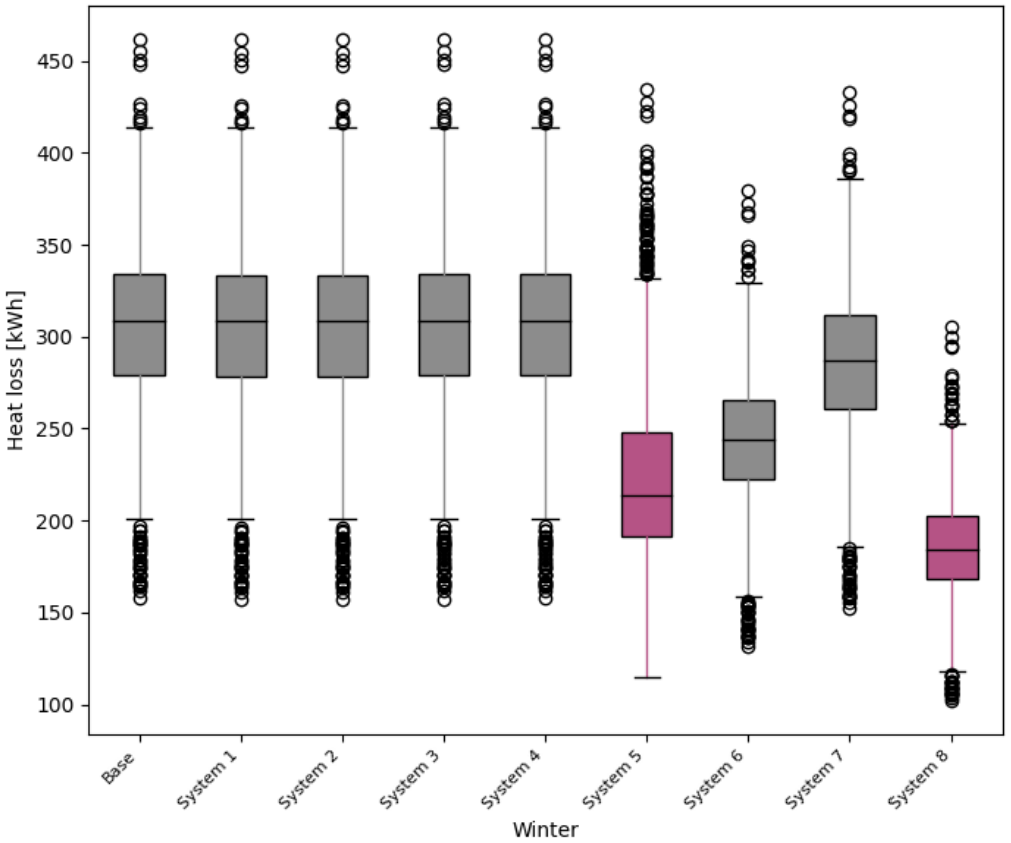
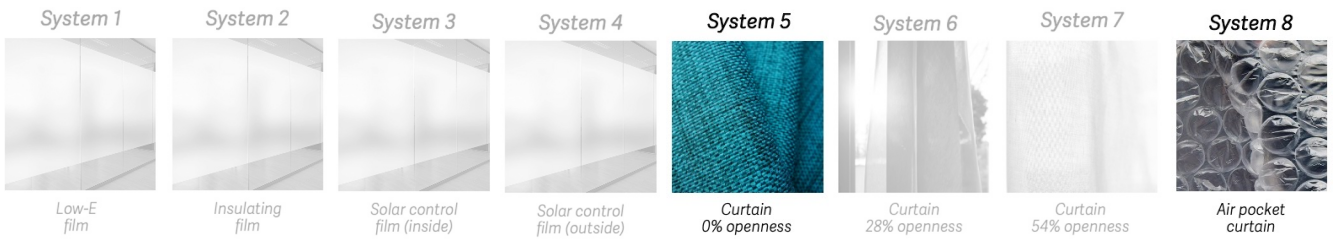
Solar control film (outside)
System 5
Curtain 0% openness
System 6
Curtain 28% openness
System 7
Curtain 54% openness
System 8
Air pocket curtain


Heat gain [kWh]
0
50
100
150
200
Base
System 1
System 2
System 3
System 4
System 5
System 6
System 7
System 8
Summer


Heat loss [kWh]
100
150
200
250
300
350
400
450
Base
System 1
System 2
System 3
System 4
System 5
System 6
System 7
System 8
Winter


System 1
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Curtain 0% openness
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Curtain 28% openness
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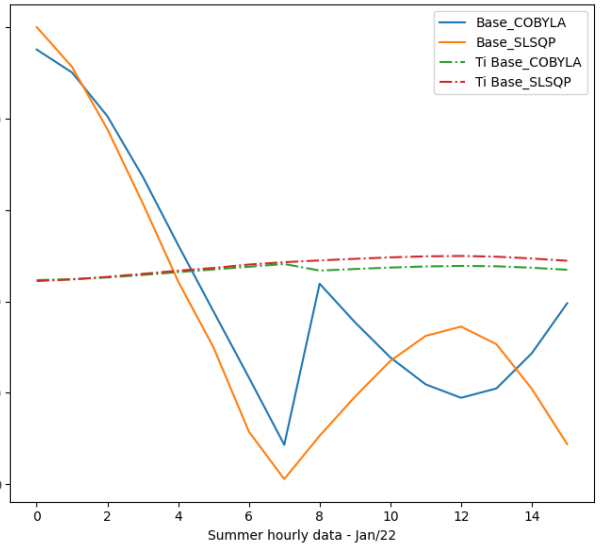
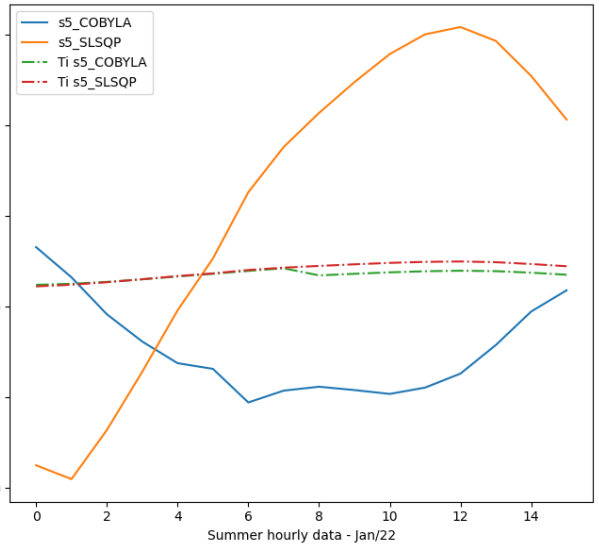
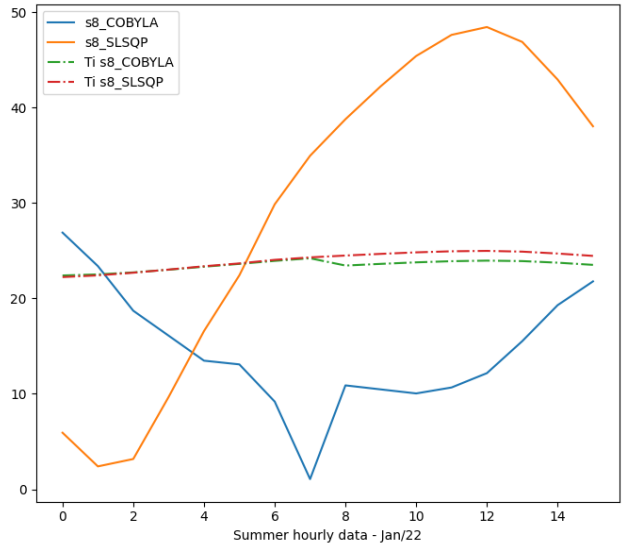
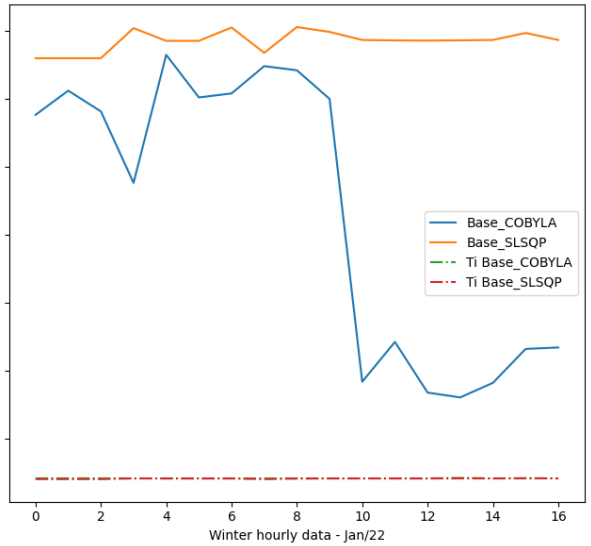
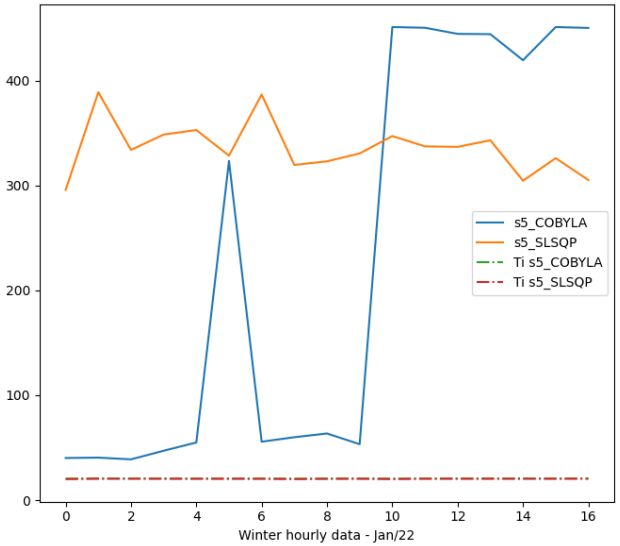
Curtain 54% openness
System 8
Air pocket curtain

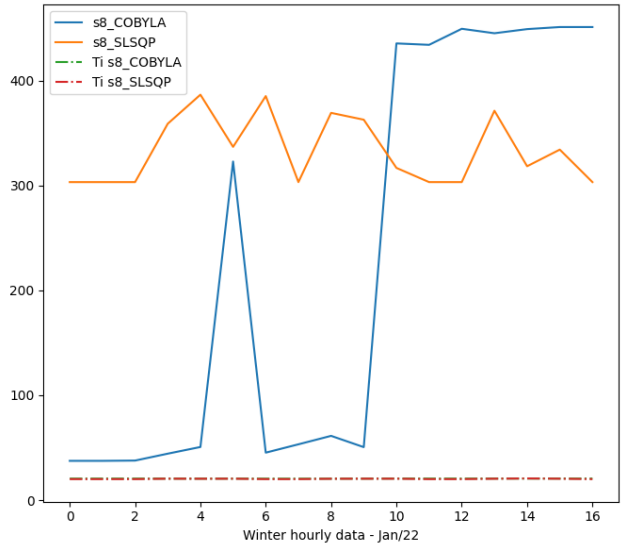






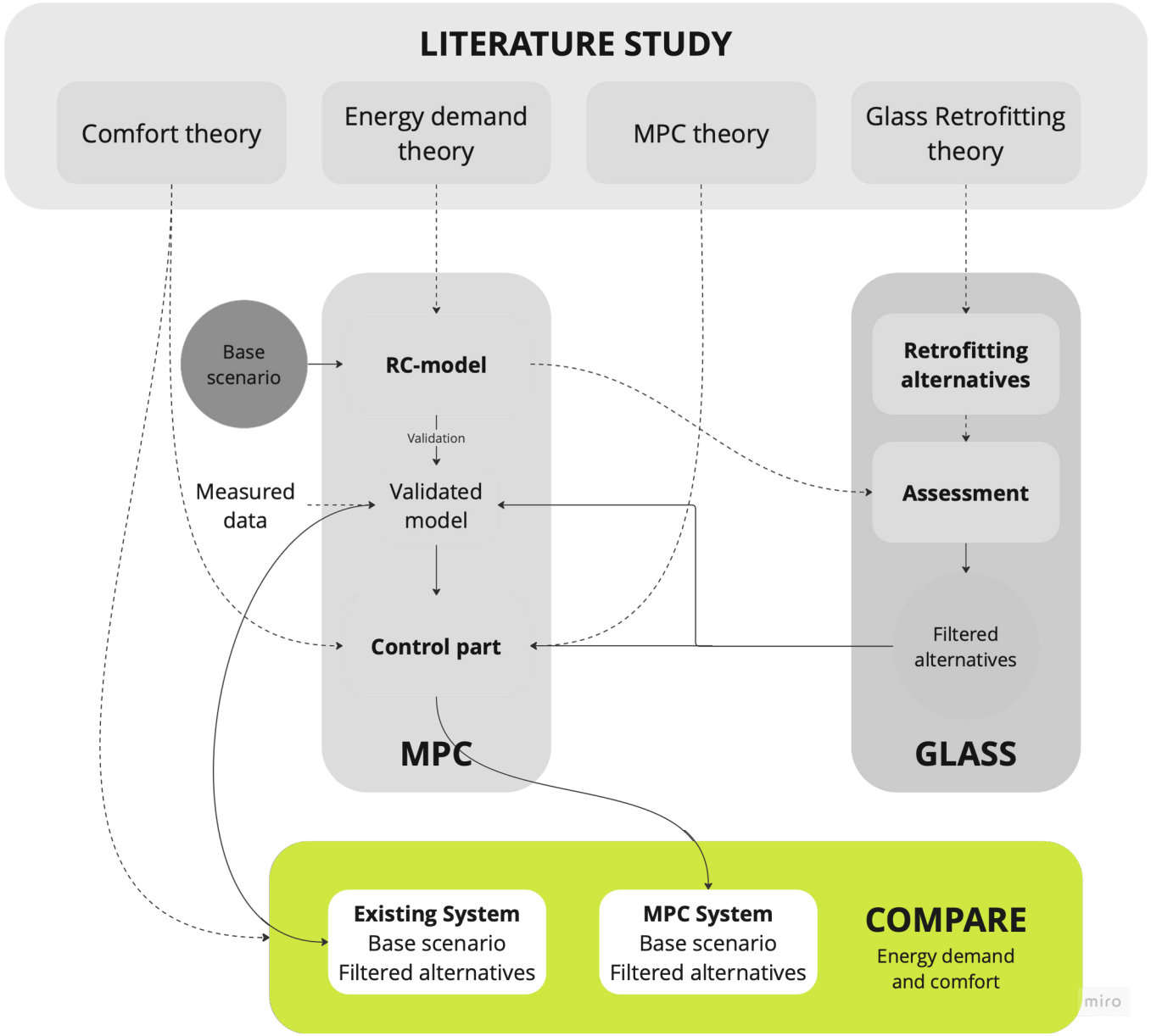


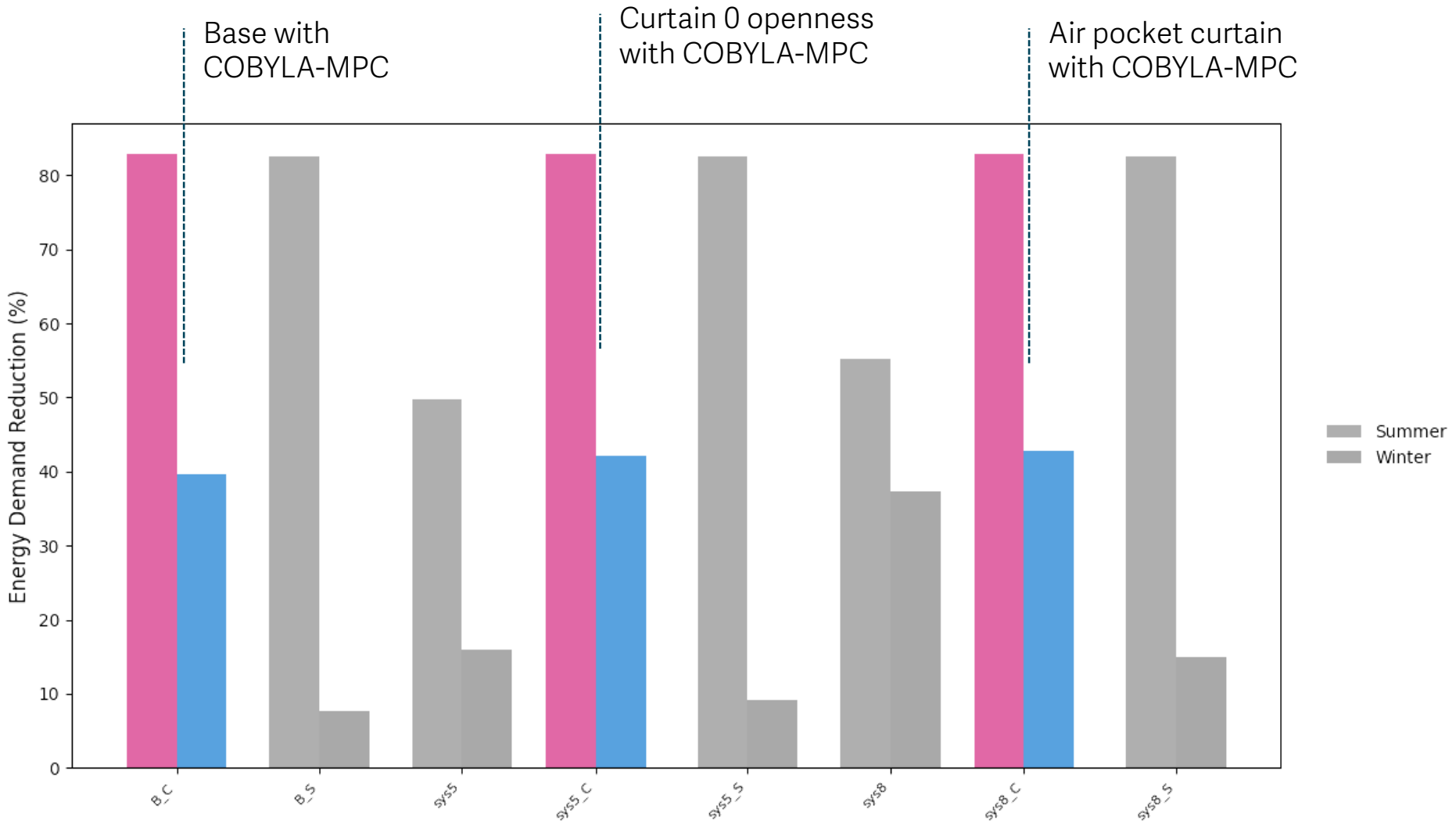




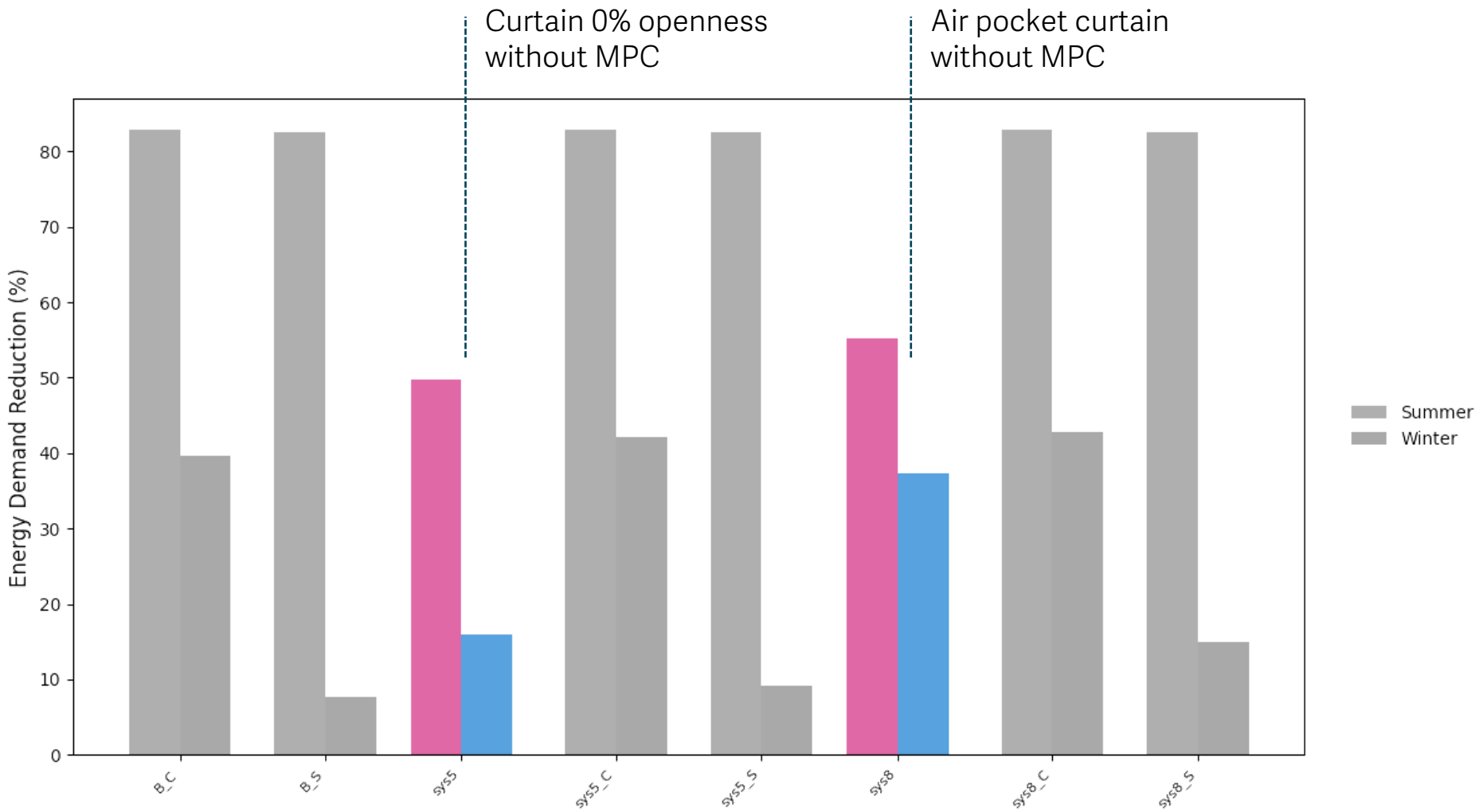
SLSQP tends prioritize comfort

COBYLA tends to save more energy

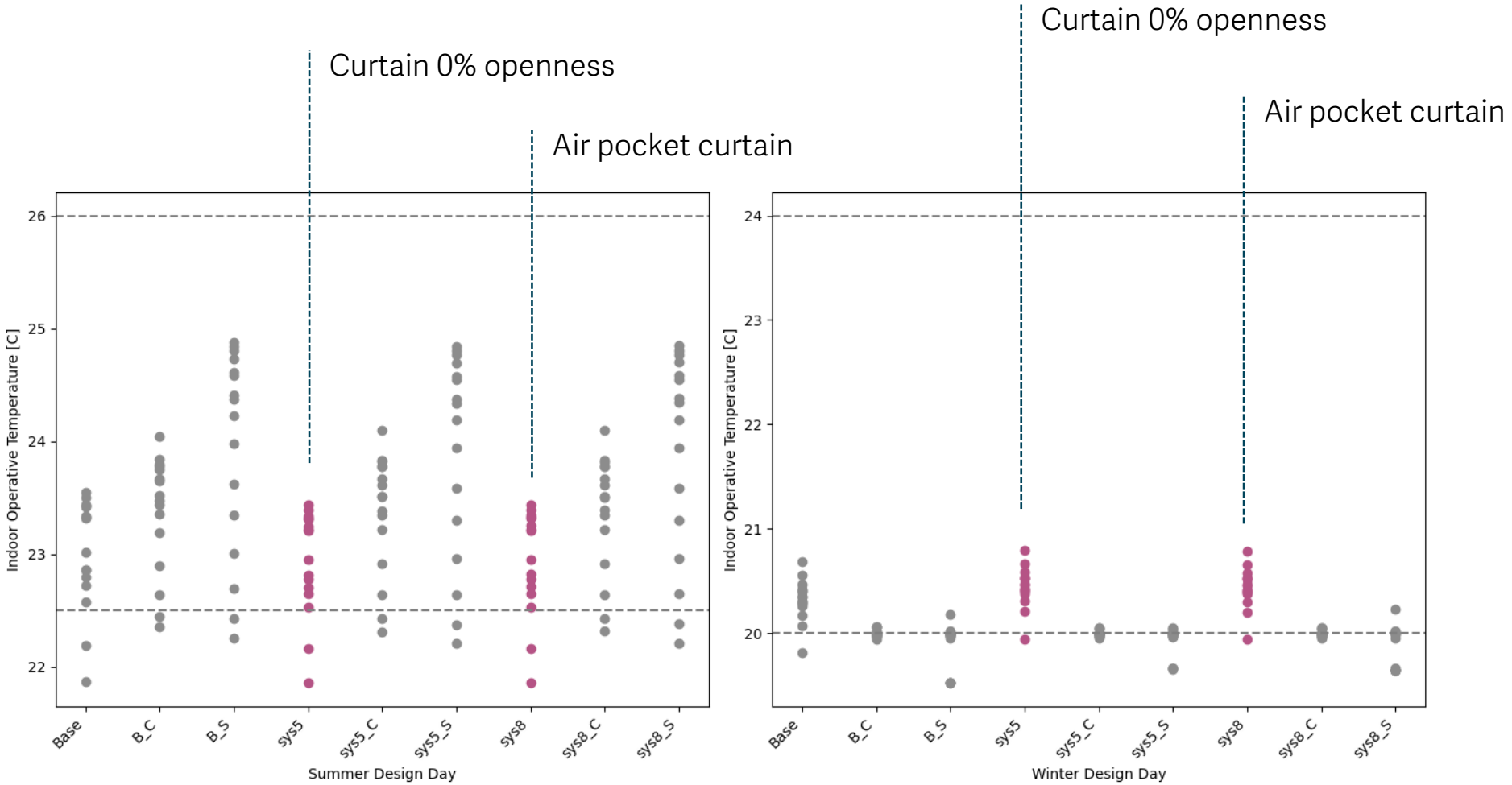

LITERATURE STUDY
Comfort theory
Energy demand theory
MPC theory
Glass Retrofitting theory
Base scenario
RC-model
Validation
Measured data
Validated model
Control part
MPC
Retrofitting alternatives
Assessment
Filtered alternatives
GLASS
Existing System
Base scenario
Filtered alternatives
MPC System
Base scenario
Filtered alternatives
COMPARE
Energy demand and comfort
miro



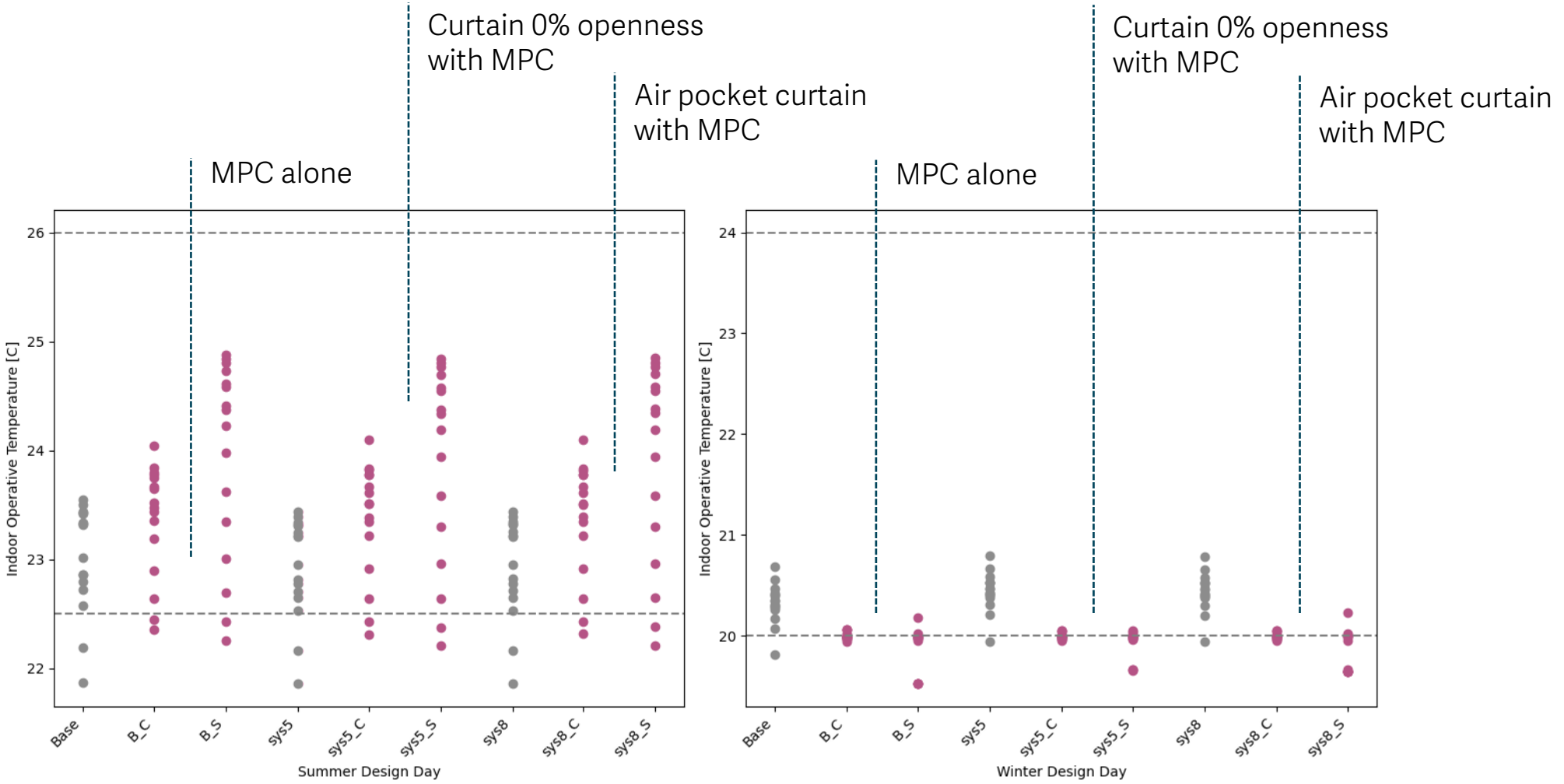
Systems with COBYLA-MPC are overpowering in terms of energy saving



Curtains alone only reduce a low amount of energy demand



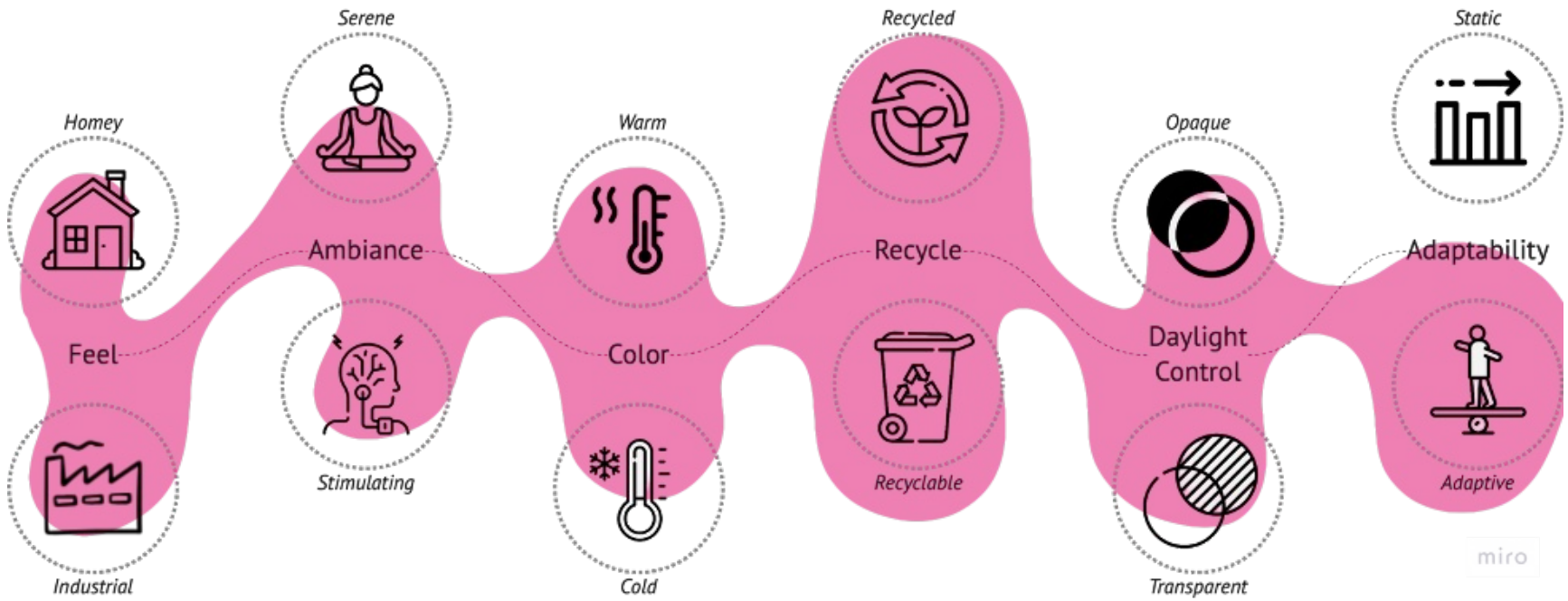
Curtains alone are overpowering in terms of thermal comfort

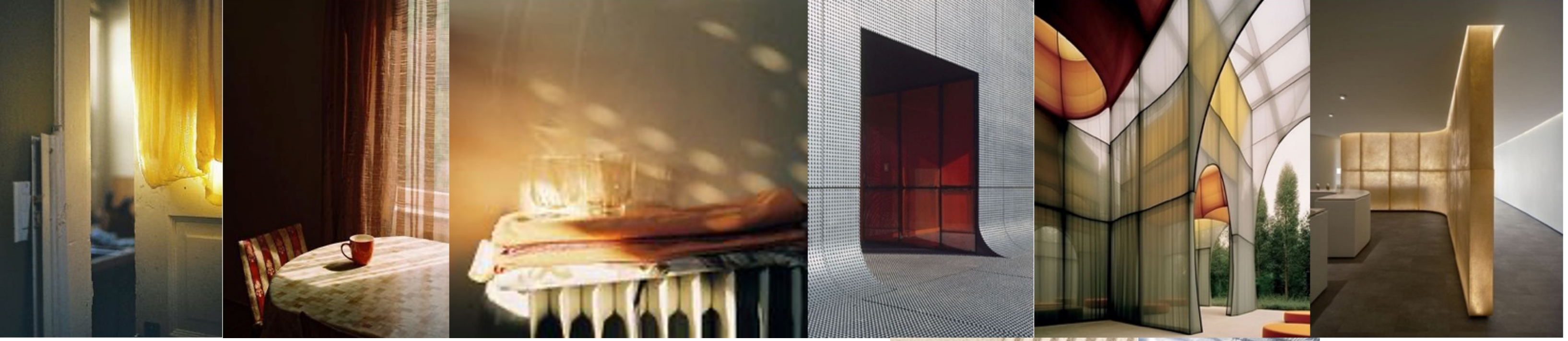
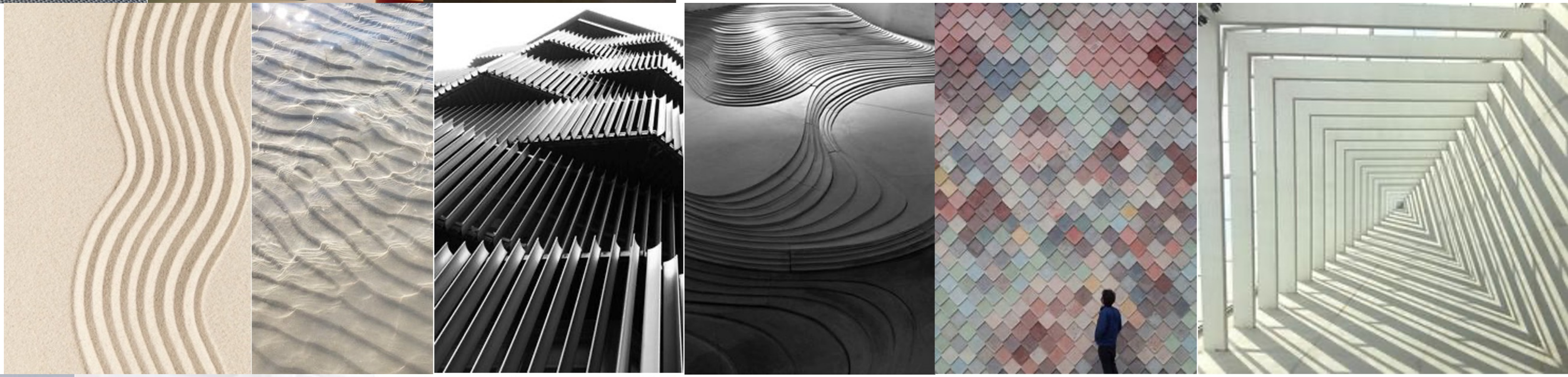


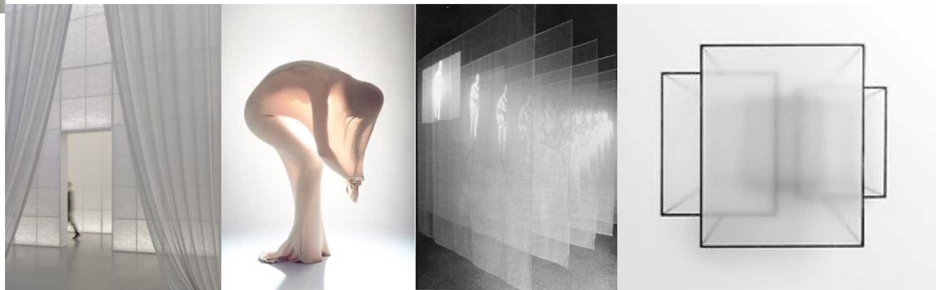
MPC systems are pushing towards the comfort limits

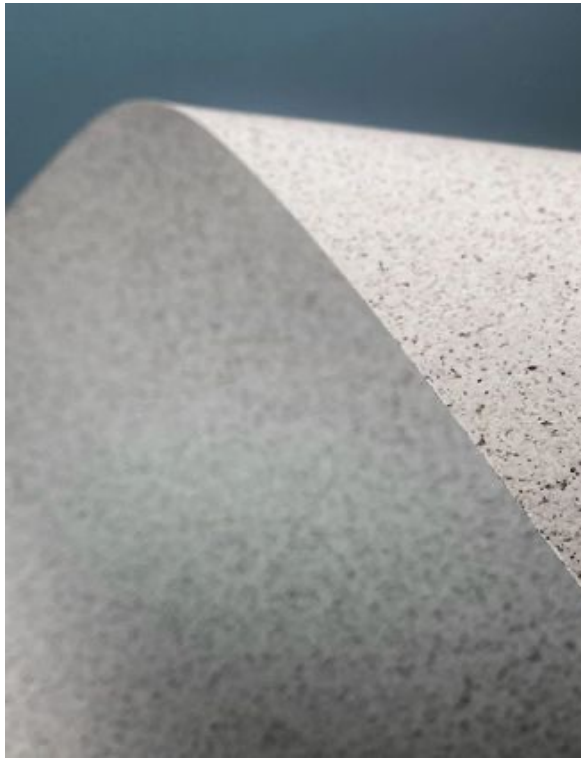
Trade off

If I were to fix Pulse...

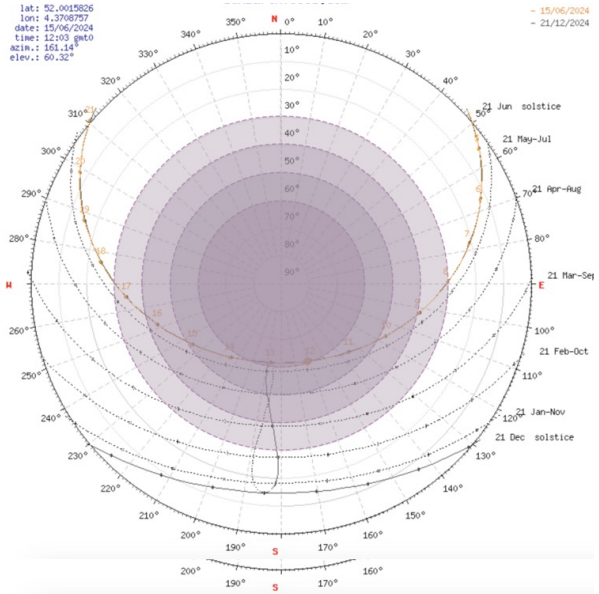

Homey
Serene
Warm
Recycled
Opaque
Static
Feel
Ambiance
Color
Recycle
Daylight Control
Adaptability
Industrial
Stimulating
Cold
Recyclable
Transparent
Adaptive
miro
Not selected
Selected
In between
Both

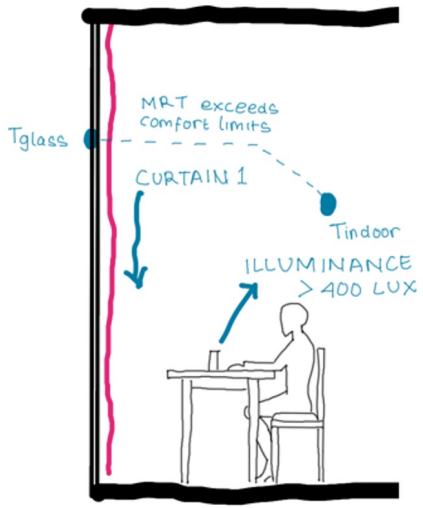





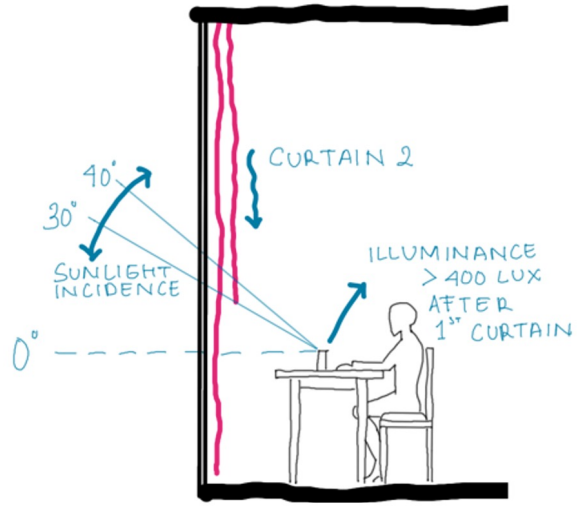


Recycled Papers

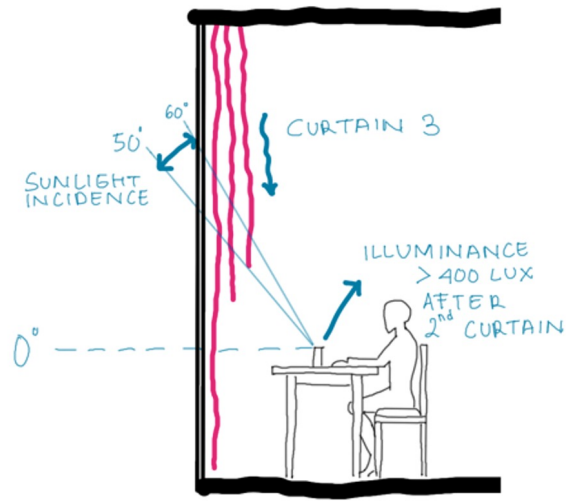




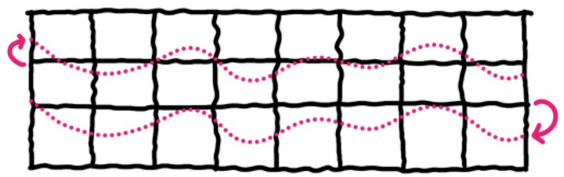
Curtain 1



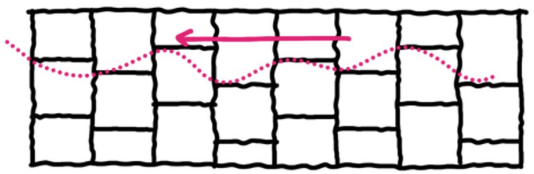
Curtain 2



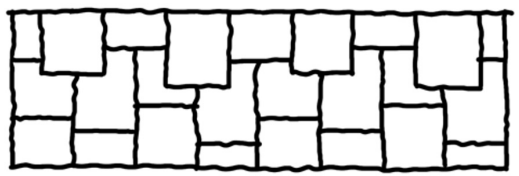
Curtain 3



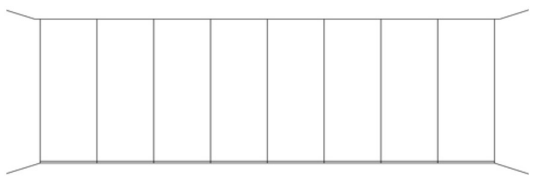
Step 1



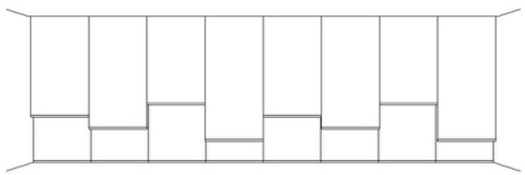
Step 2



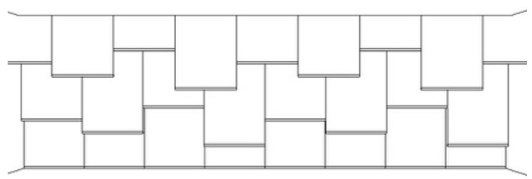
Step 3



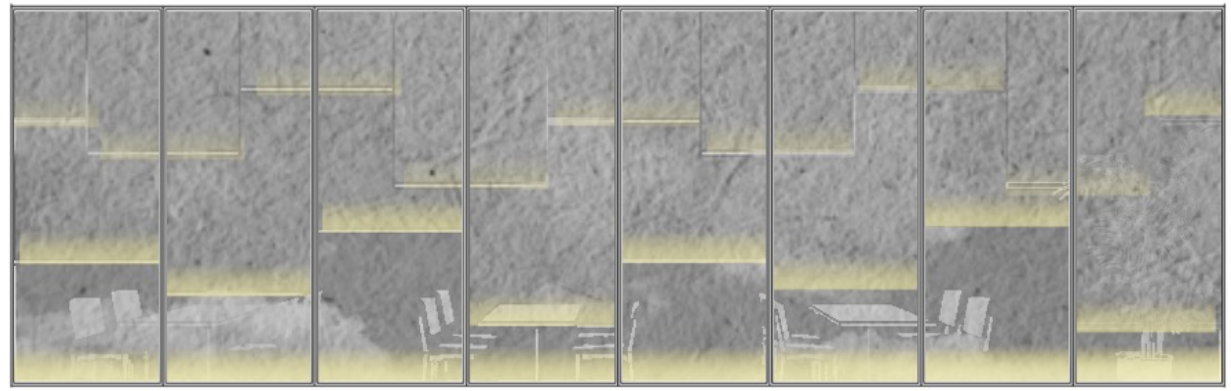
Layer 1



Layer 2



Layer 3



Recap.

[ˈriːkap] *verb.*

---

state again as a summary; recapitulate.

Lumped model works, but it has limitations

Lumped model works, but it has limitations

Algorithms behave differently, choose wisely

Lumped model works, but it has limitations

Algorithms behave differently, choose wisely

A **trade-off** consequences

Lumped model works, but it has limitations

Algorithms behave differently, choose wisely

A **trade-off** consequences

Simple retrofitting strategies can work

At the end of the day, it's all about priority.

Smart system is to save energy; retrofitting strategies are to improve comfort.

Use both to help complement each other.

Thank you!