

# LT-Set: A Surrogate Model-Based Decision Tool for Low-Temperature Heating Refurbishment

## **Graduation Presentation**

Naeem Kantawala | 5621925

## **Energy Upgrades & Computation**

First Mentor: Dr.ing. Thaleia Konstantinou

Second Mentor: Dr. ir. Michela Turrin

Third Mentor: Ir. P. Prateek Wahi

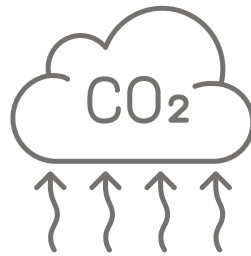


# Context

## Challenges & Targets



Paris agreement which commits to limit global warming below **2 °C**.



Reduce Greenhouse gasses by **49%** before 2030



**90%** of built environment is dependent on natural gas for heating is contributing to the emissions

# Context

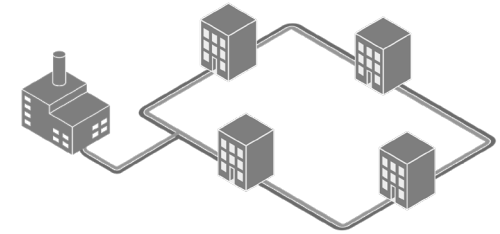
## Challenges & Targets



**1.5 million** homes need  
be phased out of natural  
gas by 2030.



Renovation target of  
**200,000** homes per  
year

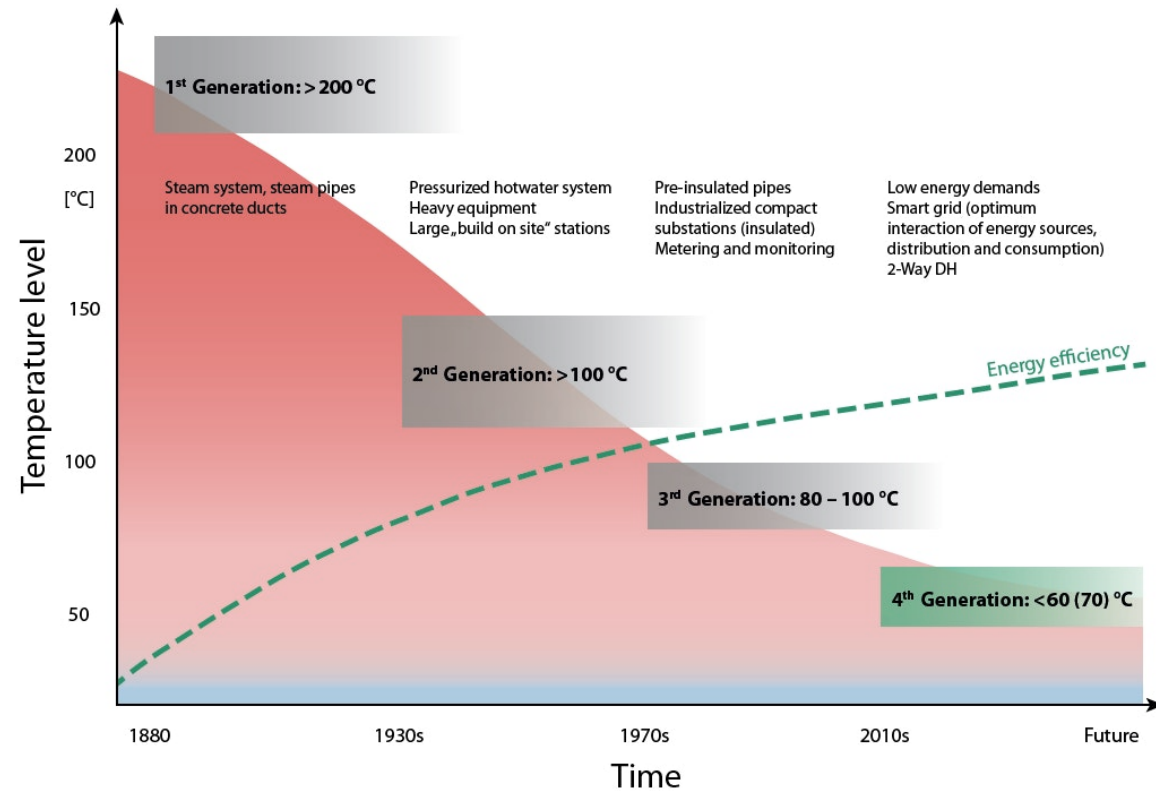


**6.4%** household district heating  
demand for household expected to  
grow to **38%** 2030.

# Context

## Low temperature heat networks

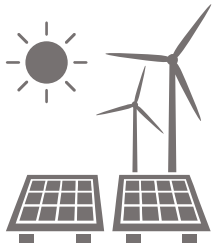
4<sup>th</sup> Generation heat supply:  
**50 – 60 °C.**





# Context

Benefits of low temperature heat networks



Integration of **renewable** and **waste energy sources** of lower quality and densities.



**Improved efficiency** due to reduced distribution losses.



**Improved thermal comfort** and **air quality**



Ensures **price stability** and **reduced energy bills**.

# Problem

The dwellings need to be **refurbished** in order to transition to low temperature heating networks whilst **maintaining comfort standards**.



# Problem

The dwellings need to be **refurbished** in order to transition to low temperature heating networks whilst **maintaining comfort standards**.

However, refurbishments rates are too low.



# Problem statements

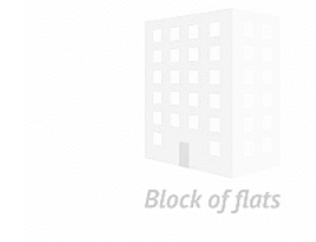
## Urban challenge



Refurbishment addressed at neighbourhood **scale**.



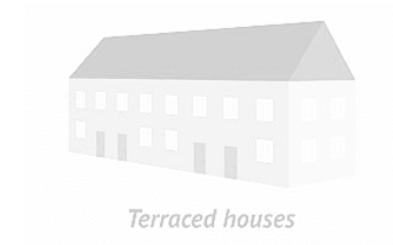
*Detached house*



*Block of flats*



*Semi-detached houses*



*Terraced houses*

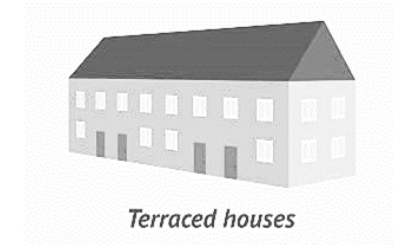
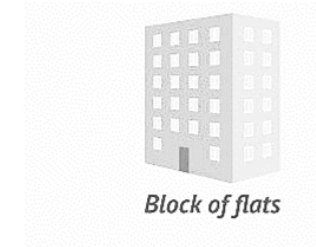
Districts comprise of multiple **housing archetypes** across multiple **construction years**.

# Problem statements

## Urban challenge



Refurbishment addressed at neighbourhood **scale**.



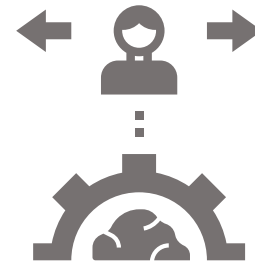
Districts comprise of multiple **housing archetypes** across multiple **construction years**.

# Problem statements

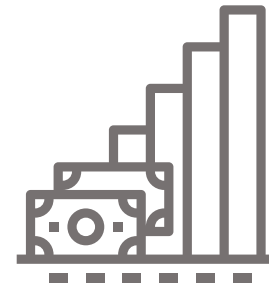
## Homeowners



**Complexity** of evaluating combination of refurbishment strategies using performance indicators.

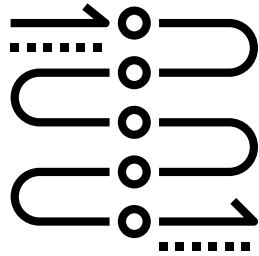


Uncertainty introduced due to lack of consideration for **occupancy behaviour** consideration and the overall **lifecycle cost** of the refurbishment measures.

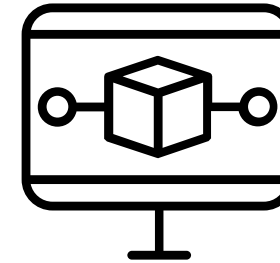


# Problem statements

## Computational



Majority of the current decision tool **assume steady-state conditions** and do not account for **dynamic** or transient effects.



Advanced dynamic tools are **computationally expensive** and **inaccessible** to decision makers.

# Research Questions

## Main & Sub questions

How to develop a **surrogate model-based decision-making** tool to select **combined, no-regret refurbishment measures** using **performance indicators** for **multiple Dutch housing typologies** considering **occupancy behaviour** and **lifecycle cost** to transition to **low-temperature** district heating?

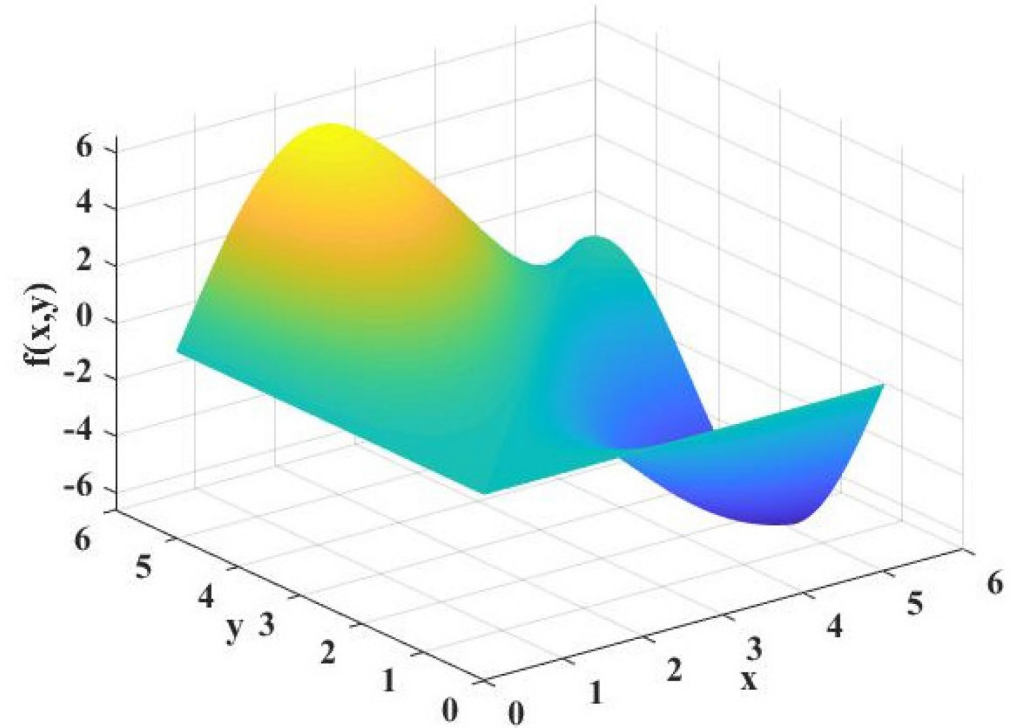


# Definition

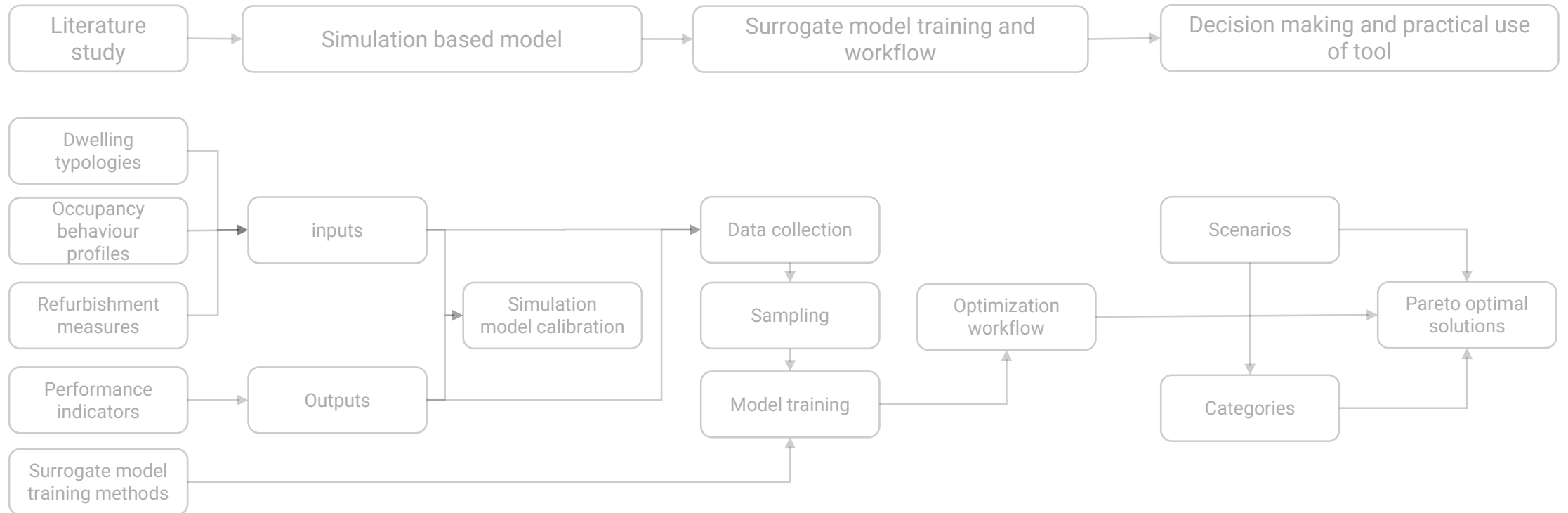
What are surrogate models?

Surrogate models are **simplified mathematical models** that mimic the behaviour of complex systems.

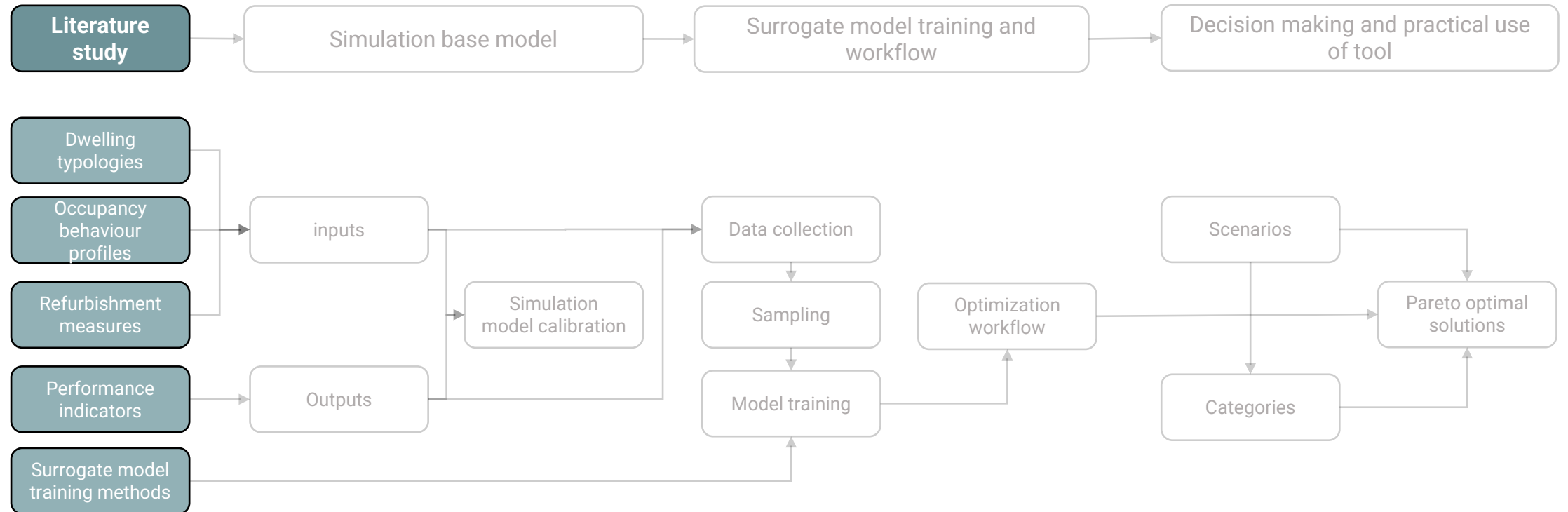
Enables **faster simulations**, optimization, and decision-making processes.



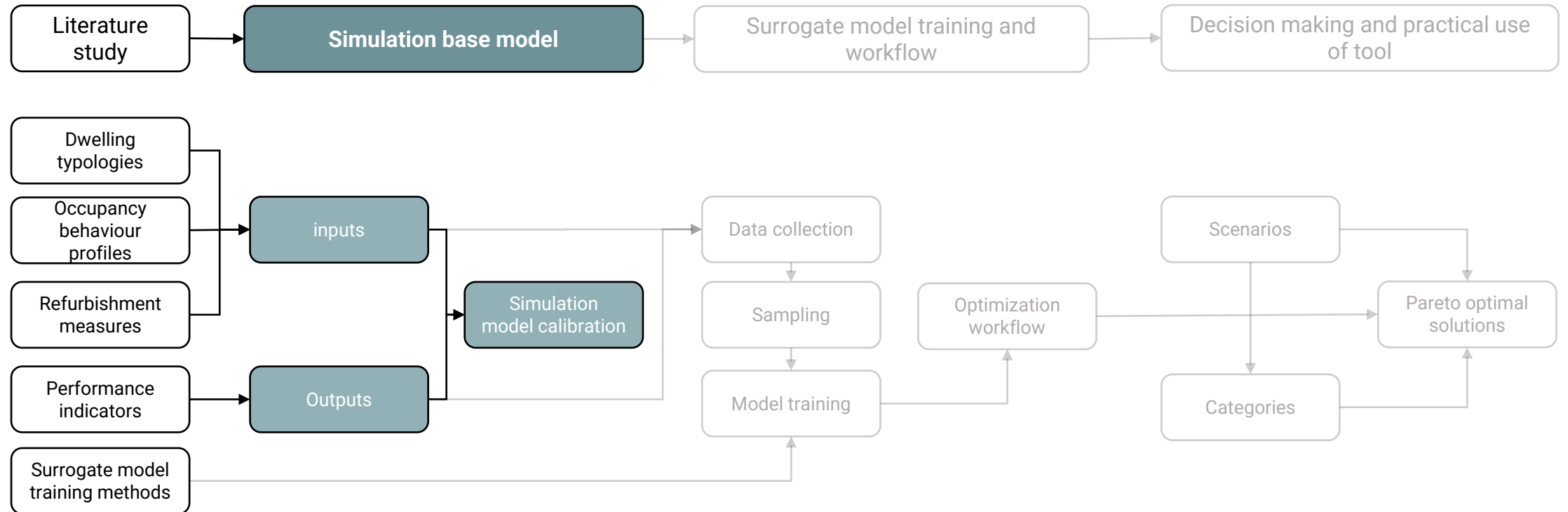
# Research framework



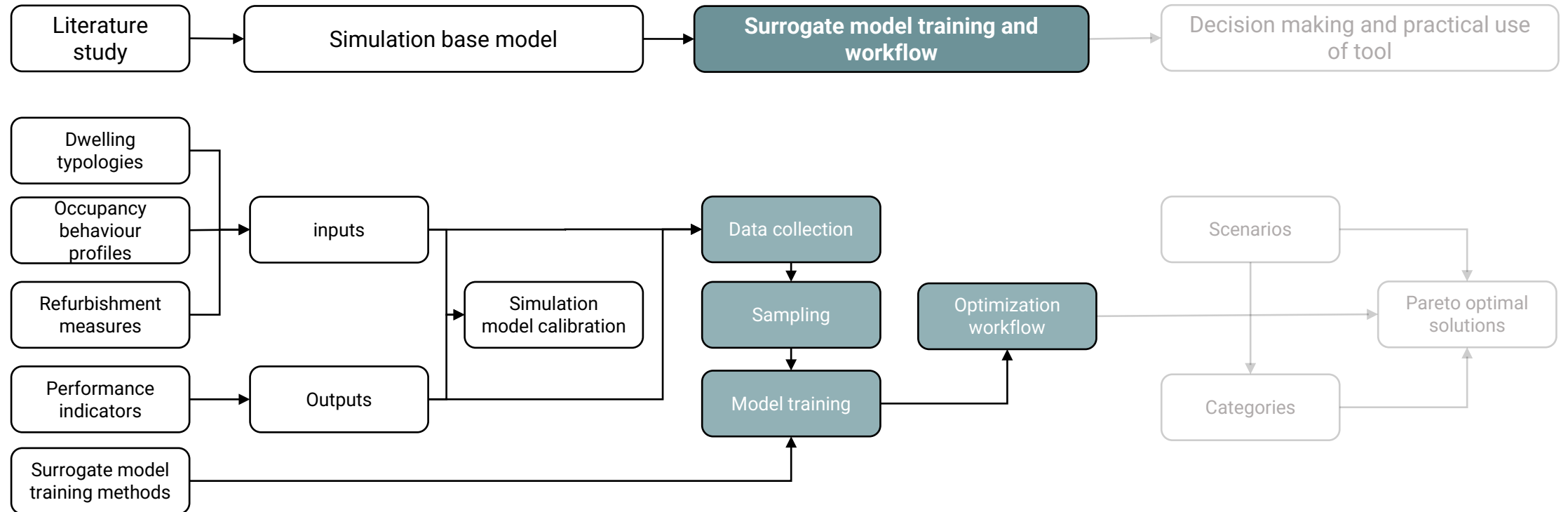
# Research framework



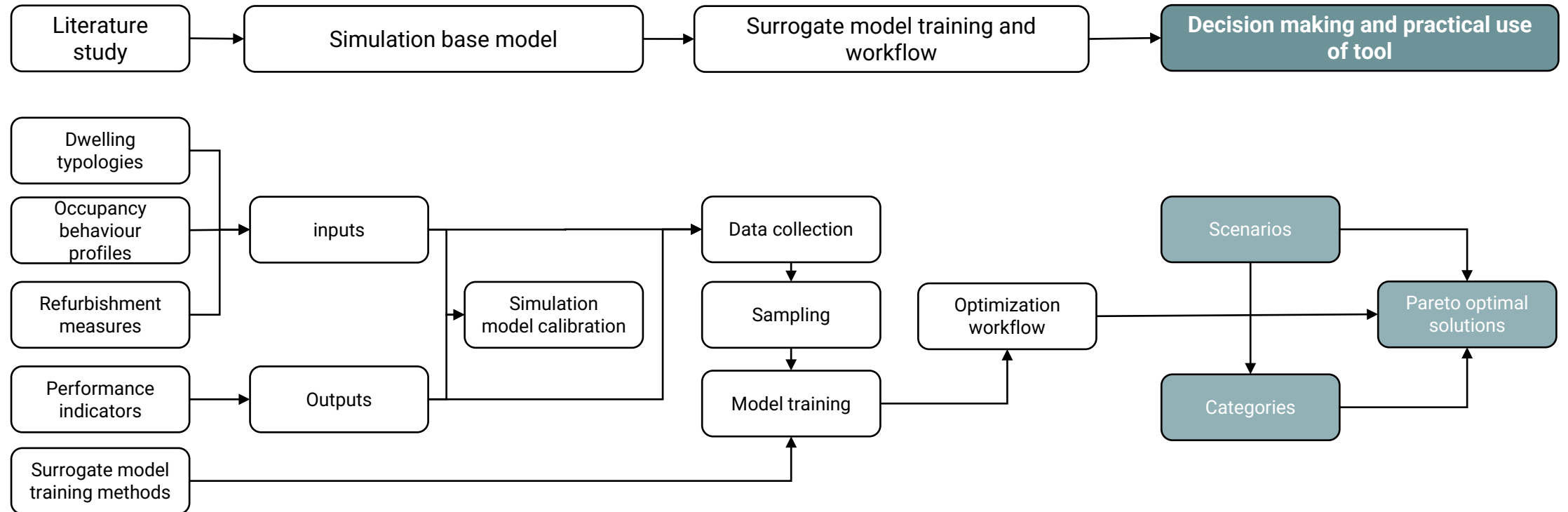
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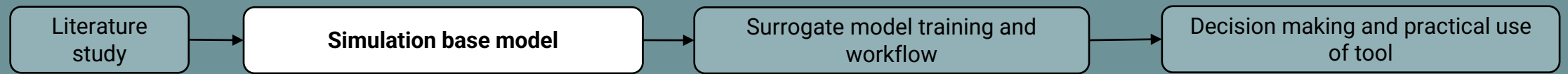


# Research framework

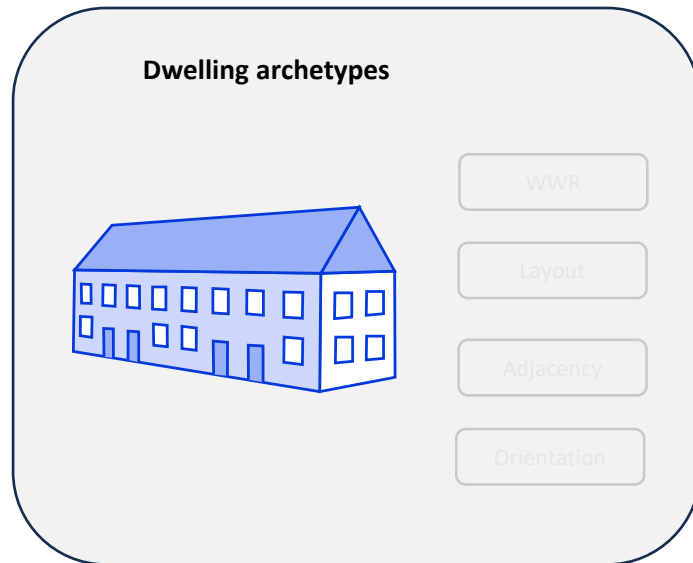


# Research framework





# Simulation model

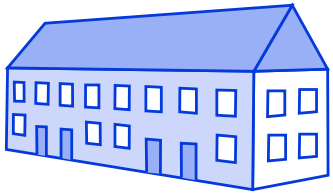




# Simulation model



## Dwelling archetypes



WWR

Layout

Adjacency

Orientation

## Household profiles

Single Parent

Senior couple

Adult couple

Nuclear family

## Zone programs

Bedrooms

Living room

Kitchen

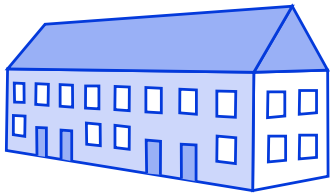
Bathroom

Corridor space

# Simulation model



## Dwelling archetypes



WWR

Layout

Adjacency

Orientation

## Household profiles

Single Parent

Senior couple

Adult couple

Nuclear family

## Zone programs

Bedrooms

Living room

Kitchen

Bathroom

Corridor space

## Envelope Parameters

Facade

Pitched Roof

Floor

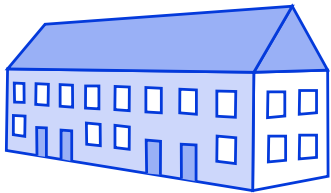
Window

Airtightness

# Simulation model



## Dwelling archetypes



WWR

Layout

Adjacency

Orientation

## Household profiles

Single Parent

Senior couple

Adult couple

Nuclear family

## Zone programs

Bedrooms

Living room

Kitchen

Bathroom

Corridor space

## Envelope Parameters

Facade

Pitched Roof

Floor

Window

Airtightness

## Ventilation systems

Natural Ventilation

Mechanical exhaust

Mechanical exhaust CO2 controlled

Balanced ventilation

## Radiator capacities

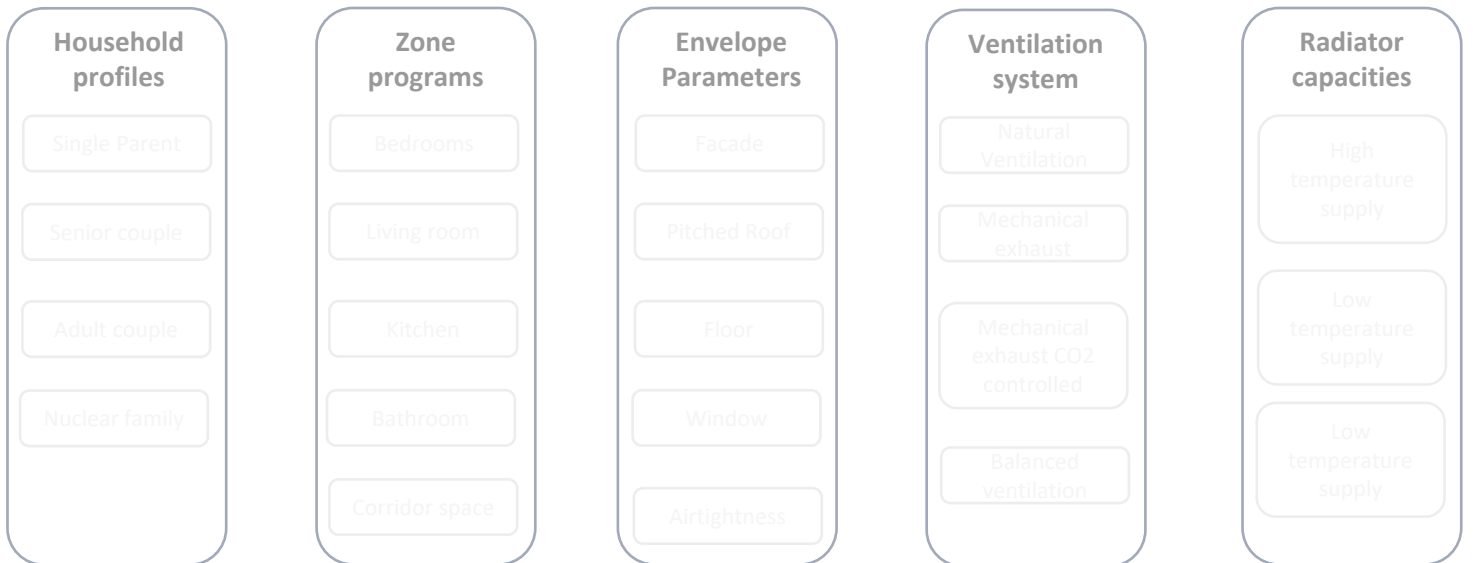
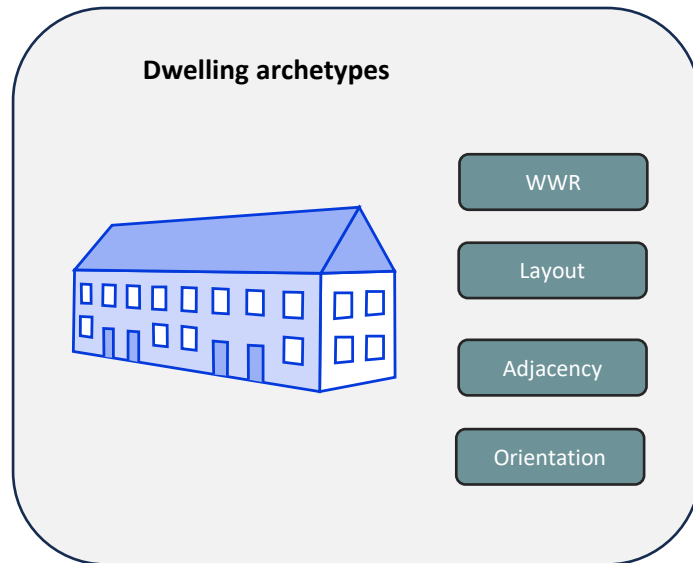
High temperature supply

Low temperature supply

Low temperature supply

# Simulation model

Dwelling archetype



# Dwelling archetype

## Geometry Parameters



### Terraced



### Semi - Detached



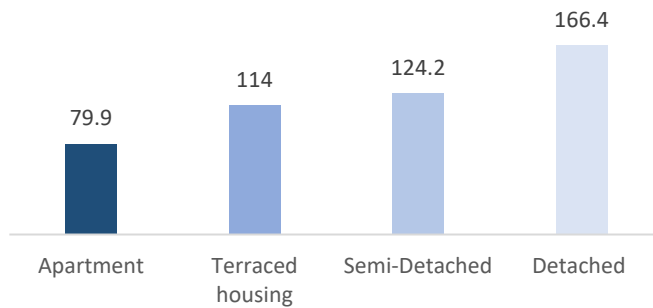
### Detached



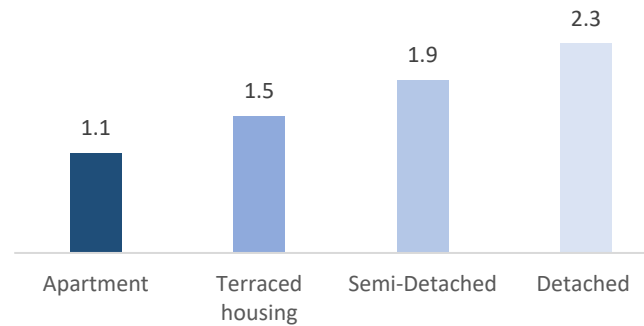
### Portiek apartment



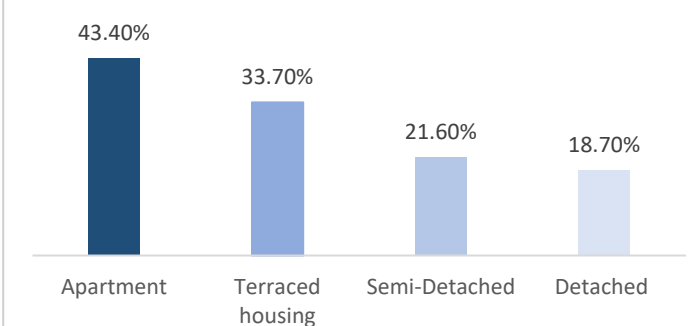
#### Average Floor area



#### Average Compactness ratio



#### Average Window to Wall Ratio



# Dwelling archetype

## Geometry Parameters



### Terraced



### Semi - Detached



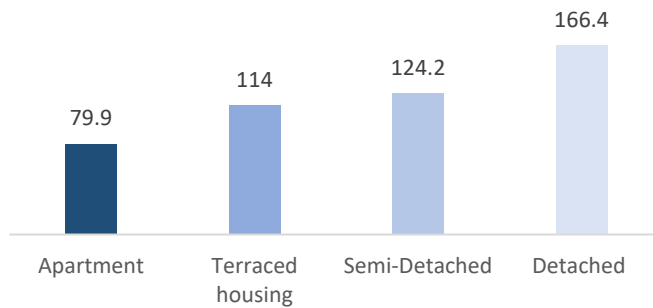
### Detached



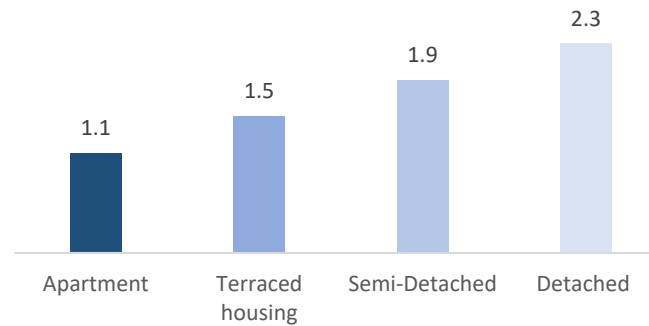
### Portiek apartment



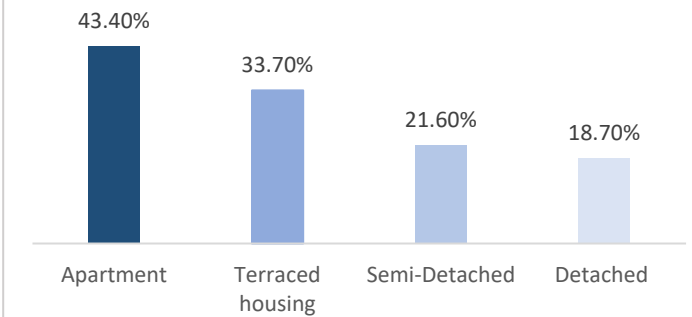
### Average Floor area



### Average Compactness ratio



### Average Window to Wall Ratio





# Dwelling archetype

## Geometry Parameters



**Terraced**



**Semi - Detached**



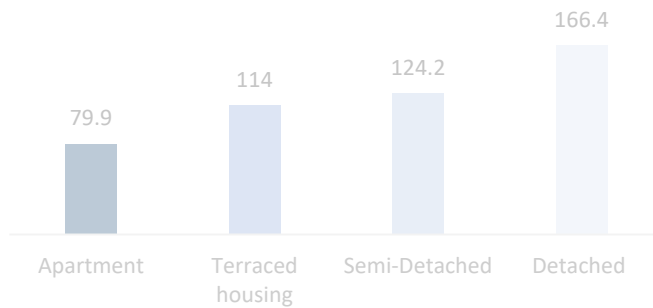
**Dethatched**



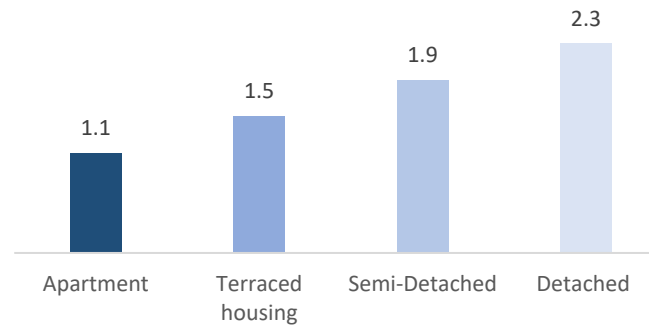
**Portiek apartment**



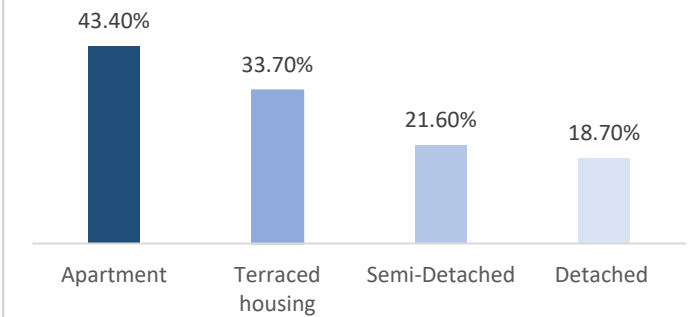
**Average Floor area**



**Average Compactness ratio**

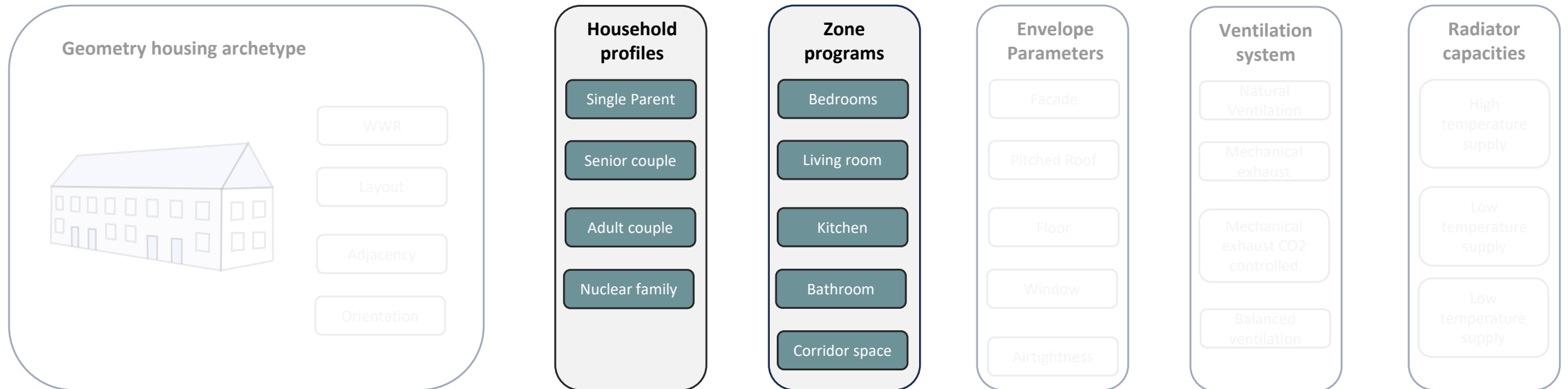


**Average Window to Wall Ratio**



# Simulation model

## Profiles and Program





# Occupancy behaviour

Household type and profiles



Occupancy behaviour parameters

Household profiles

	Presence	Temperature	Setback	Radiators bedroom	Radiators, others
<b>1 senior</b>	More	Warm	Wasteful	Semi-open	Semi-open
<b>1 adult</b>	Less	Cool	Setback	Semi-open	Closed
<b>3 adults</b>	Average	Average	Wasteful	Closed	Open
<b>2 adults</b>	Less	Average	Setback	Semi-open	Semi-open
<b>Single parent</b>	Average	Average	Setback	Open	Closed
<b>2 seniors</b>	More	Warm	Setback	Semi-open	Open
<b>Nuclear family</b>	More	Average	Wasteful	Open	Semi-open
<b>High behavior</b>	Average	Warm	Wasteful	Open	Open
<b>Low behavior</b>	Average	Low	Setback	Close	Close

# Pre-refurbishment Occupancy behaviour

Household type and profiles



	Presence	Temperature	Setback	Radiators bedroom	Radiators, others
1 senior	More	Warm	Wasteful	Semi-open	Semi-open
1 adult	Less	Cool	Setback	Semi-open	Closed
3 adults	Average	Average	Wasteful	Closed	Open
2 adults	Less	Average	Setback	Semi-open	Semi-open
Single parent	Average	Average	Setback	Open	Closed
2 seniors	More	Warm	Setback	Semi-open	Open
Nuclear family	More	Average	Wasteful	Open	Semi-open
High behavior	Average	Warm	Wasteful	Open	Open
Low behavior	Average	Low	Setback	Close	Close

# Post-refurbishment Occupancy behaviour

Household type and profiles



	Presence	Temperature	Setback	Radiators bedroom	Radiators, others
1 senior	More	Warm	Wasteful	Semi-open	Semi-open
1 adult	Less	Cool	Setback	Semi-open	Closed
3 adults	Average	Average	Wasteful	Closed	Open
2 adults	Less	Average	Setback	Semi-open	Semi-open
Single parent	Average	Average	Setback	Open	Closed
2 seniors	More	Warm	Setback	Semi-open	Open
Nuclear family	More	Average	Wasteful	Open	Semi-open
High behavior	Average	Warm	Wasteful	Open	Open
Low behavior	Average	Low	Setback	Close	Close

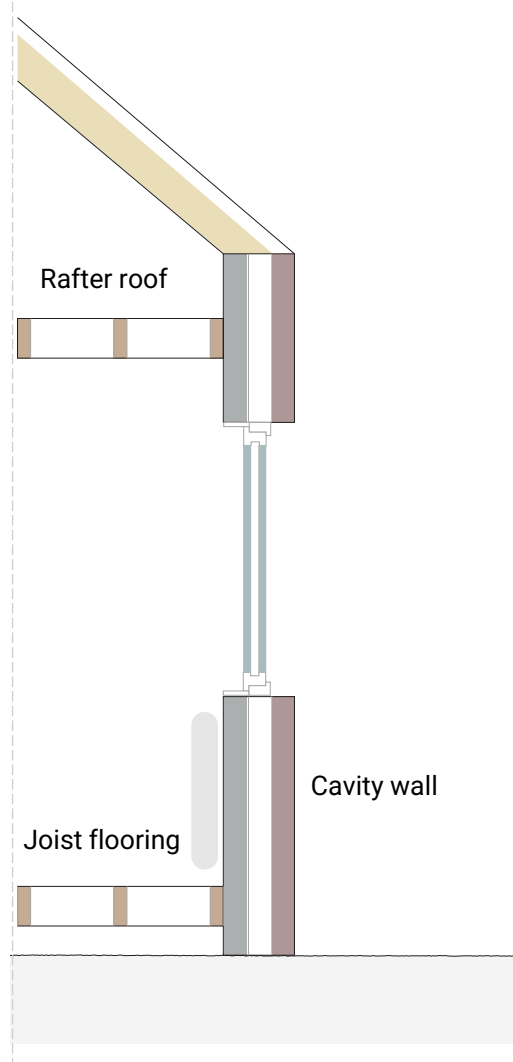
# Simulation model

## Envelope parameters

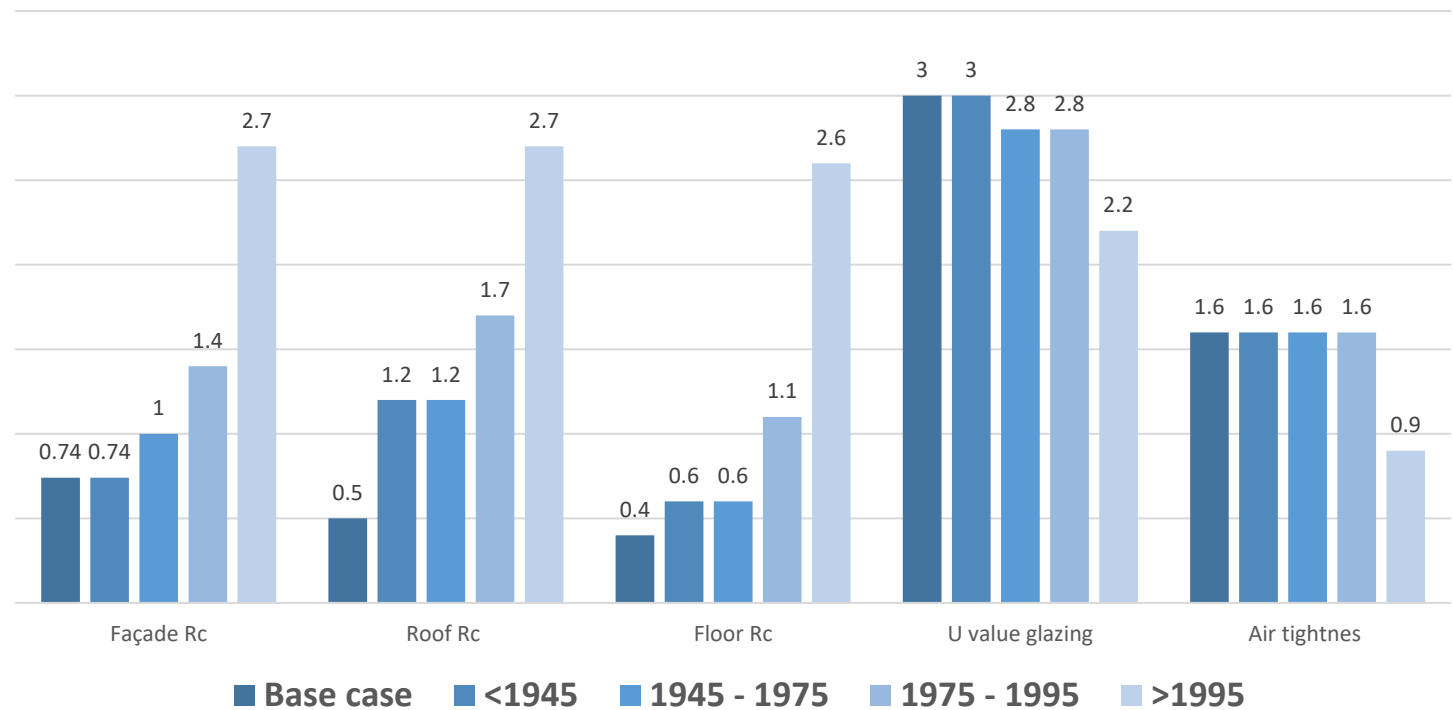


# Envelope parameter

Base construction and construction year envelope thermal resistance

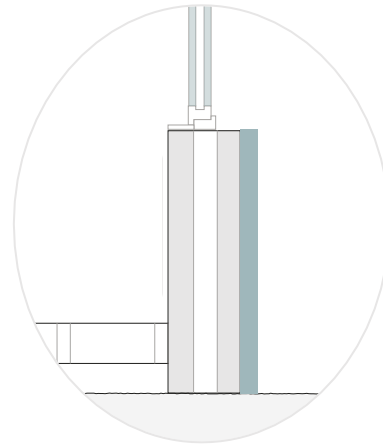
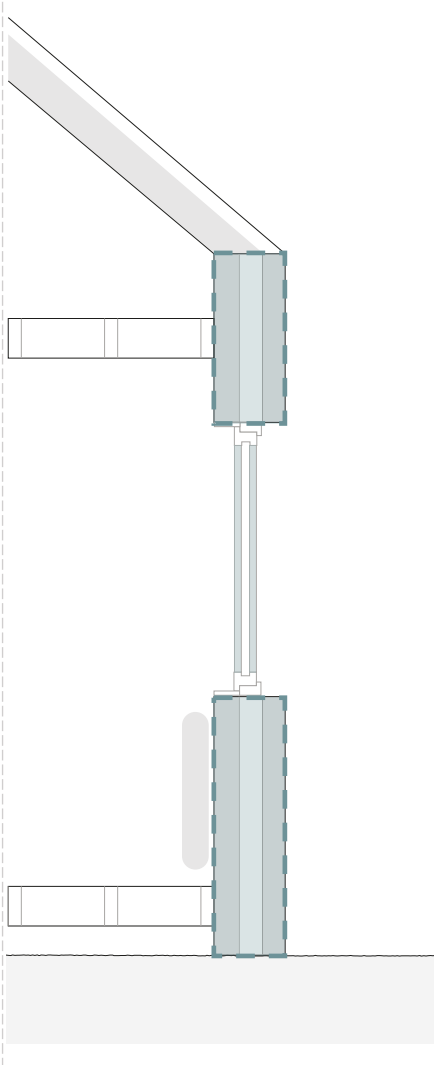


## Envelope thermal performance across construction years

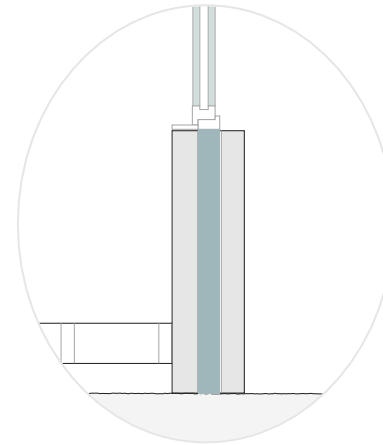


# Envelope parameter

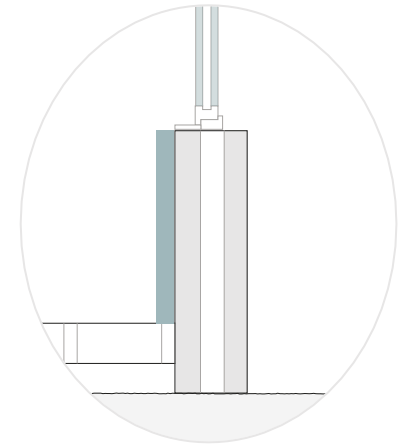
Wall



**External**



**Cavity**

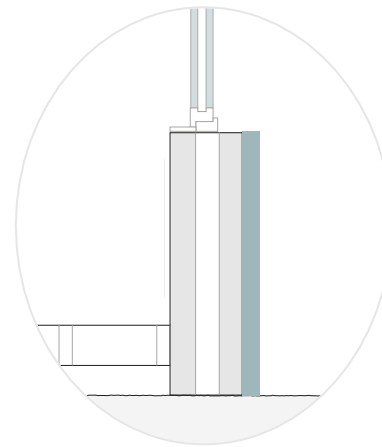
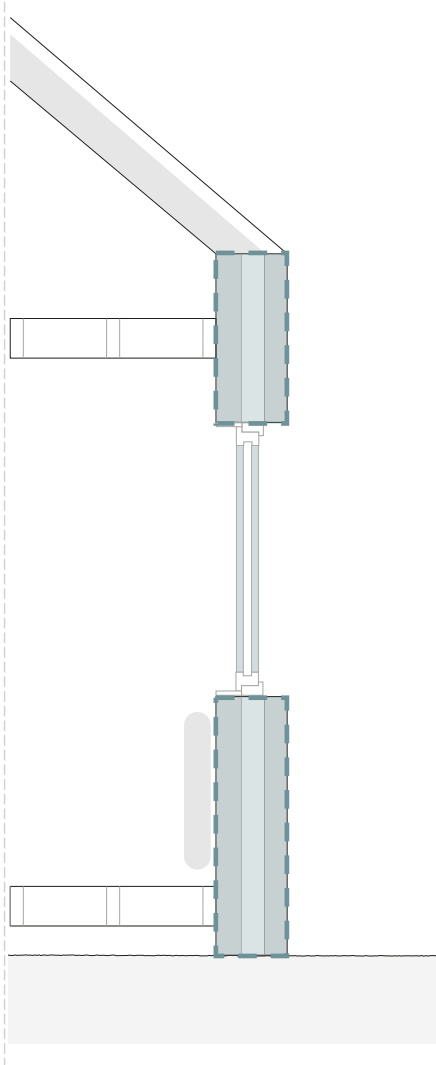


**Internal**

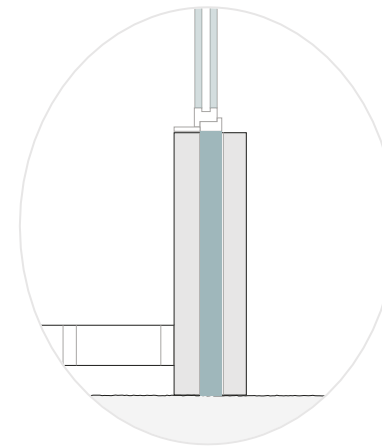


# Envelope parameter

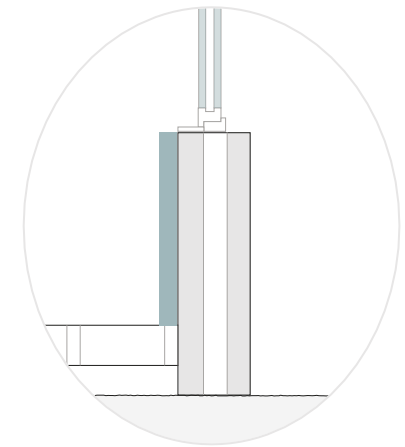
## Wall



**External**



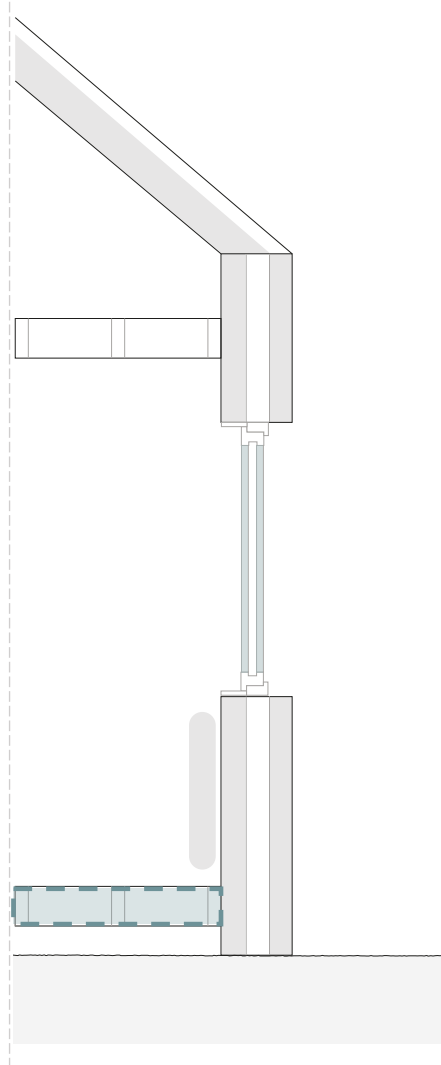
**Cavity**



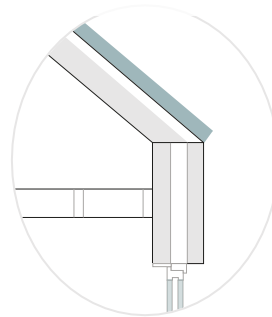
**Internal**

Range	0 – 5.0			0 – 2.0		0 – 4.0		
Step- size	0.5			0.5		0.5		
Rc	3.5	4.5	5.0	1.5	2.0	1.5	2.5	4
Cost/m2	122.5	126.2	128.3	22.8	26.1	67.7	74.7	80.4

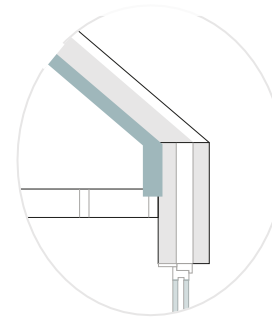
# Envelope parameter



**Roof**

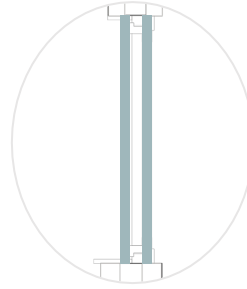


External

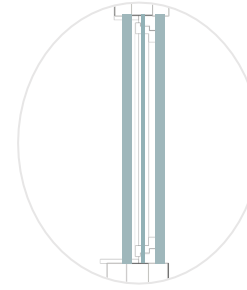


Internal

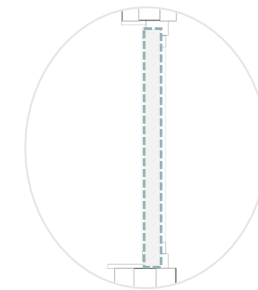
**Window**



HR++

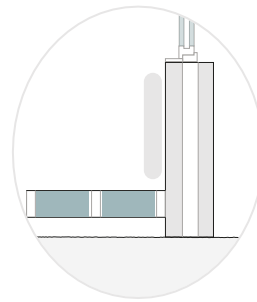


Triple

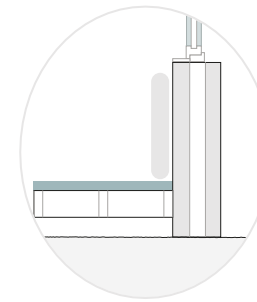


Airtightness

**Floor**



Underfloor

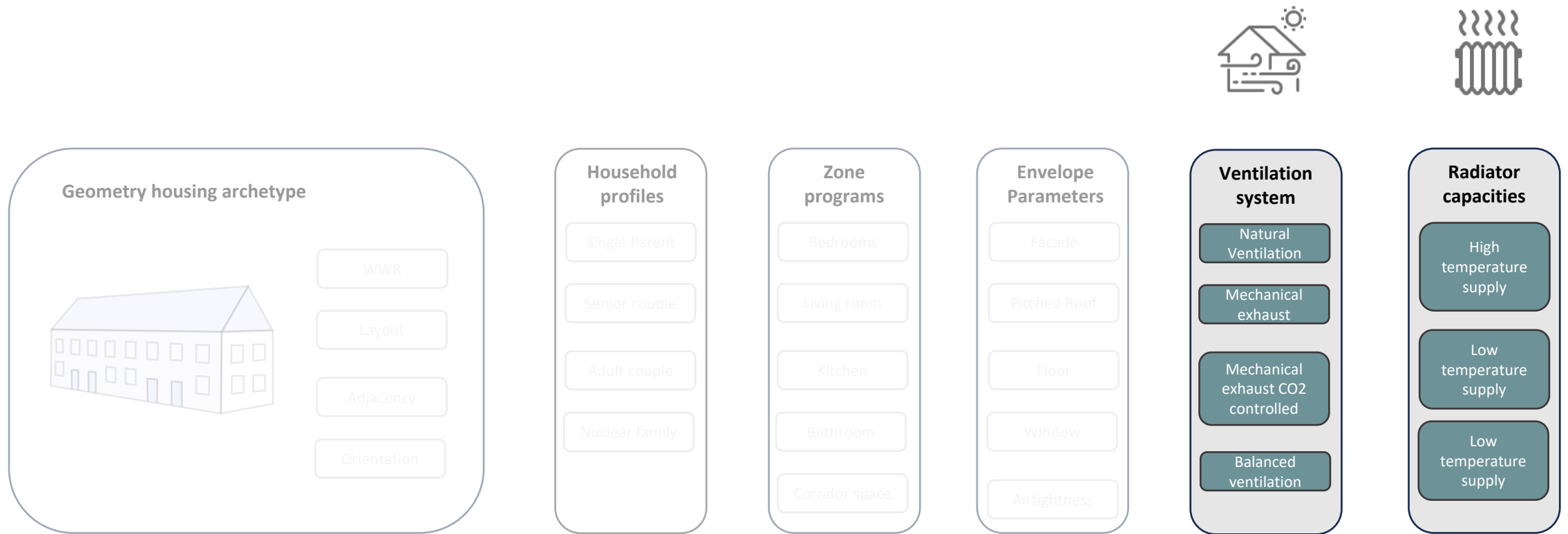


Floor top

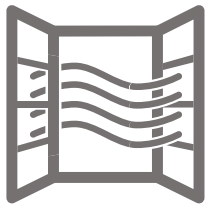


# Simulation model

## Building installations



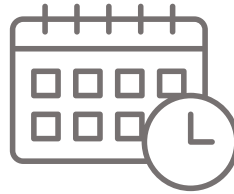
# Ventilation types



Window  
opening %



Ventilation  
rate



Operation  
schedule

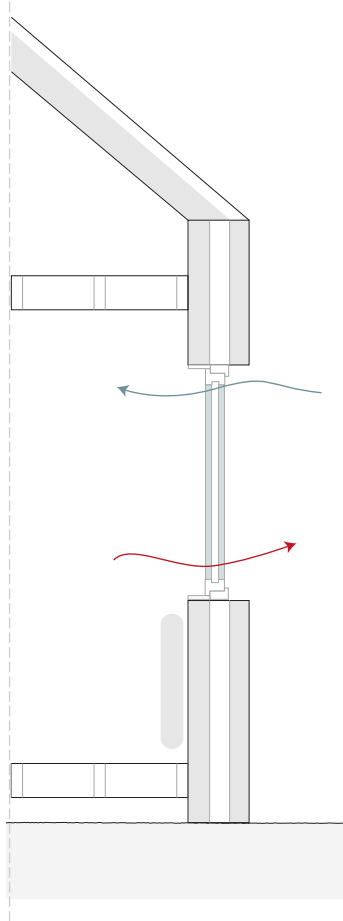


Setpoint  
temperature

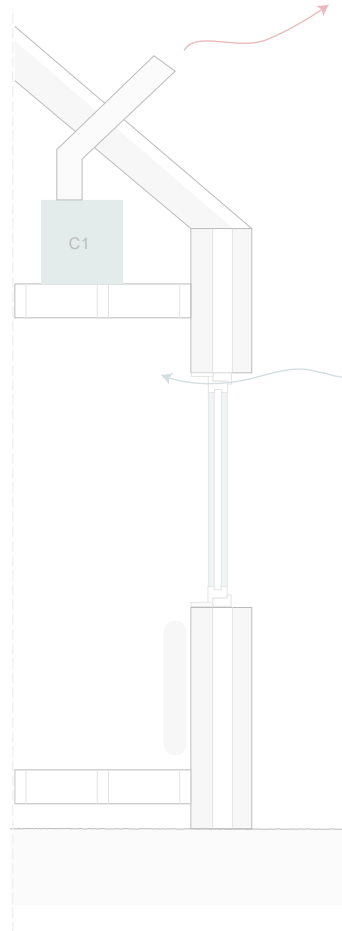


Heat-  
recovery

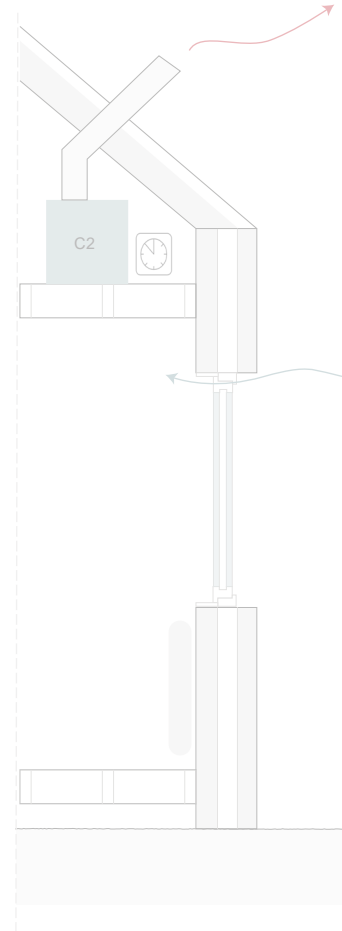
# Ventilation types



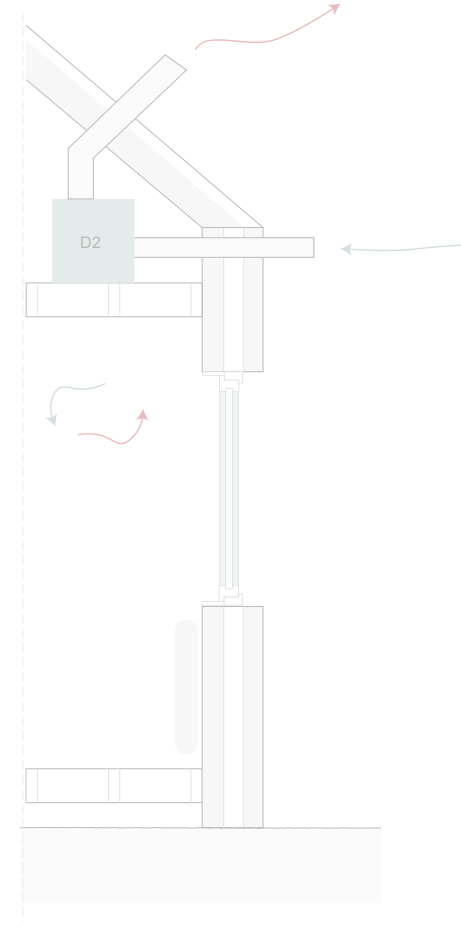
Natural  
ventilation



Mechanical  
exhaust

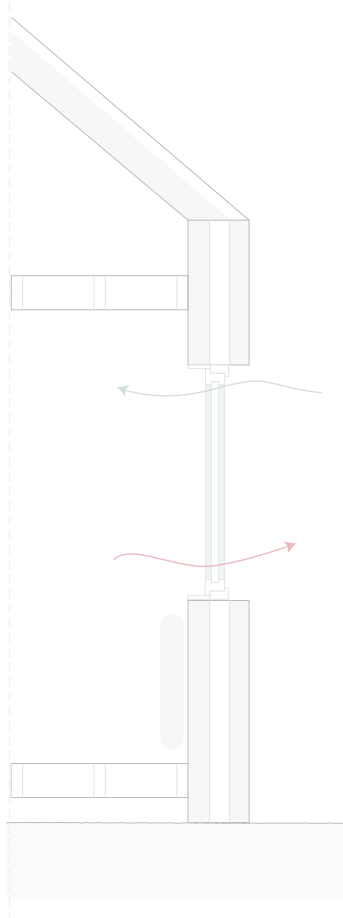


Mechanical  
exhaust +  
CO2 control

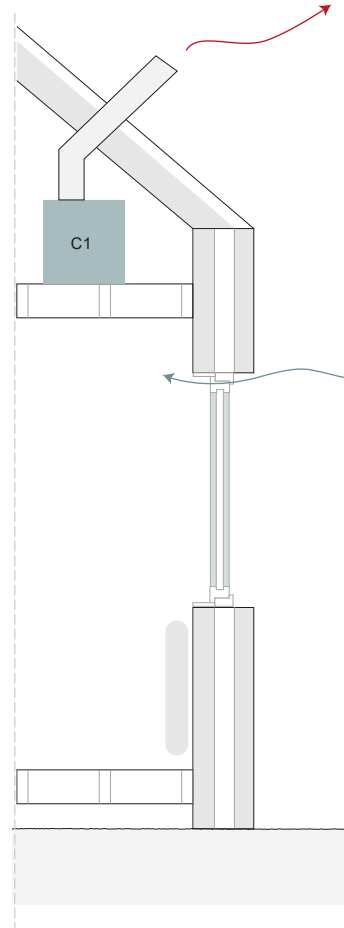


Balanced  
ventilation

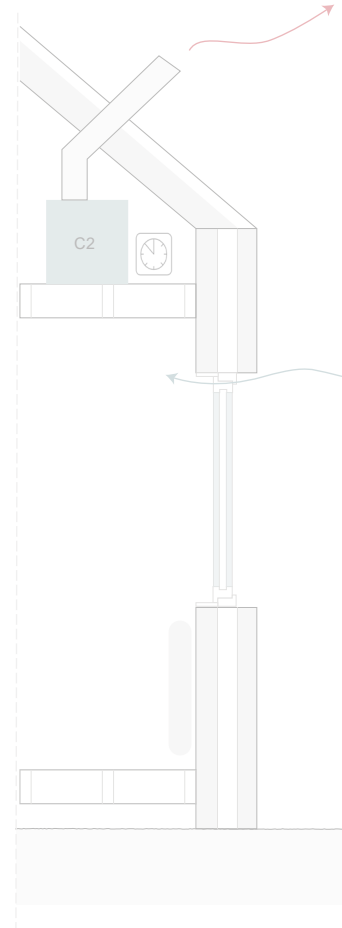
# Ventilation types



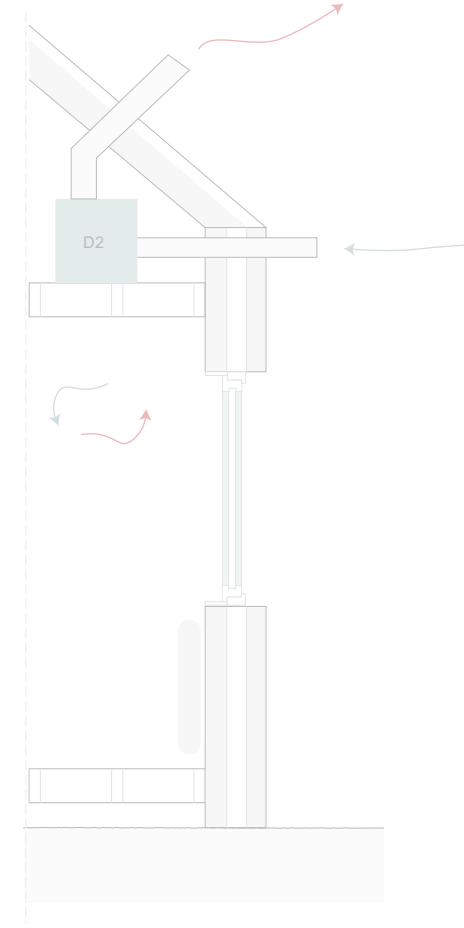
Natural  
ventilation



Mechanical  
exhaust

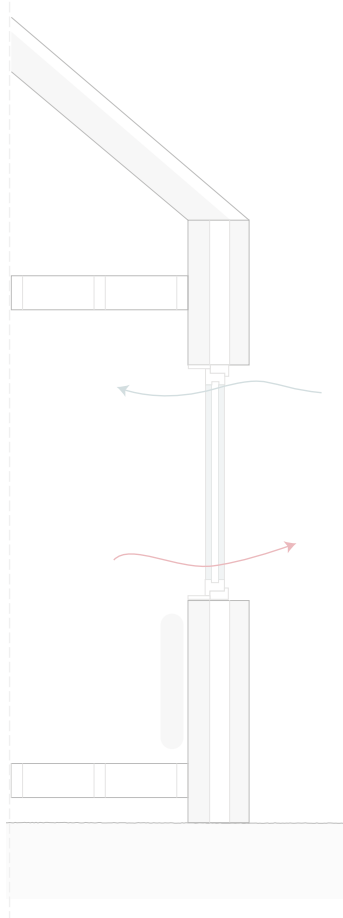


Mechanical  
exhaust +  
CO2 control

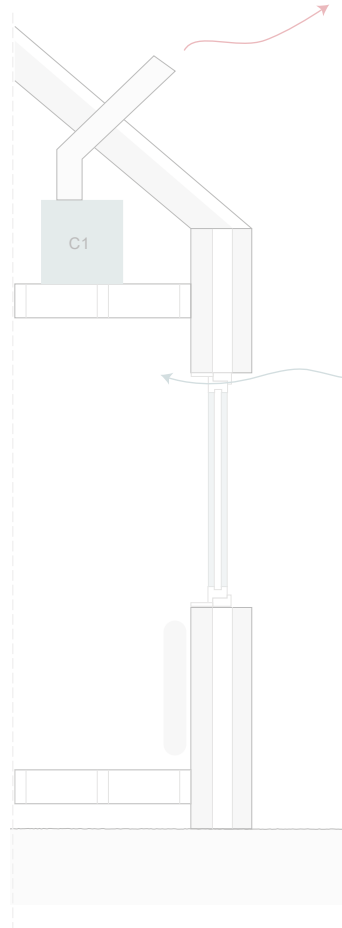


Balanced  
ventilation

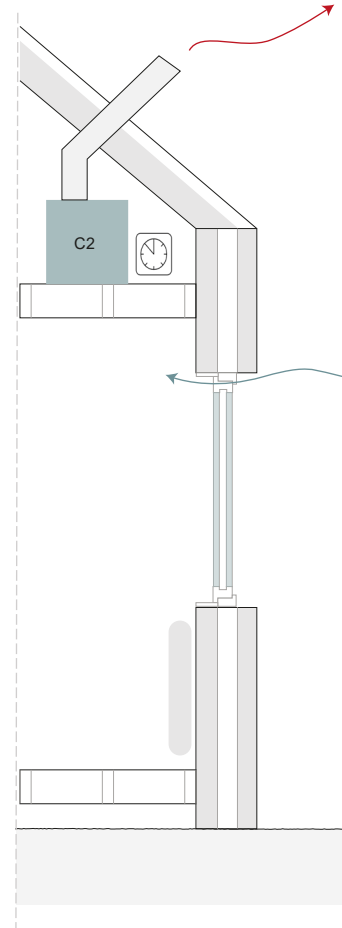
# Ventilation types



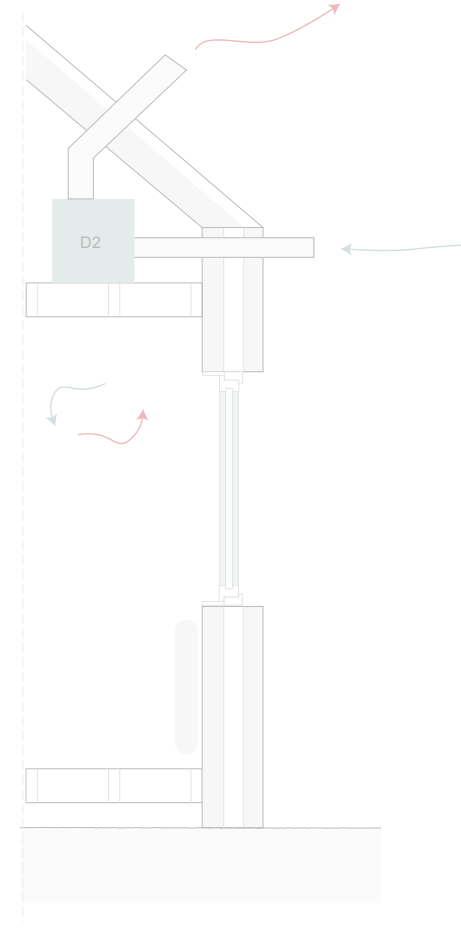
Natural  
ventilation



Mechanical  
exhaust

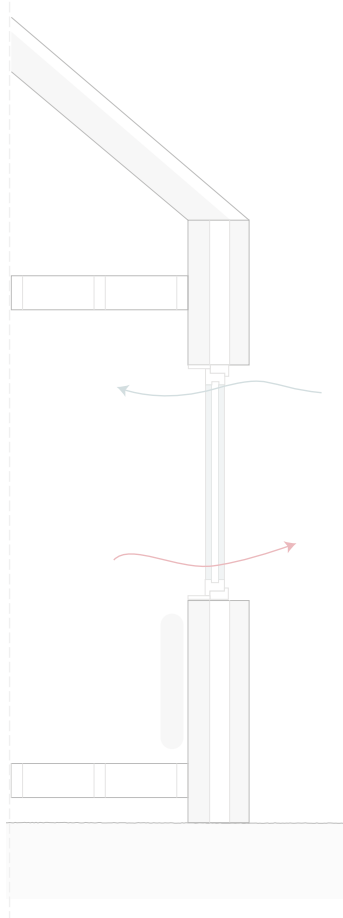


Mechanical  
exhaust +  
CO2 control

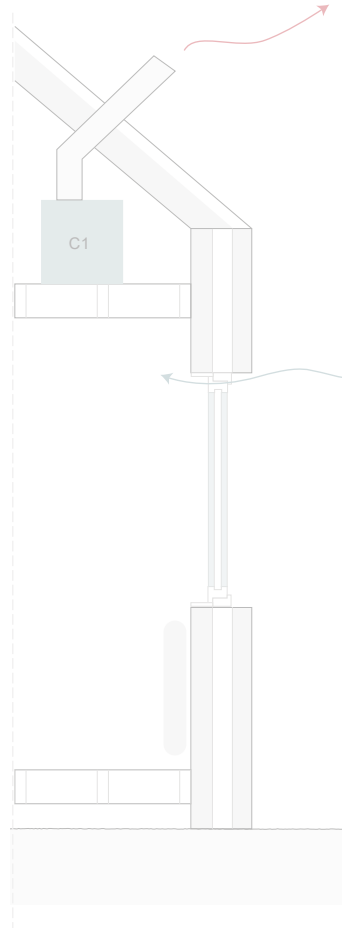


Balanced  
ventilation

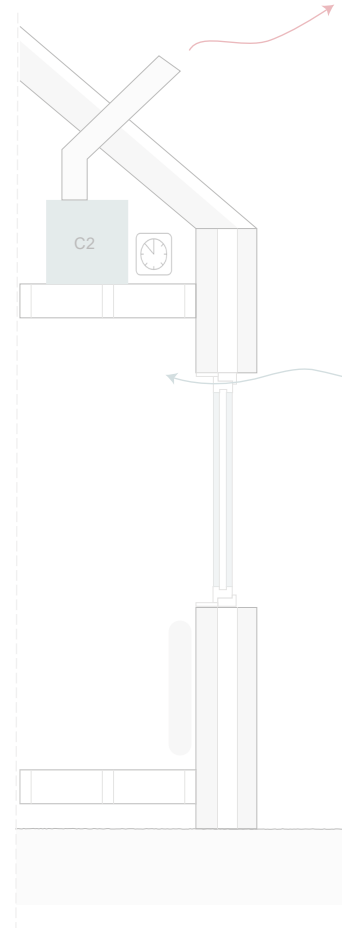
# Ventilation types



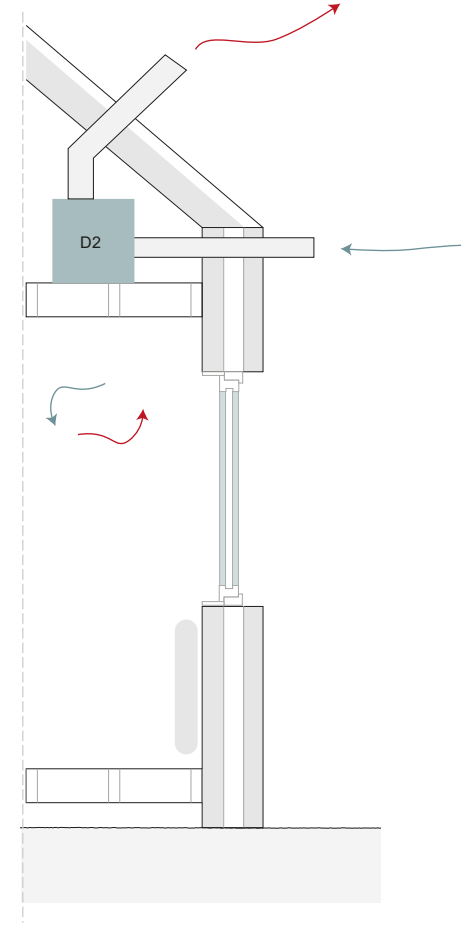
Natural  
ventilation



Mechanical  
exhaust

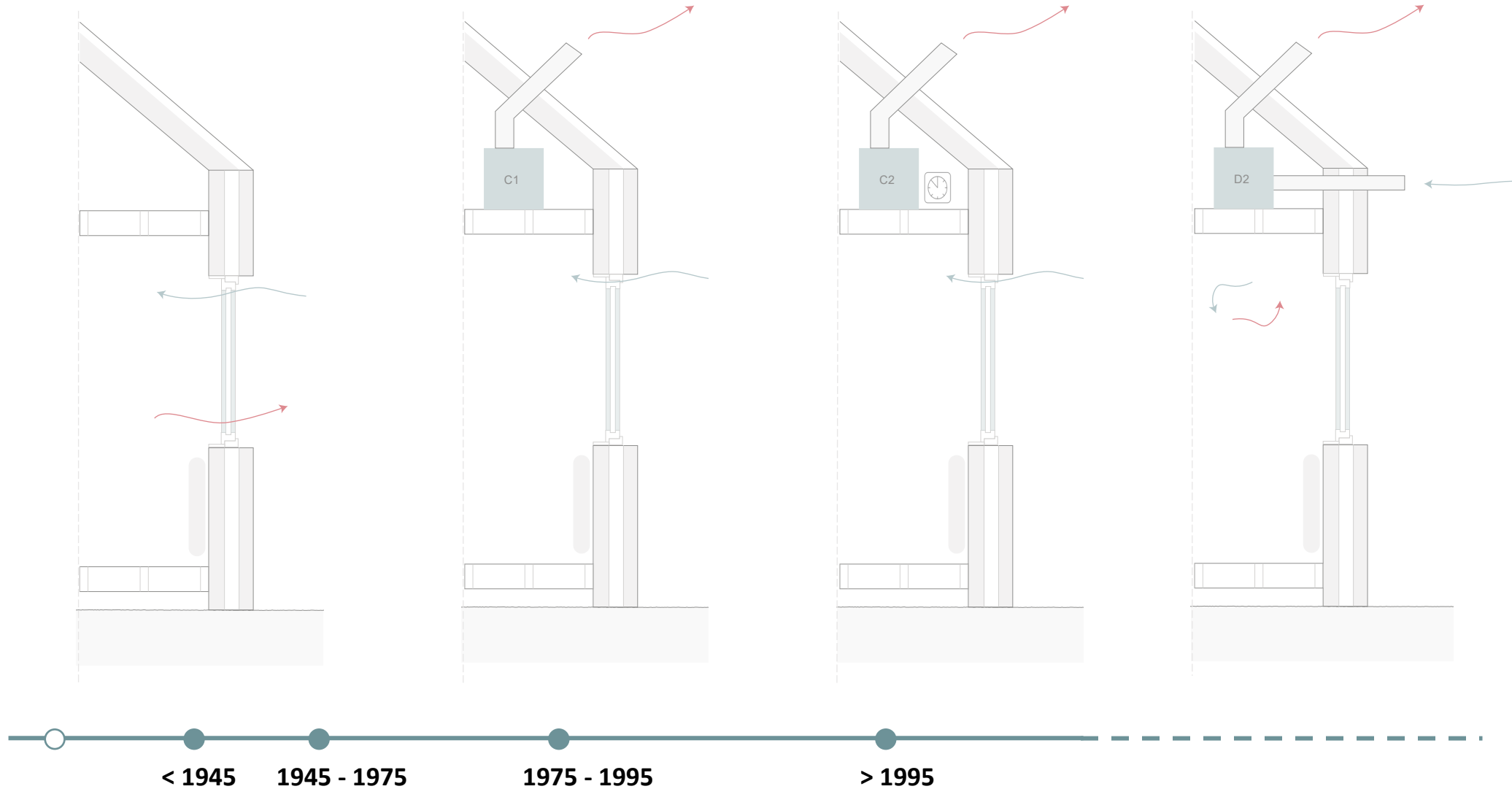


Mechanical  
exhaust +  
CO2 control



Balanced  
ventilation with  
heat recovery

# Ventilation types



# Radiator capacity

Living room



90/70 °C

ISSO 51 Radiator  
capacity sizing



55/45 °C

Low temperature  
supply radiator  
capacity



Low temperature  
comfort radiator  
capacity

Radiator capacity  
correlating with  
construction year

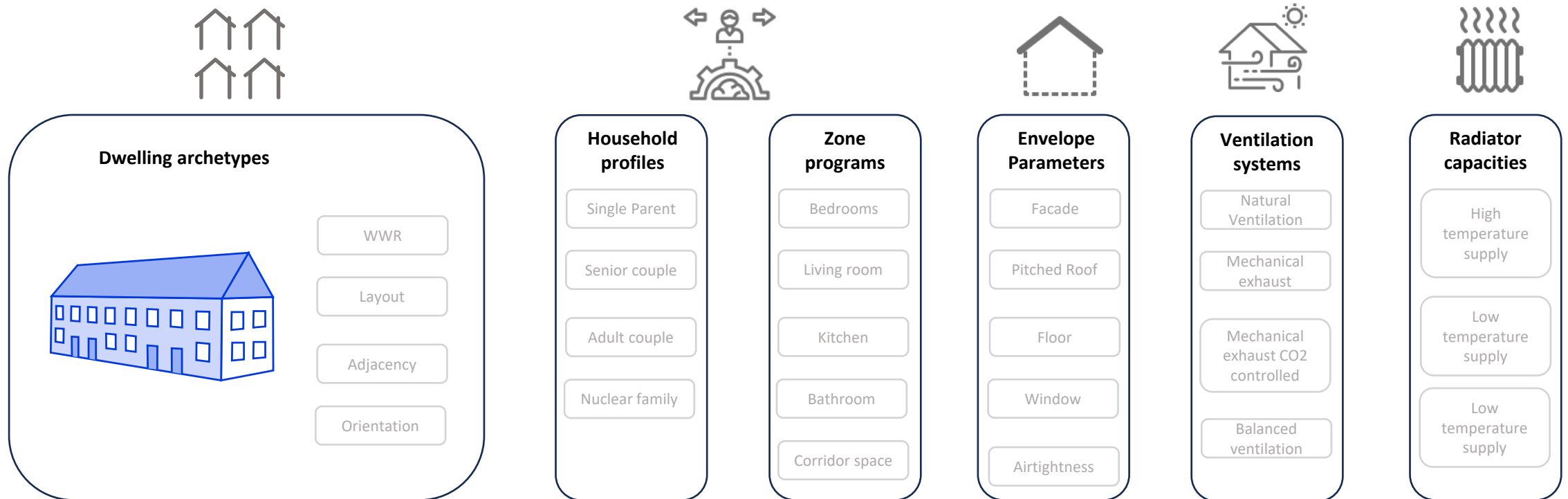
$$Q_{heat\ emitter} = \left( \frac{\Delta\theta\ lower\ supply}{\Delta\theta\ original\ supply} \right)^n \cdot \varphi_0$$

LT radiator factor **x 1.3**

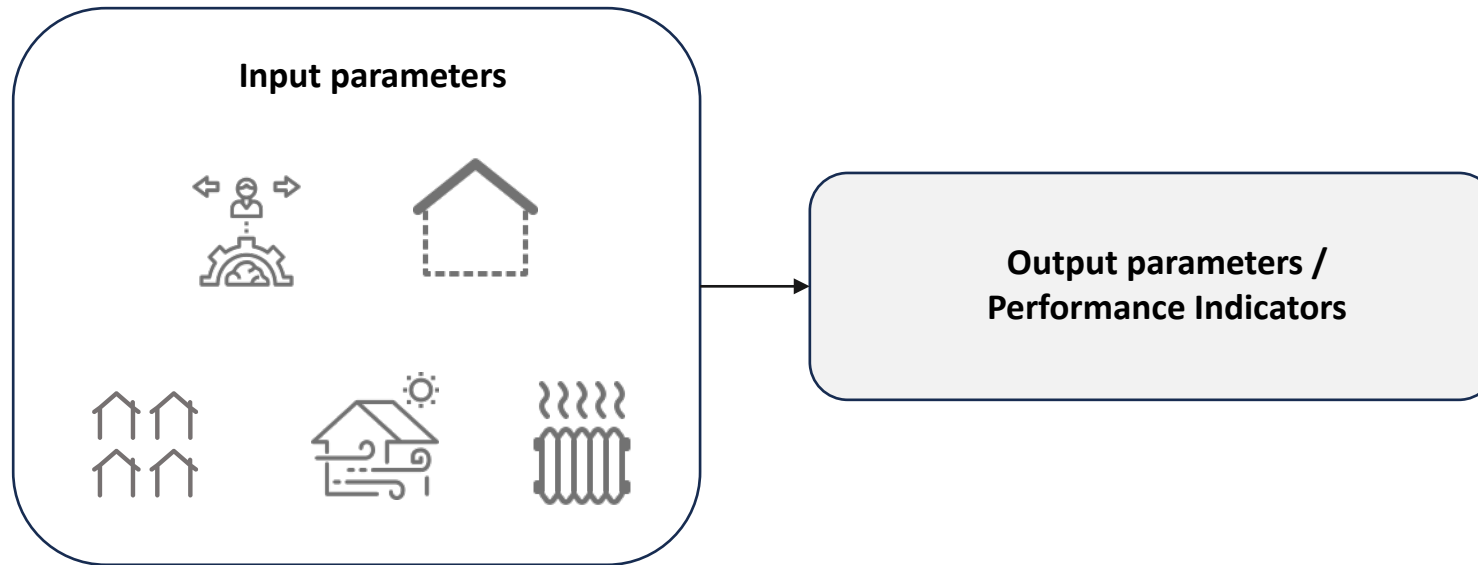


# Simulation model

## Final Input Parameters

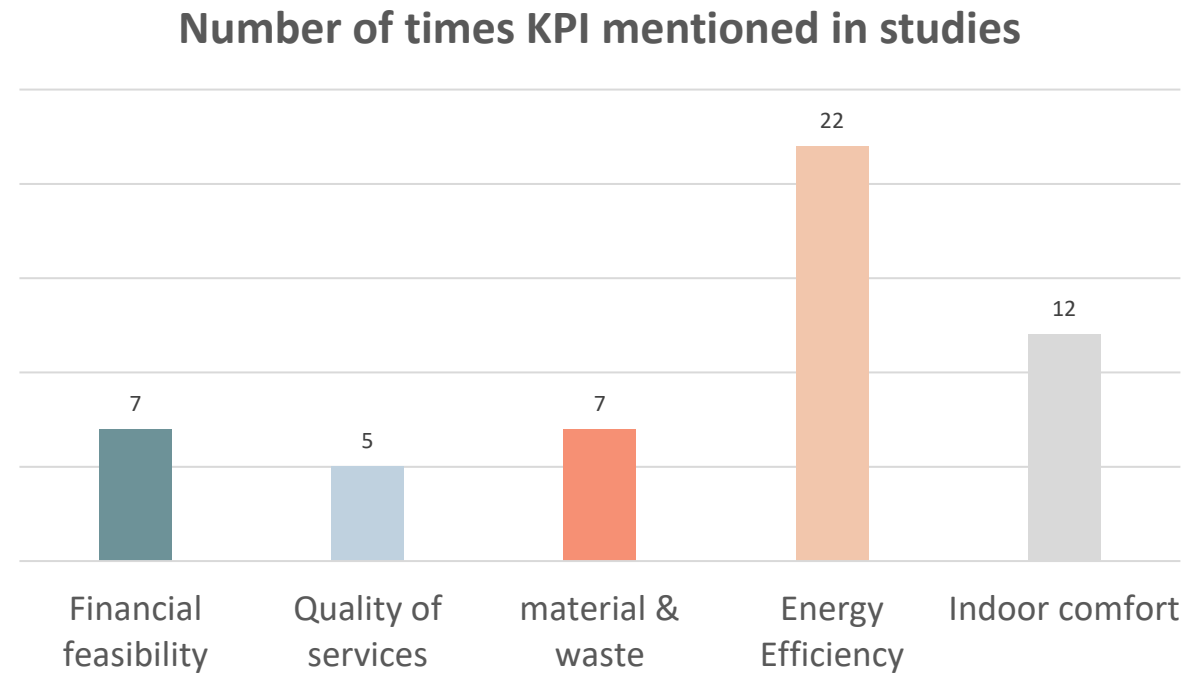


# Simulation model



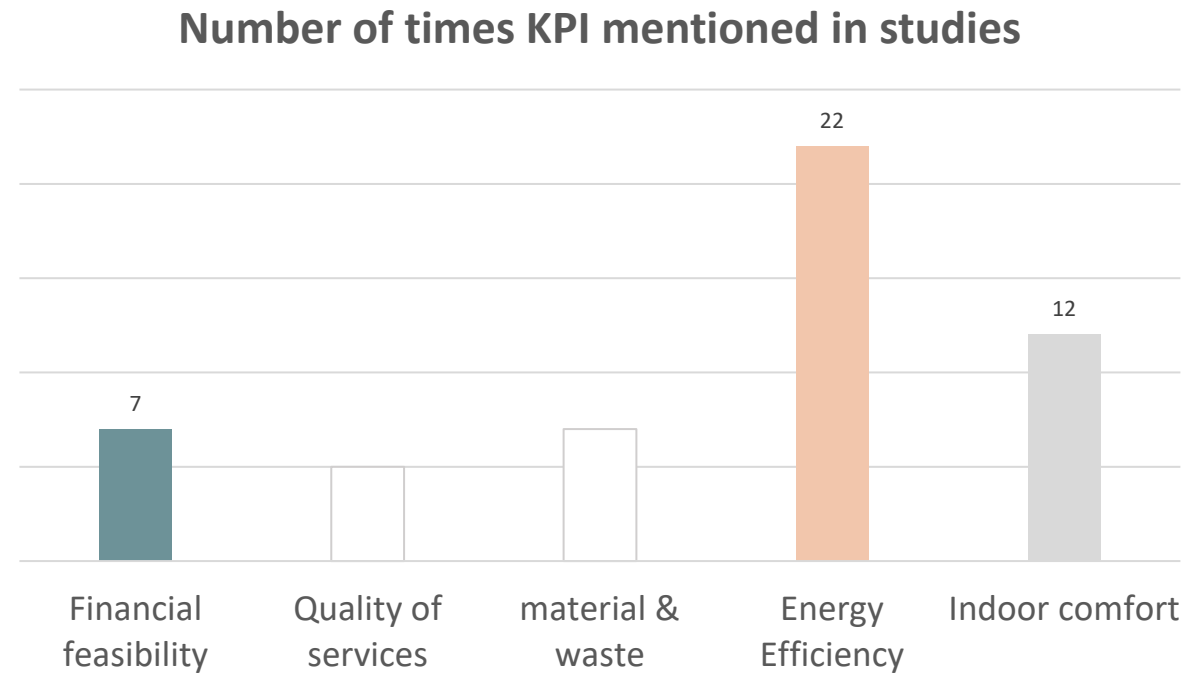
# Performance indicators

Prominently used indicators



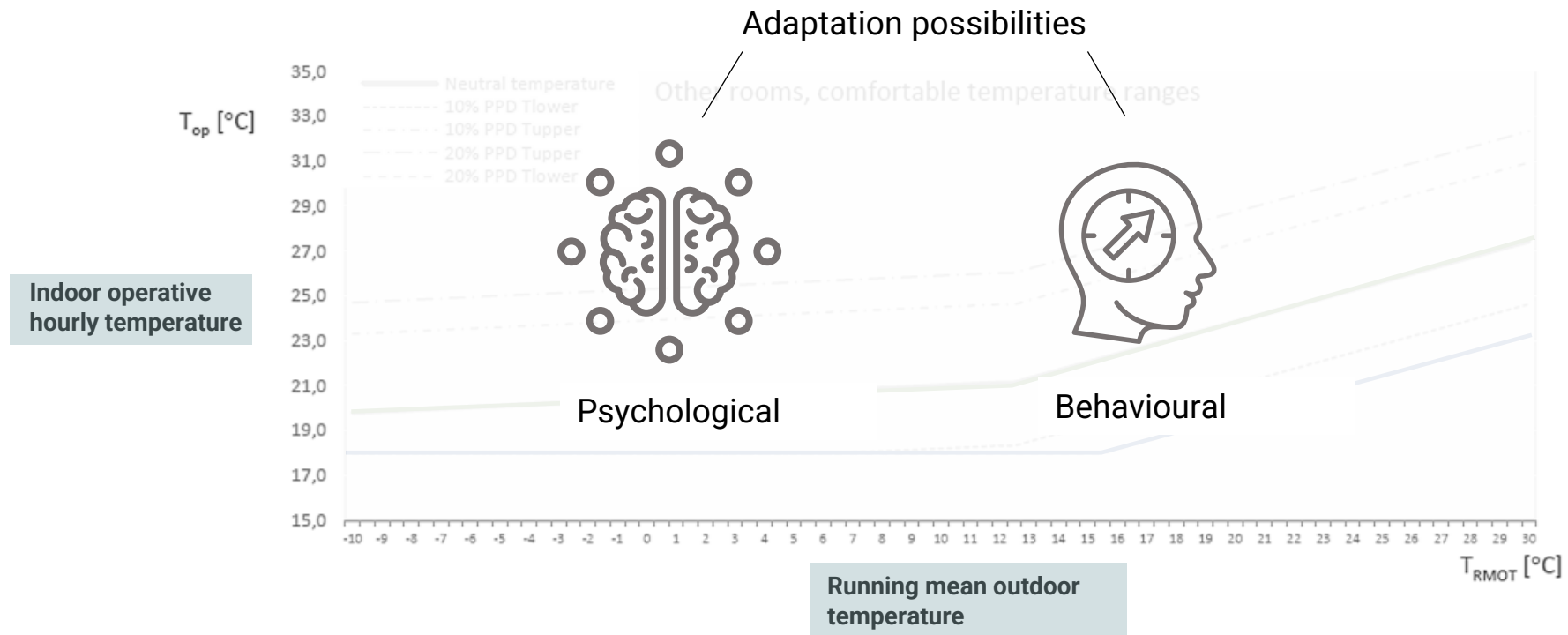
# Performance indicators

Prominently used indicators



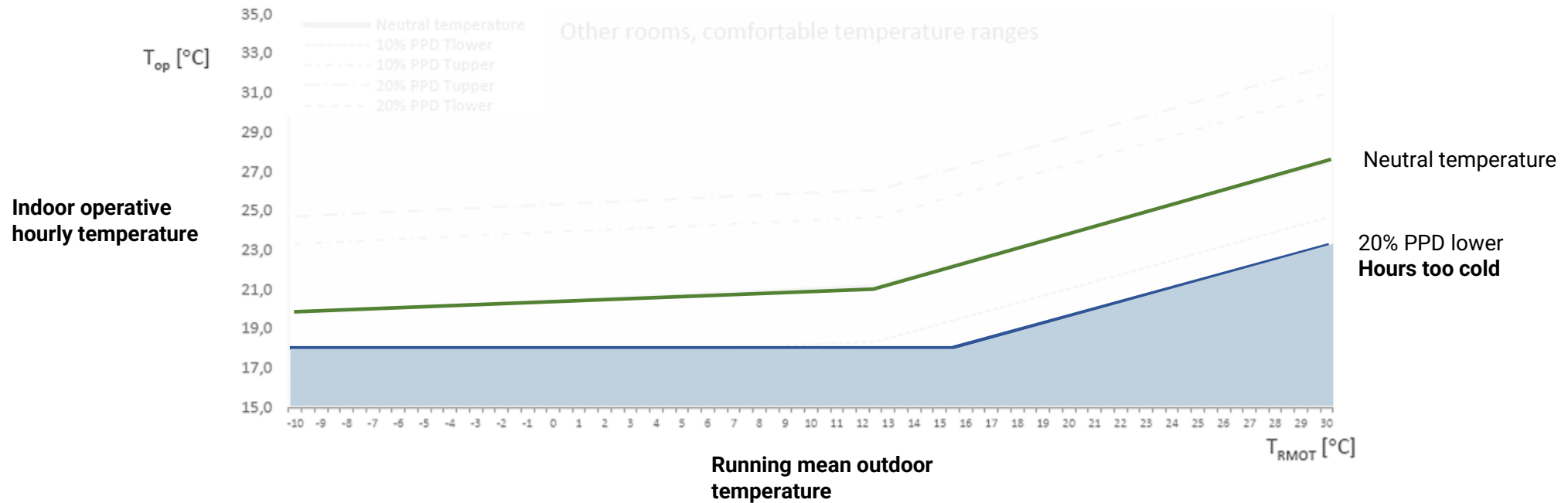
# Thermal comfort

## Adaptive thermal limit



# Thermal comfort

## Adaptive thermal limit

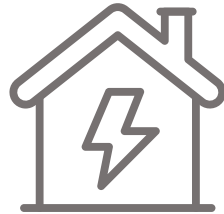


# Energy consumption

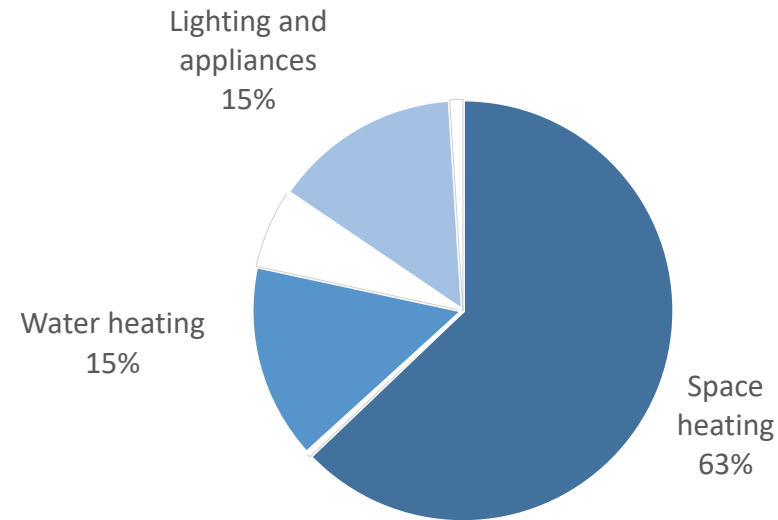
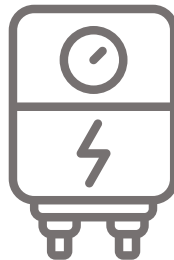
Total dwelling



Energy demand



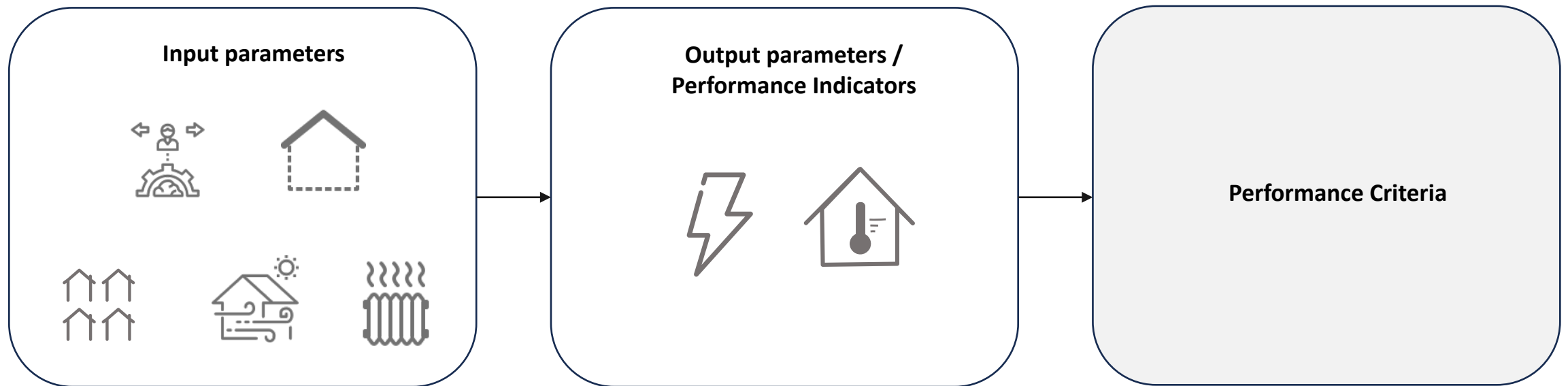
Final Input energy  
consumption :  
Operational energy



+

Equipment	COP
Gas boiler	0.85
Heat pumps	2.8
District heating (heat exchangers)	0.9

# Simulation model





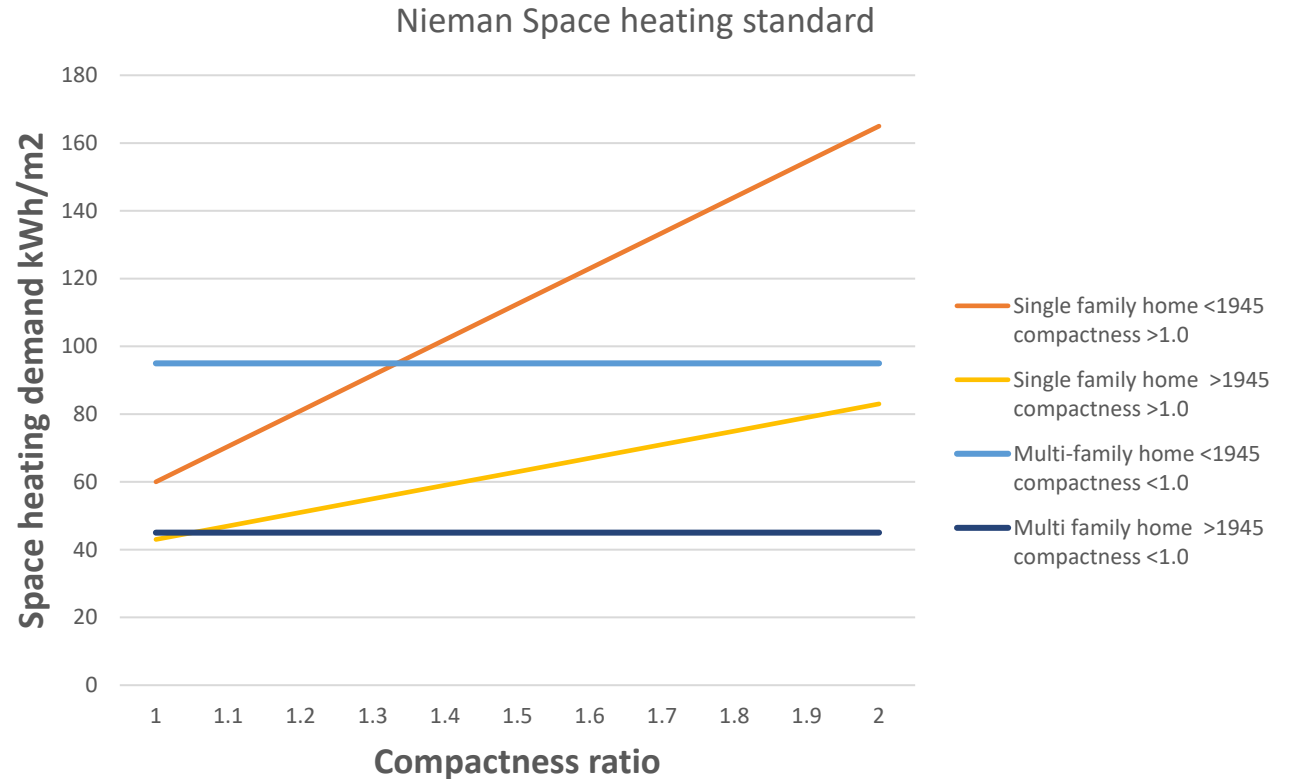
# Performance Criteria

## Space heating demand

### No regret refurbishment

Owner will no longer need to further modify refurbished components within the technical lifespan in anticipation of the transition to district heating.

- **Maximum Space heating limit**



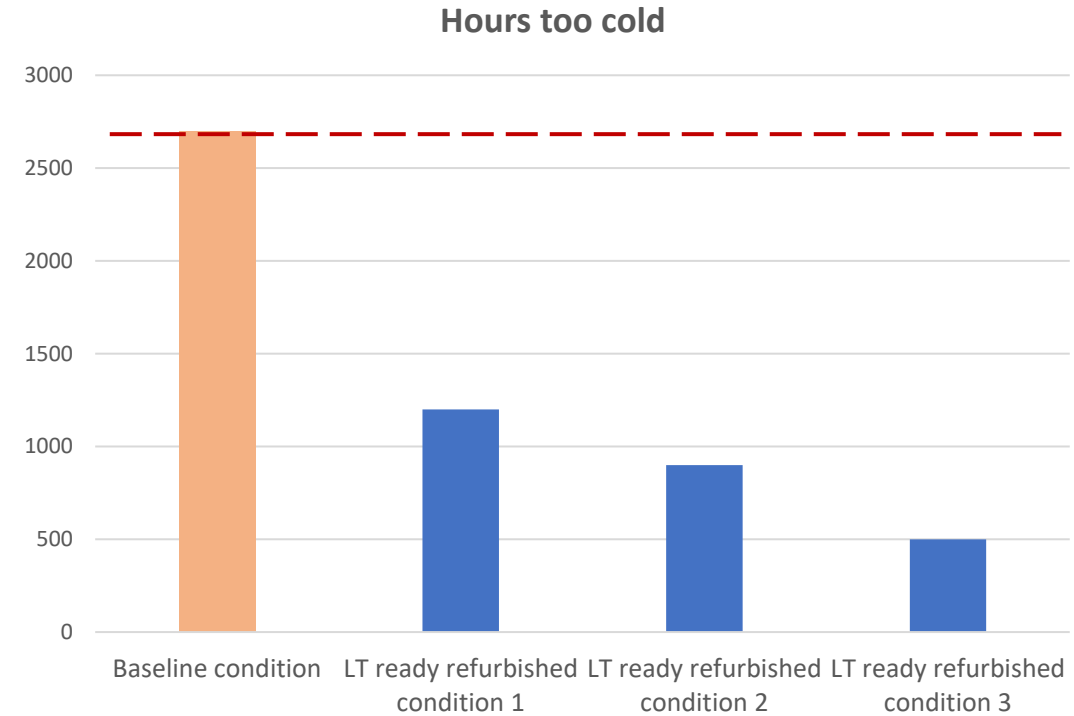
# Performance Criteria

## Thermal comfort

### No regret refurbishment

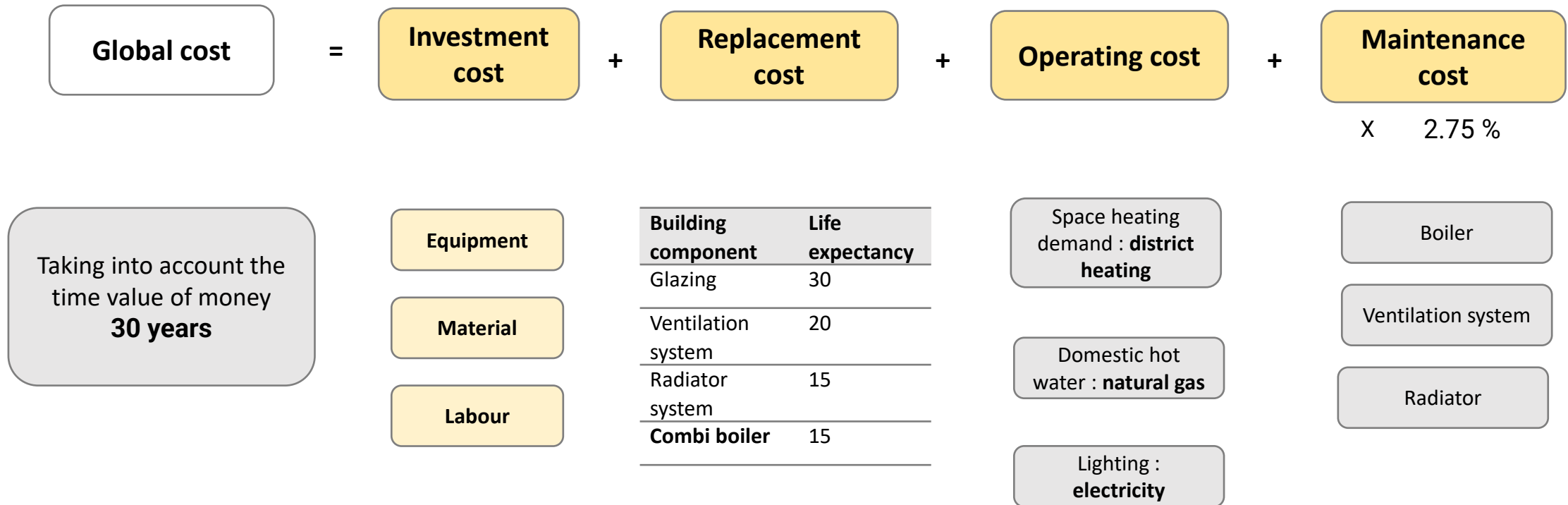
Owner will no longer need to further modify refurbished components within the technical lifespan in anticipation of the transition to district heating.

- **Maximum Space heating limit**
- **Maximum Hours too cold limit**



# Financial Feasibility

Global cost



# Recap

## Inputs



Envelope



Ventilation  
system



Occupancy  
behaviour



Radiator  
capacity



Housing  
typologies



Space heating  
demand



ATL thermal  
comfort



Global cost

# Recap



Envelope



Ventilation  
system



Occupancy  
behaviour



Radiator  
capacity



Housing  
typologies

## Outputs



Space heating  
demand



ATL thermal  
comfort



Global cost

**No regret refurbishment criteria**

**Feasibility**

# Recap



Envelope



Ventilation  
system



Occupancy  
behaviour



Radiator  
capacity



Housing  
typologies



Space heating  
demand

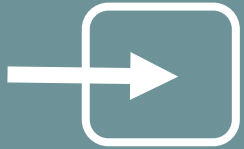


ATL thermal  
comfort



Global cost

# Recap



**13**

**Input variables**



**3**

**Output variables**



**2000**

**samples**

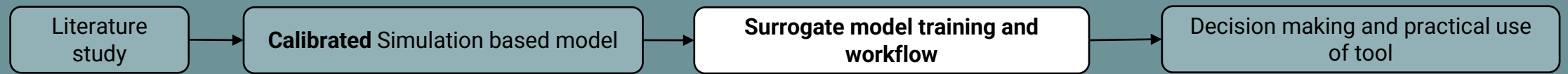
**Per housing  
archetype**



**20**

**hours**

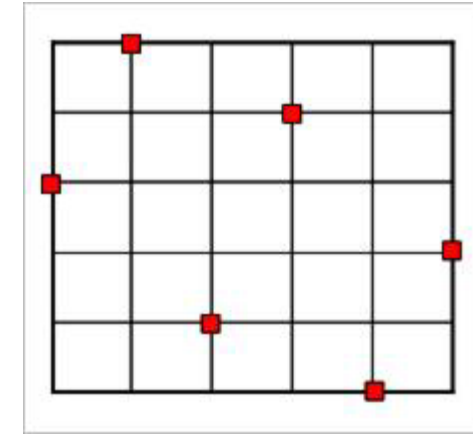
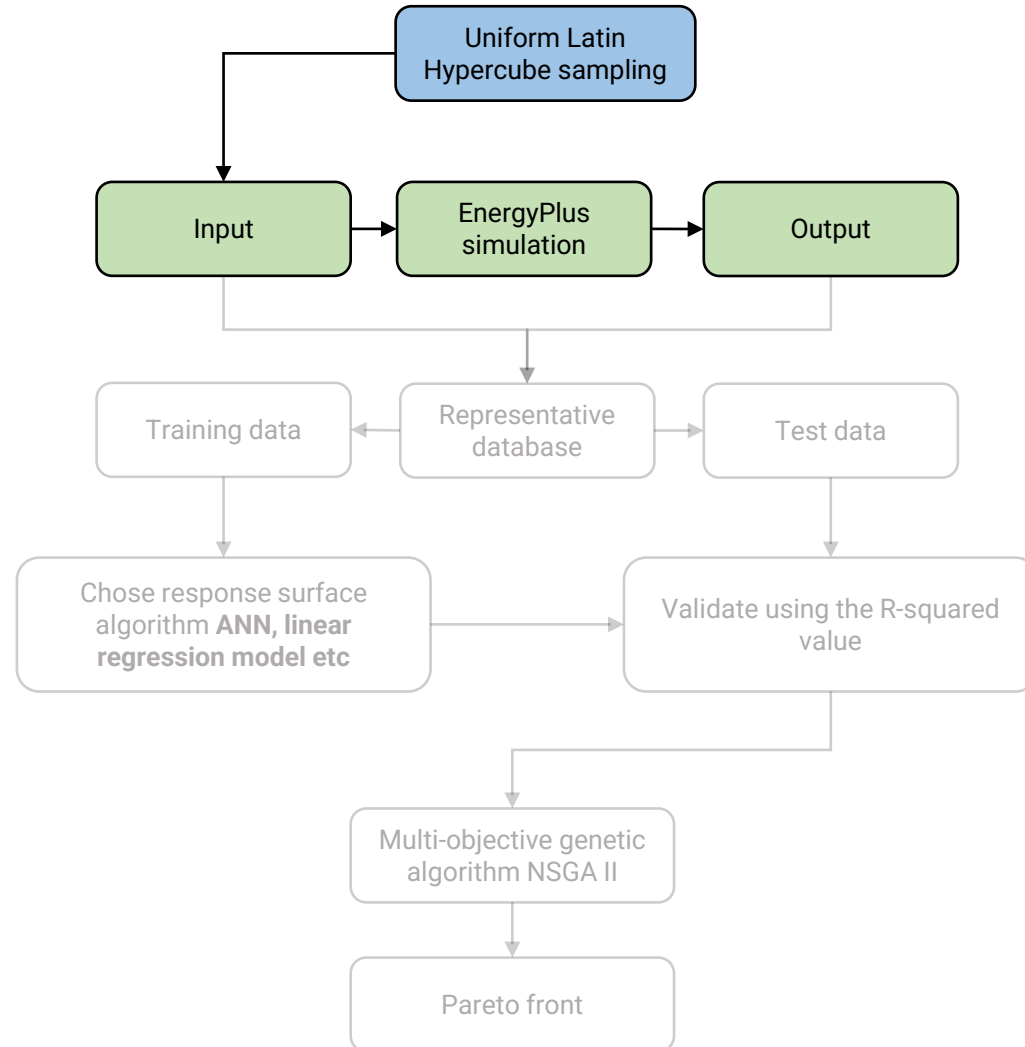
**Sample Simulation time  
per housing archetype**





# Surrogate model training

## Workflow

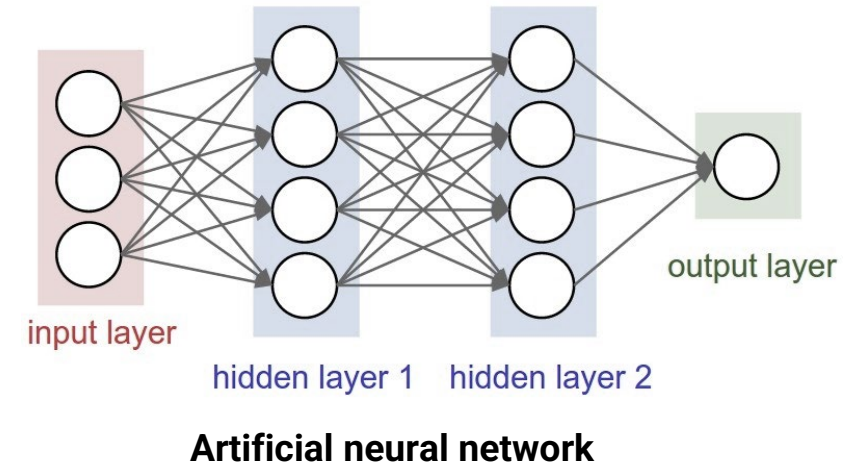
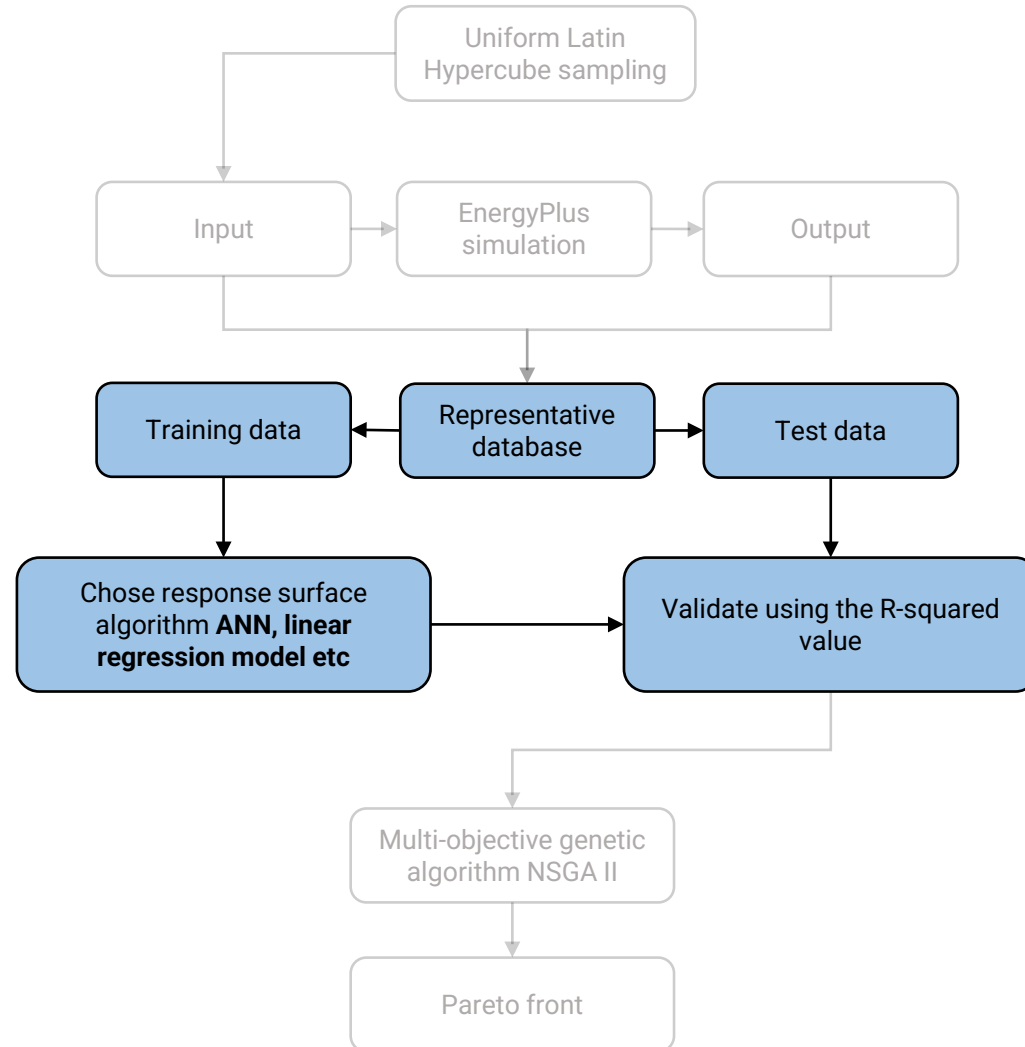


Uniform Latin Hypercube



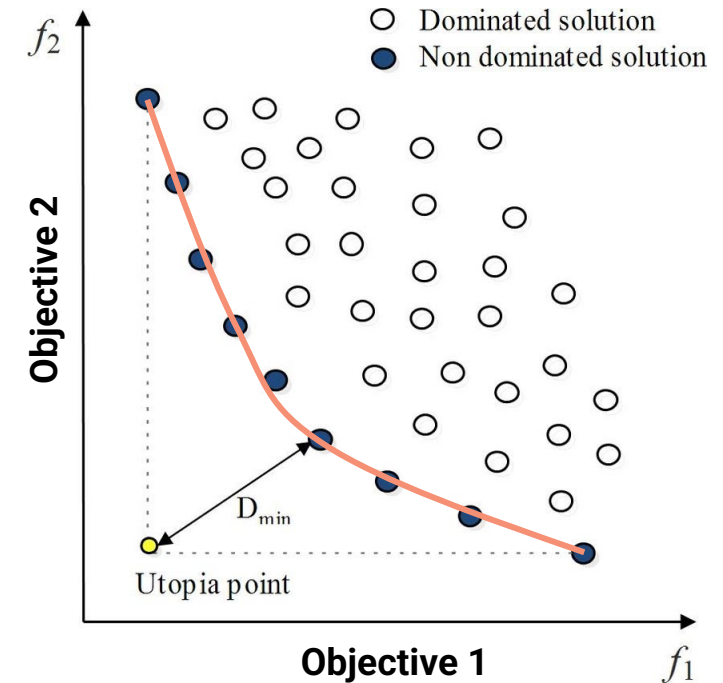
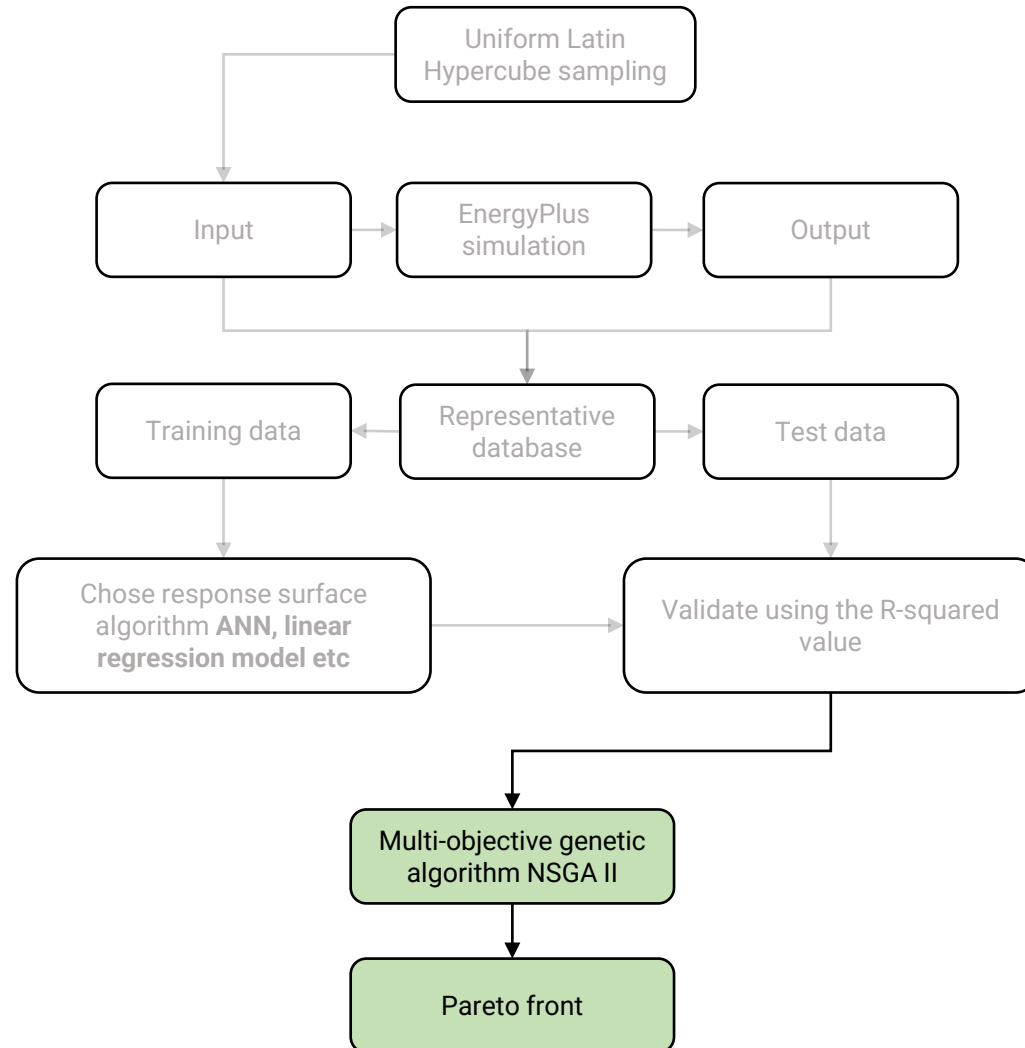
# Surrogate model training

## Workflow



# Surrogate model training

## Workflow



# Surrogate model training

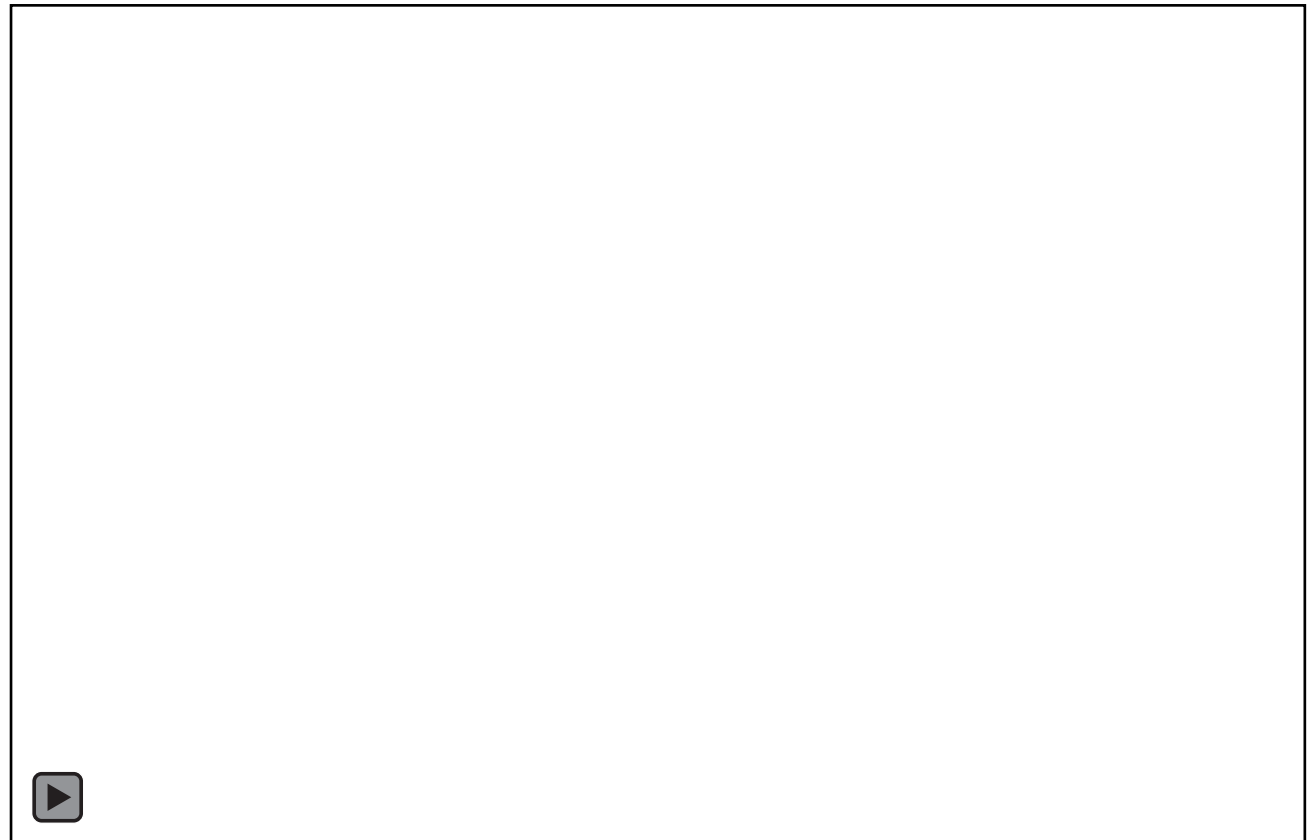
## Model validations

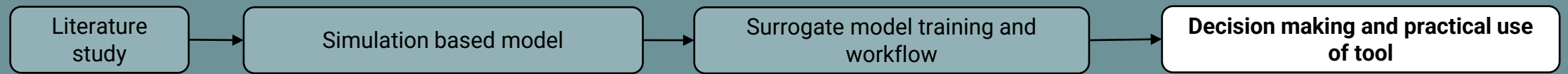
### Heating demand

Training algorithm	$R^2$
Stepwise regression	0.951
Kriging	0.976
Gaussian Process	0.991
Neural network	0.991

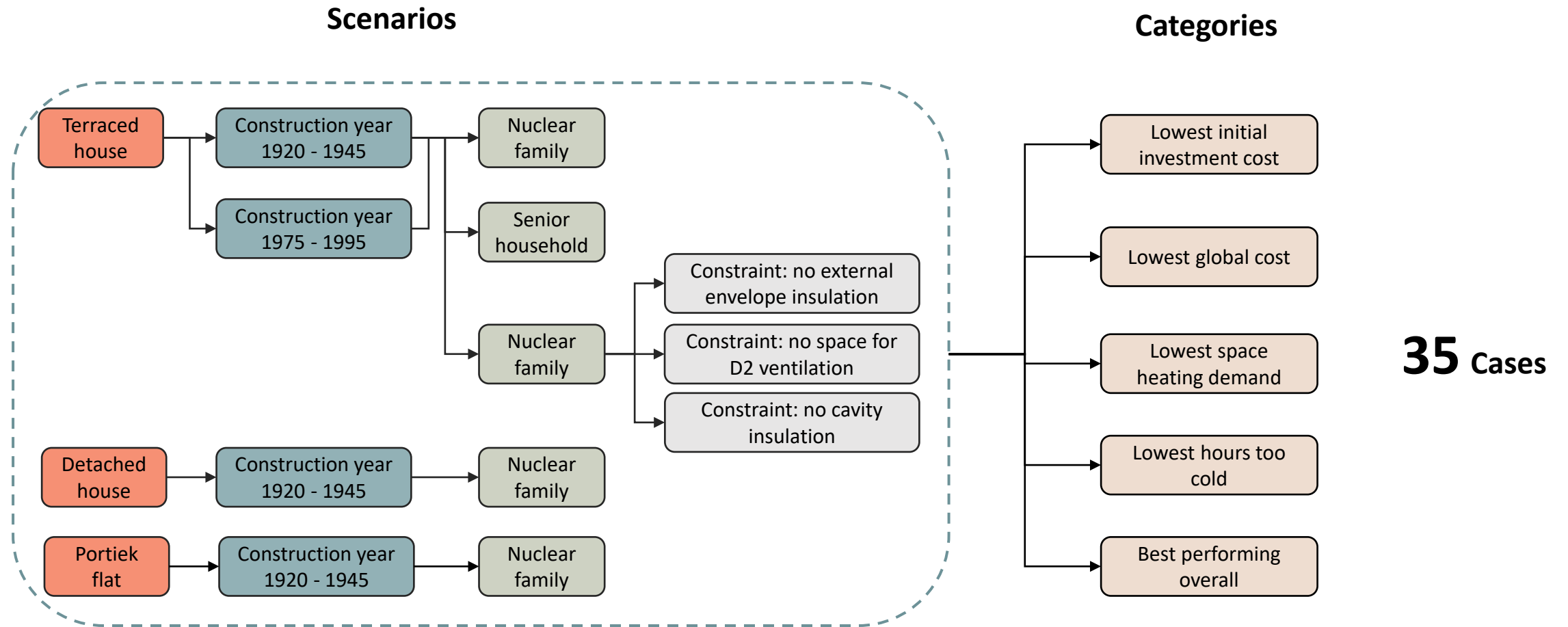
### Hours too cold

Training algorithm	$R^2$
Stepwise regression	0.973
Kriging	0.992
Gaussian Process	0.993
Neural network	0.994



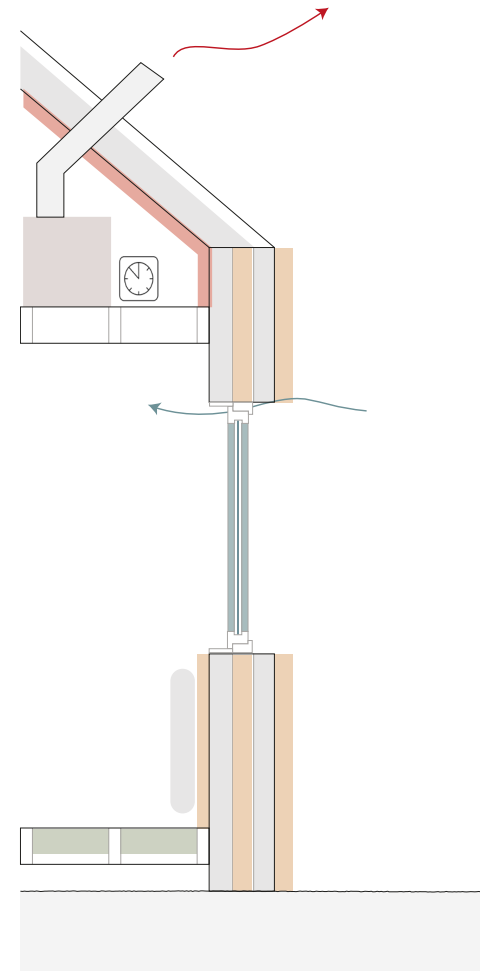


# Decision making process and practical use of tool



# Results Discussion

## Evaluation by Scenarios



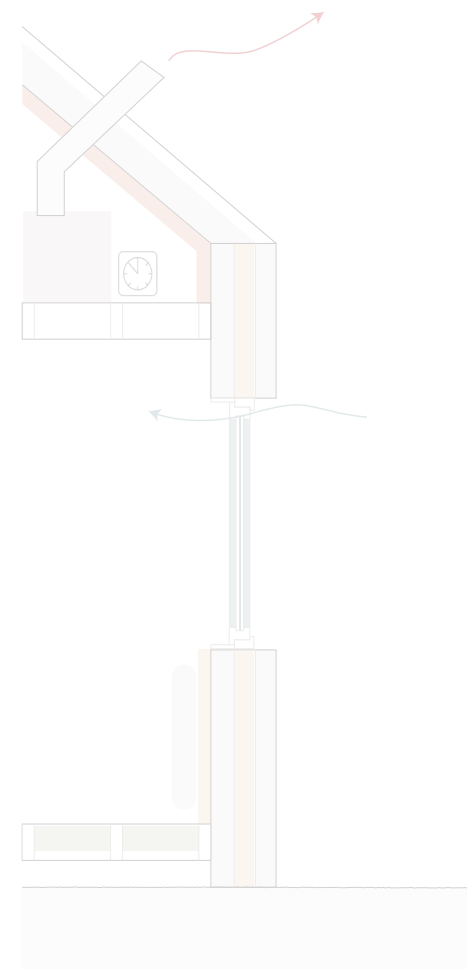
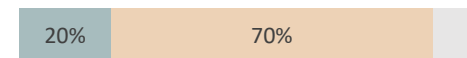
### Scenario 1

#### Terraced house Construction year <1945 & 1975 – 1995

External wall 158mm EPS insulation  
Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Original radiator LT

10 – 18 kWh/m<sup>2</sup> < 102 kWh/m<sup>2</sup>  
< 300 hours too cold < 2447 hours

Global cost: € 80,000 – 90,000

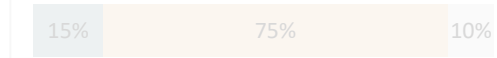


#### Constraint : No external insulation

Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Original radiator LT

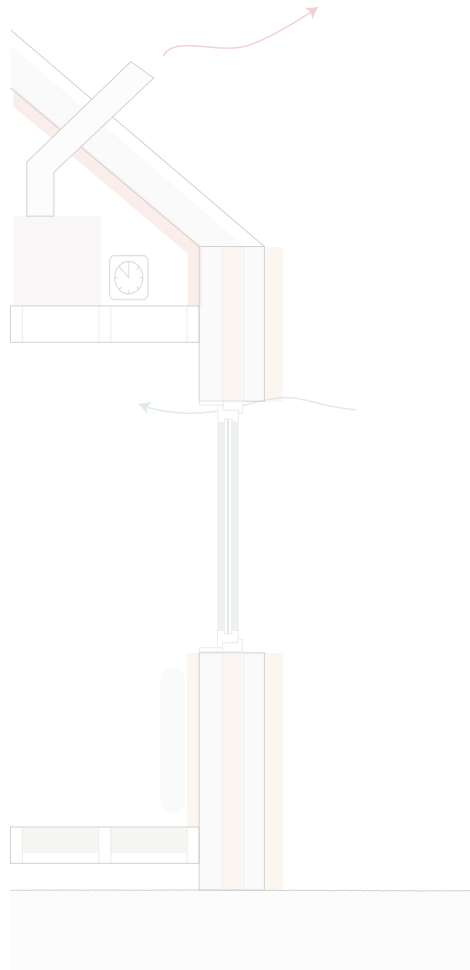
18 – 25 kWh/m<sup>2</sup> < 102 kWh/m<sup>2</sup>  
< 600 hours too cold < 2447 hours

Global cost: € 82,000 – 112,000



# Results Discussion

## Evaluation by Scenarios

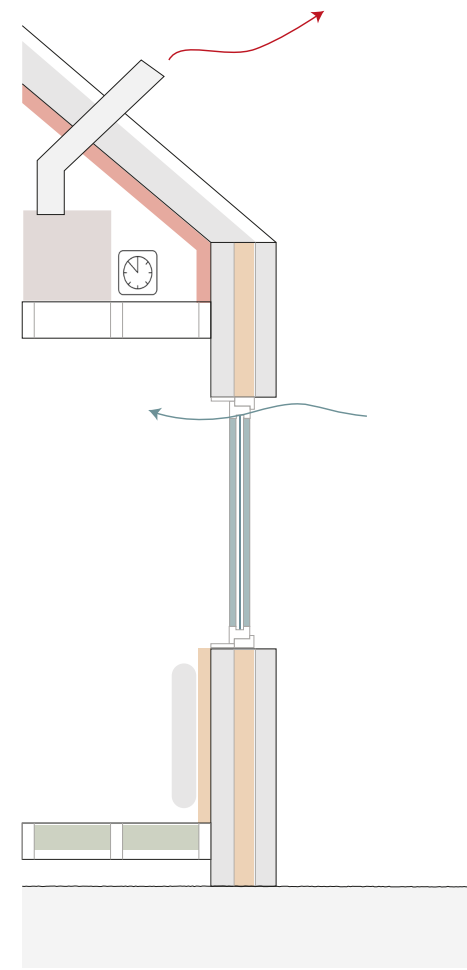
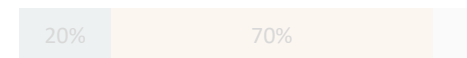


### Terraced house Construction year <1945 & 1975 – 1995

External wall 158mm EPS insulation  
Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Original radiator LT

10 – 18 kWh/m<sup>2</sup> < 102 kWh/m<sup>2</sup>  
< 300 hours too cold < 2447 hours

Global cost: € 80,000 – 90,000



### Scenario 2

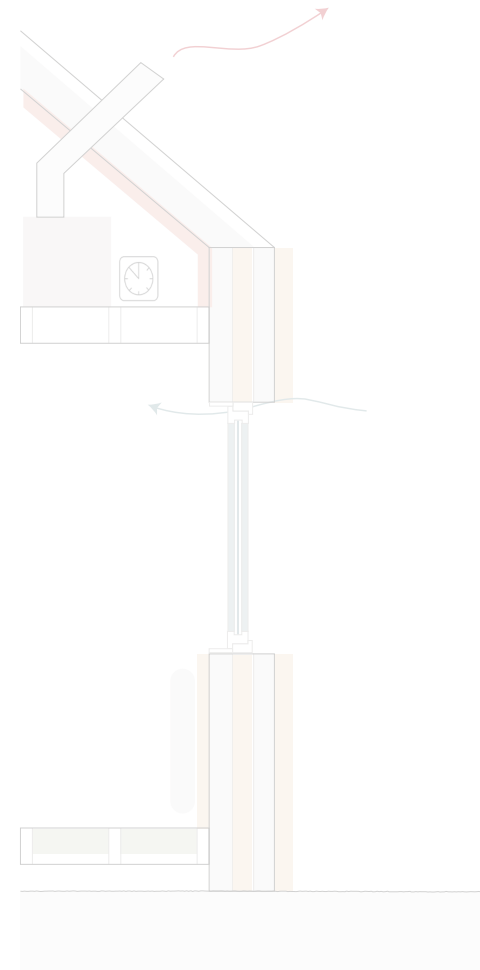
#### Constraint : No external insulation

Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Original radiator LT



# Results Discussion

## Evaluation by Scenarios

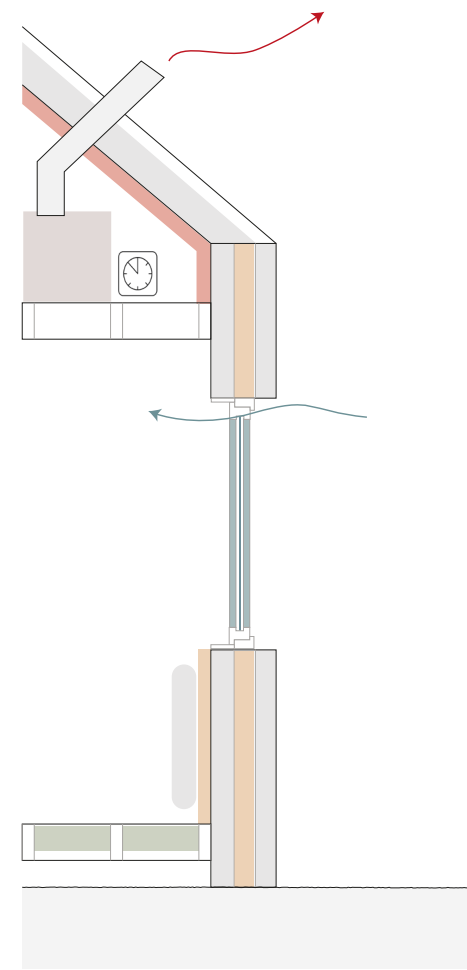
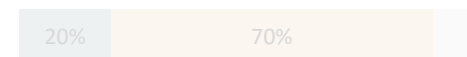


### Terraced house Construction year <1945 & 1975 – 1995

External wall 158mm EPS insulation  
Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Original radiator LT

10 – 18 kWh/m<sup>2</sup> < 102 kWh/m<sup>2</sup>  
< 300 hours too cold < 2447 hours

Global cost: € 80,000 – 90,000



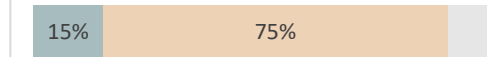
### Scenario 2

#### Constraint : No external insulation

**Cavity wall** 50mm foam beads insulation  
**Internal wall** 54mm Mineral wool insulation  
**Internal roof** 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Original radiator LT

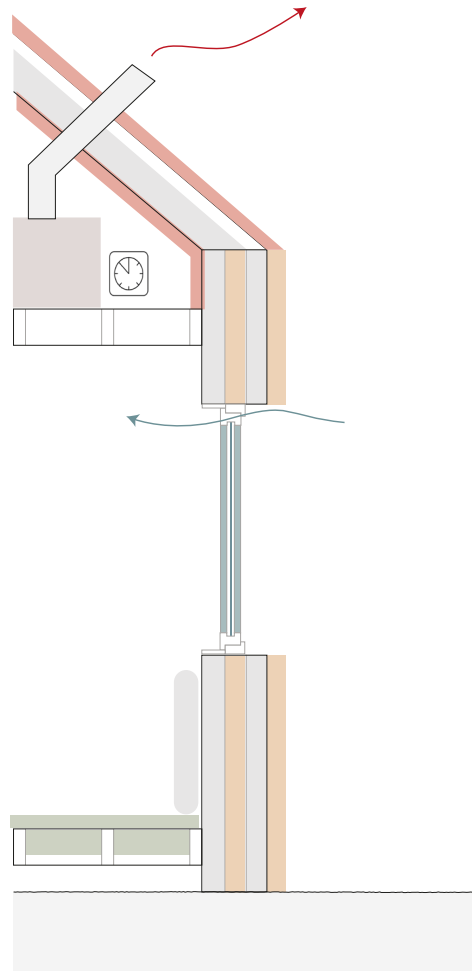
18 – 25 kWh/m<sup>2</sup> < 102 kWh/m<sup>2</sup>  
< 600 hours too cold < 2447 hours

Global cost: € 82,000 – 112,000



# Results Discussion

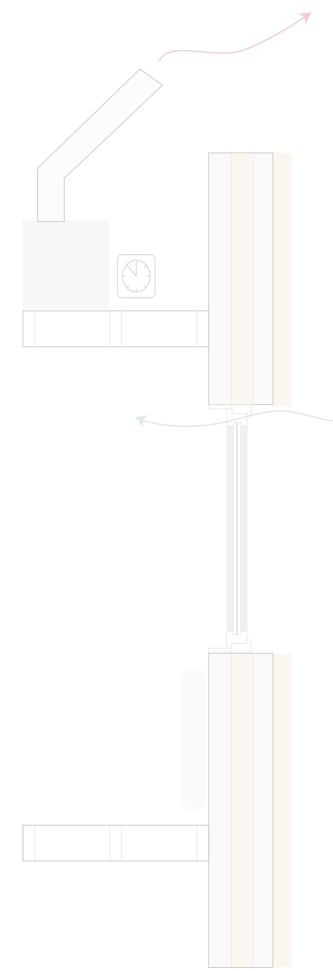
## Evaluation by Scenarios



### Scenario 1

#### Detached house

External wall 178 mm EPS insulation  
Cavity wall 50mm foam beads insulation  
External roof 74mm PIR insulation  
Internal roof 74mm PIR insulation  
Top floor 60mm Resol insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Original Radiator LT

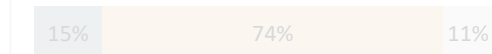


#### Constraint : No external insulation

Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Original radiator LT

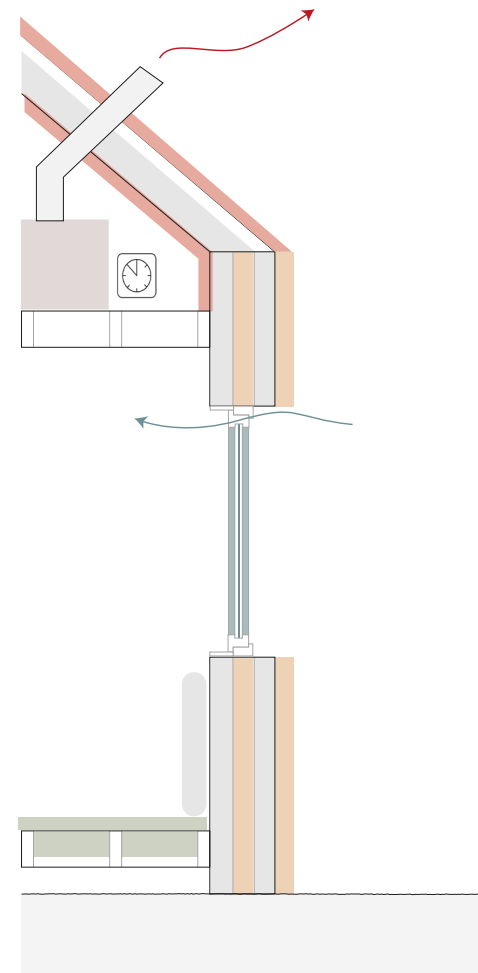
3 - 10 kWh/m<sup>2</sup> < 45 kWh/m<sup>2</sup>  
< 100 hours too cold < 1937 hours

Global cost: € 65,000 – 85,000



# Results Discussion

## Evaluation by Scenarios



### Scenario 1

#### Detached house

##### External wall 178 mm EPS insulation

Cavity wall 50mm foam beads insulation

##### External roof 74mm PIR insulation

Internal roof 74mm PIR insulation

##### Top floor 60mm Resol insulation

Underfloor 70mm Mineral wool insulation

Triple glazing

Airtightness : High

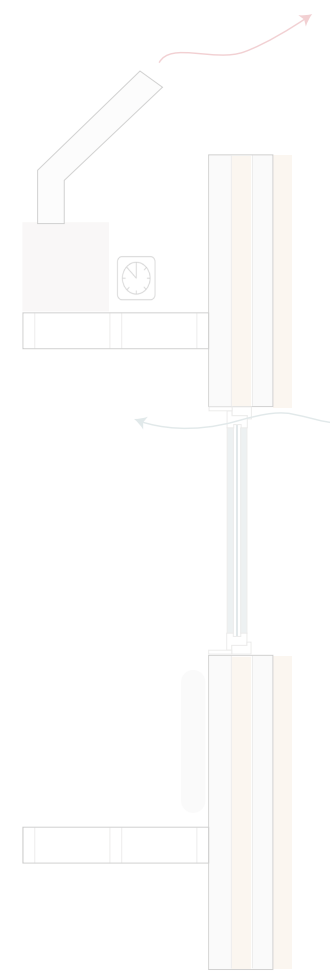
Type C2 ventilation

Original Radiator LT

25 – 40 kWh/m<sup>2</sup> < 186 kWh/m<sup>2</sup>

< 600 hours too cold < 2474 hours

Global cost: € 155,000 – 165,000



#### Constraint : No external insulation

Cavity wall 50mm foam beads insulation

Internal wall 54mm Mineral wool insulation

Triple glazing

Airtightness : High

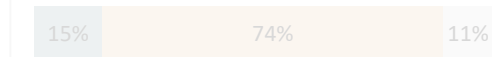
Type C2 ventilation

Original radiator LT

3 - 10 kWh/m<sup>2</sup> < 45 kWh/m<sup>2</sup>

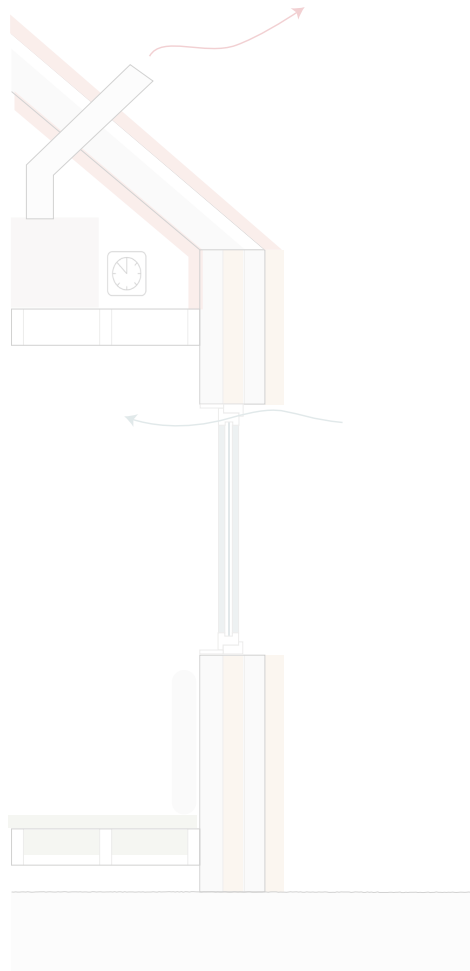
< 100 hours too cold < 1937 hours

Global cost: € 65,000 – 85,000



# Results Discussion

## Evaluation by Scenarios

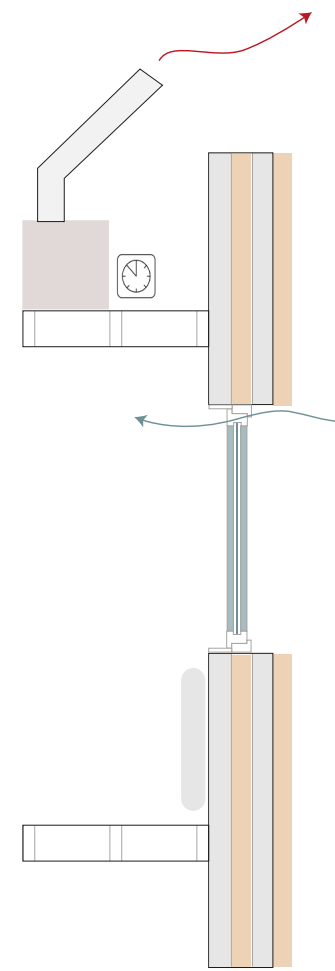


### Detached house

External wall 178 mm EPS insulation  
 Cavity wall 50mm foam beads insulation  
**External roof** 74mm PIR insulation  
**Internal roof** 74mm PIR insulation  
**Top floor** 60mm Resol insulation  
 Underfloor 70mm Mineral wool insulation  
 Triple glazing  
 Airtightness : High  
 Type C2 ventilation  
 Original Radiator LT

25 – 40 kWh/m<sup>2</sup> < 186 kWh/m<sup>2</sup>  
 < 600 hours too cold < 2474 hours

Global cost: € 155,000 – 165,000



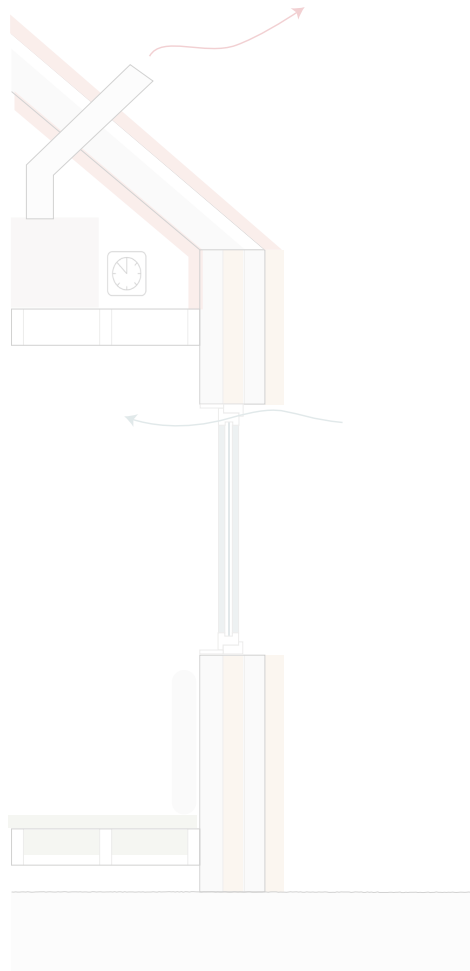
### Scenario 2

### Portiek apartment

Cavity wall 50mm foam beads insulation  
 Internal wall 54mm Mineral wool insulation  
 Triple glazing  
 Airtightness : High  
 Type C2 ventilation  
 Original radiator LT

# Results Discussion

## Evaluation by Scenarios

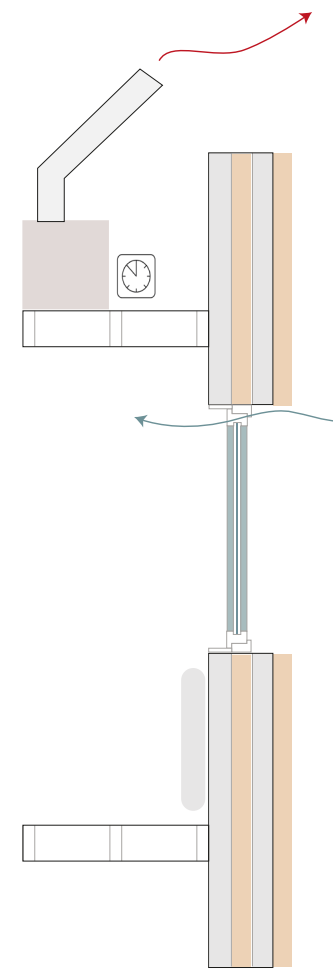
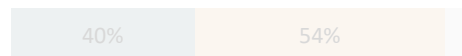


### Detached house

External wall 178 mm EPS insulation  
Cavity wall 50mm foam beads insulation  
**External roof** 74mm PIR insulation  
**Internal roof** 74mm PIR insulation  
**Top floor** 60mm Resol insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Original Radiator LT

25 – 40 kWh/m<sup>2</sup> < 186 kWh/m<sup>2</sup>  
< 600 hours too cold < 2474 hours

Global cost: € 155,000 – 165,000



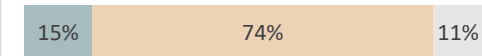
### Scenario 2

### Portiek apartment

Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Original radiator LT

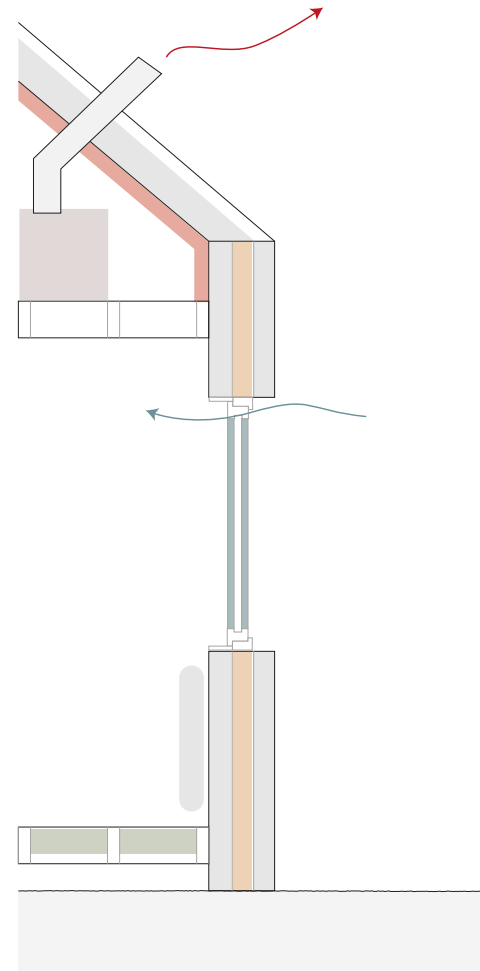
3 - 10 kWh/m<sup>2</sup> < 45 kWh/m<sup>2</sup>  
< 100 hours too cold < 1937 hours

Global cost: € 65,000 – 85,000



# Results Discussion

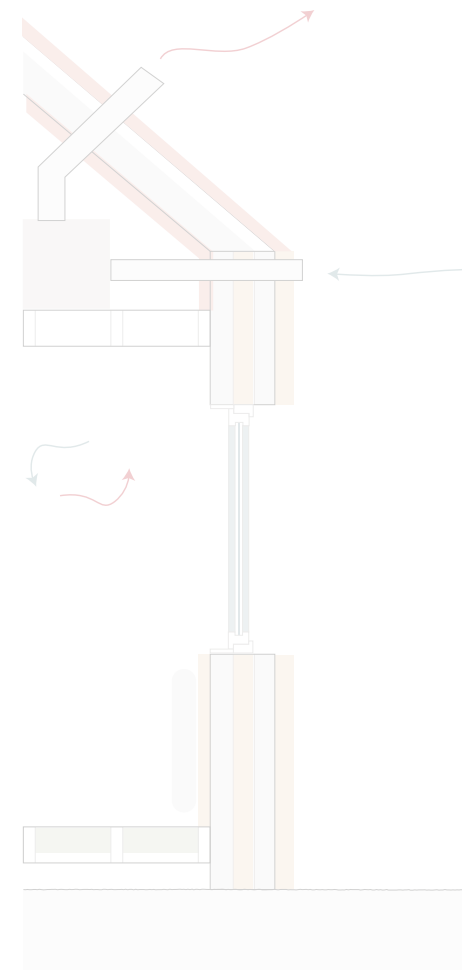
## Evaluation by Categories



### Category 1

#### Lowest Investment Cost

Cavity wall 50mm foam beads insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
HR ++ glazing  
Airtightness : High  
Type C1 ventilation  
Original Radiator LT



#### Lowest Space Heating demand

External wall 158mm EPS insulation  
Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
External roof 74mm PIR insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type D2 ventilation  
Original Radiator LT

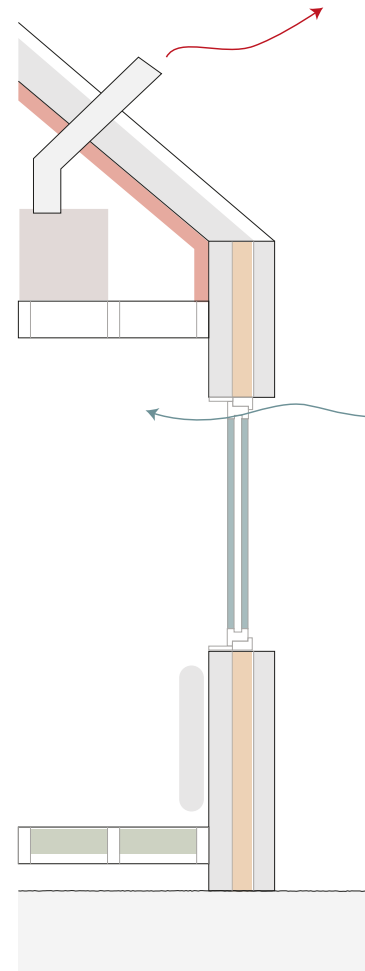
10 – 12 kWh/m<sup>2</sup>  
< 600 hours too cold

Global cost: € 80,000 – 95,000



# Results Discussion

## Evaluation by Categories



### Category 1

#### Lowest Investment Cost

##### Cavity wall 50mm foam beads insulation

Internal roof 74mm PIR insulation

Underfloor 70mm Mineral wool insulation

##### HR ++ glazing

Airtightness : High

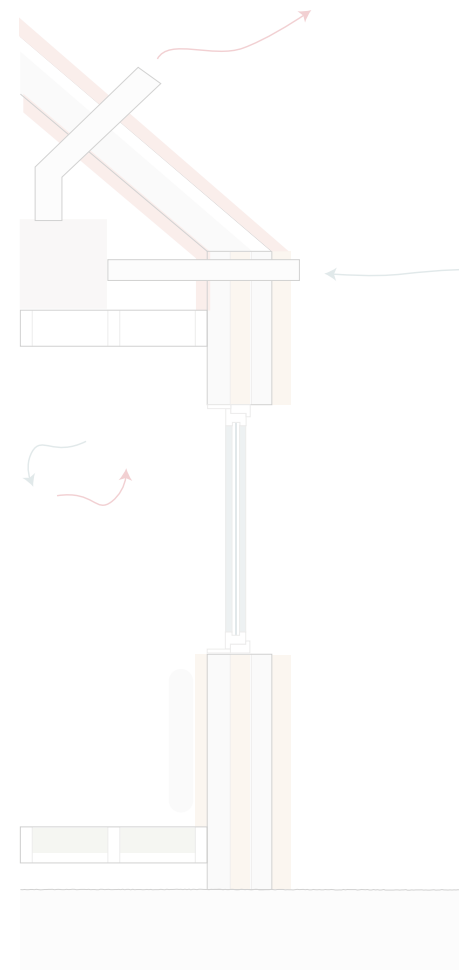
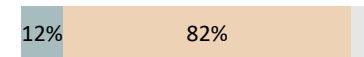
##### Type C1 ventilation

Original Radiator LT

25 – 90 kWh/m<sup>2</sup>

< 1200 hours too cold

Global cost: € 85,000 – 115,000



#### Lowest Space Heating demand

External wall 158mm EPS insulation

Cavity wall 50mm foam beads insulation

Internal wall 54mm Mineral wool insulation

External roof 74mm PIR insulation

Internal roof 74mm PIR insulation

Underfloor 70mm Mineral wool insulation

Triple glazing

Airtightness : High

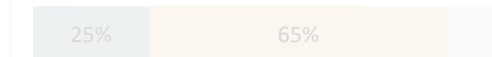
Type D2 ventilation

Original Radiator LT

10 – 12 kWh/m<sup>2</sup>

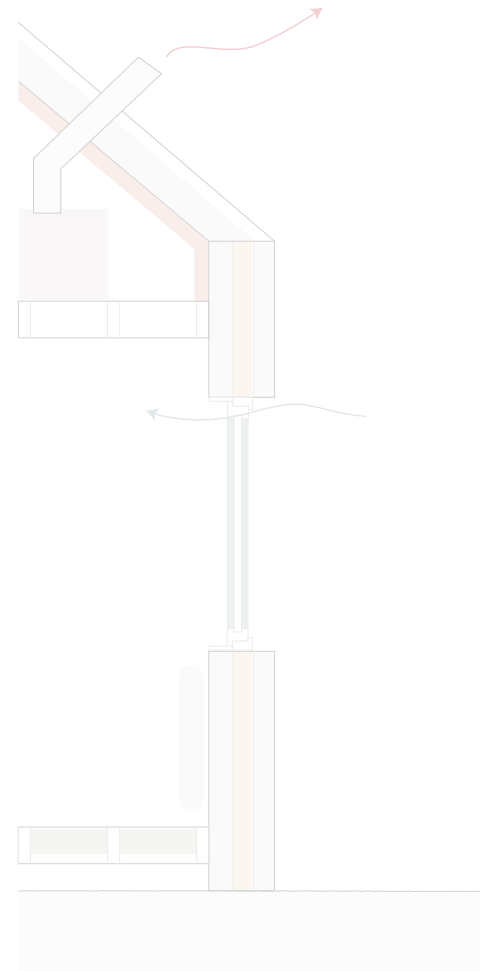
< 600 hours too cold

Global cost: € 80,000 – 95,000



# Results Discussion

## Evaluation by Categories



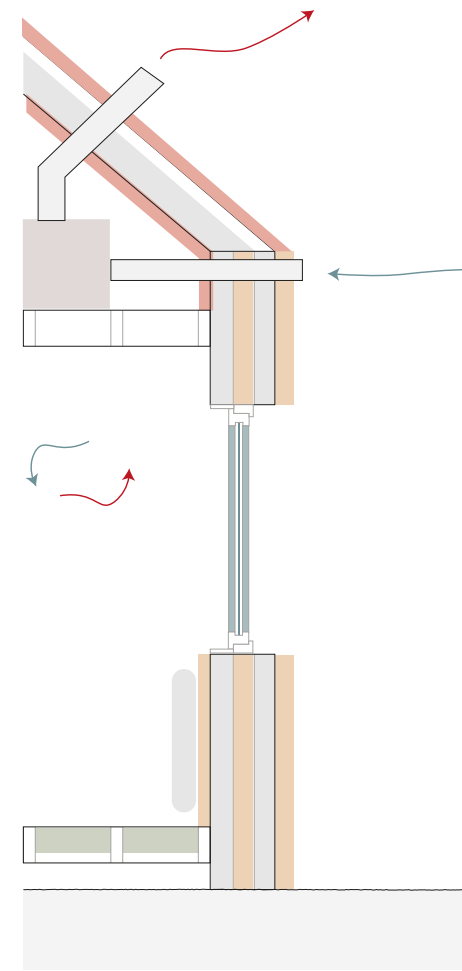
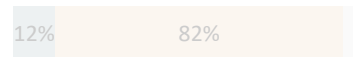
### Category 1

#### Lowest Investment Cost

Cavity wall 50mm foam beads insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
HR ++ glazing  
Airtightness : High  
Type C1 ventilation  
Original Radiator LT

25 – 90 kWh/m<sup>2</sup>  
< 1200 hours too cold

Global cost: € 85,000 – 115,000



### Category 2

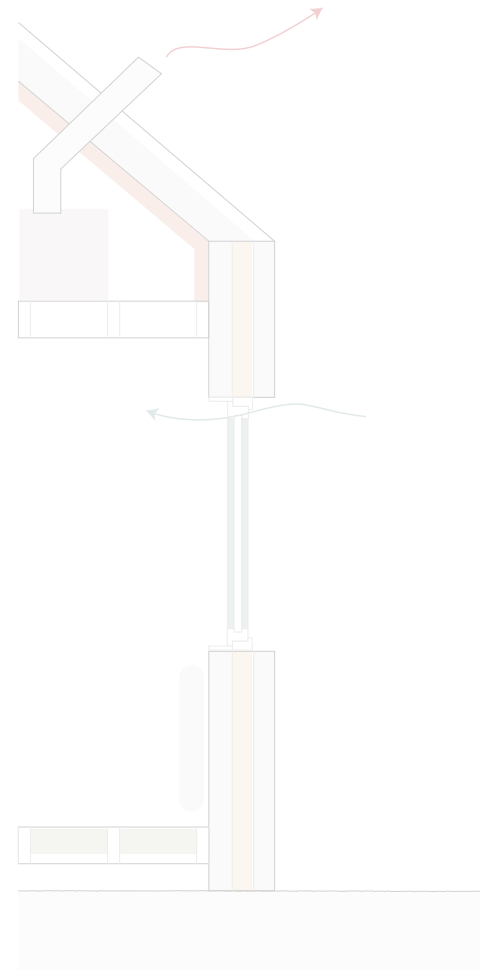
#### Lowest Space Heating demand

External wall 158mm EPS insulation  
Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
External roof 74mm PIR insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type D2 ventilation  
Original Radiator LT



# Results Discussion

## Evaluation by Categories

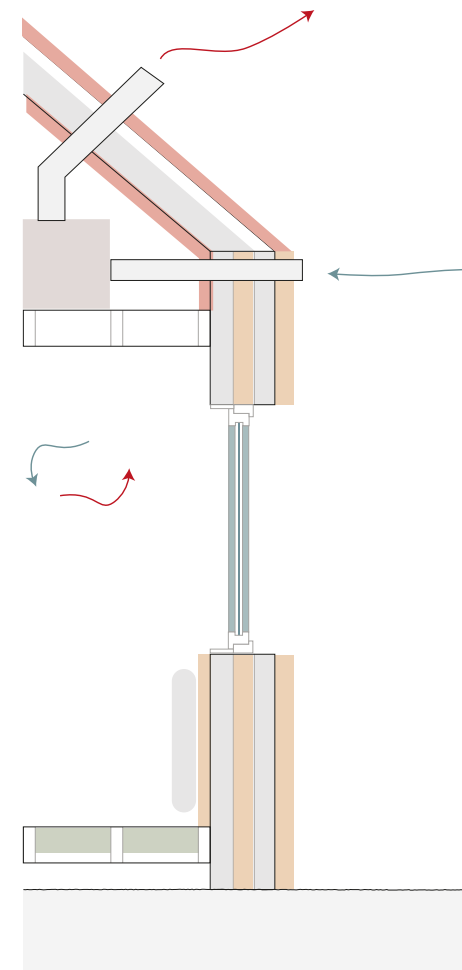
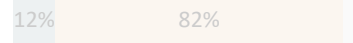


### Lowest Investment Cost

Cavity wall 50mm foam beads insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
HR ++ glazing  
Airtightness : High  
Type C1 ventilation  
Original Radiator LT

25 – 90 kWh/m<sup>2</sup>  
< 1200 hours too cold

Global cost: € 85,000 – 115,000



### Category 2

### Lowest Space Heating demand

**External wall** 158mm EPS insulation  
**Cavity wall** 50mm foam beads insulation  
**Internal wall** 54mm Mineral wool insulation  
**External roof** 74mm PIR insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
**Type D2 ventilation**  
Original Radiator LT

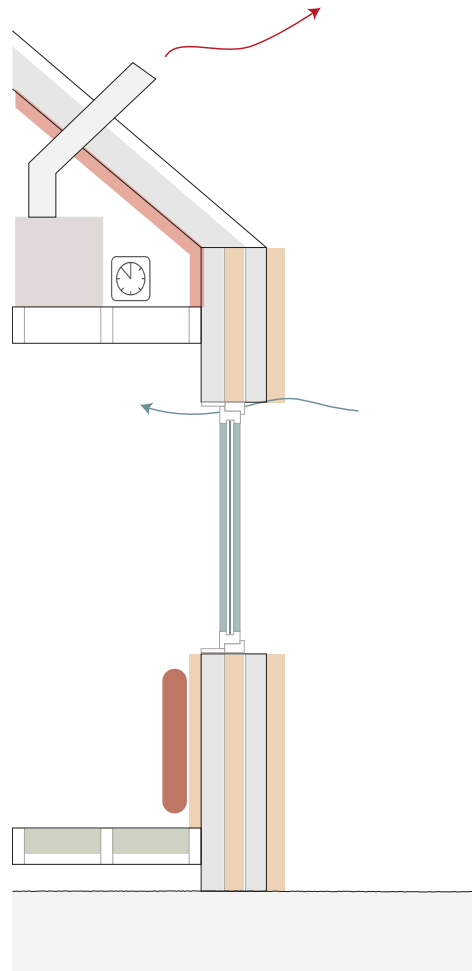
10 – 12 kWh/m<sup>2</sup>  
< 600 hours too cold

Global cost: € 80,000 – 95,000



# Results Discussion

## Evaluation by Categories

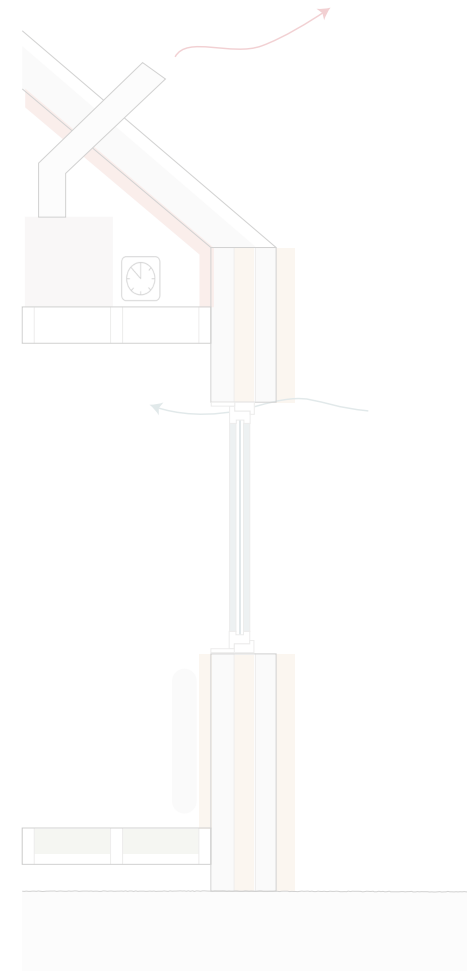


### Category 3

#### Lowest Hours Too Cold

External wall 158mm EPS insulation  
Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Comfort Radiator LT

**12 – 25 kWh/m<sup>2</sup>**  
**< 200** hours too cold

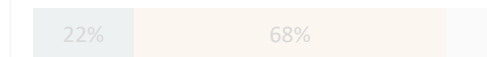


#### Best performing overall

External wall 158mm EPS insulation  
Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Original radiator

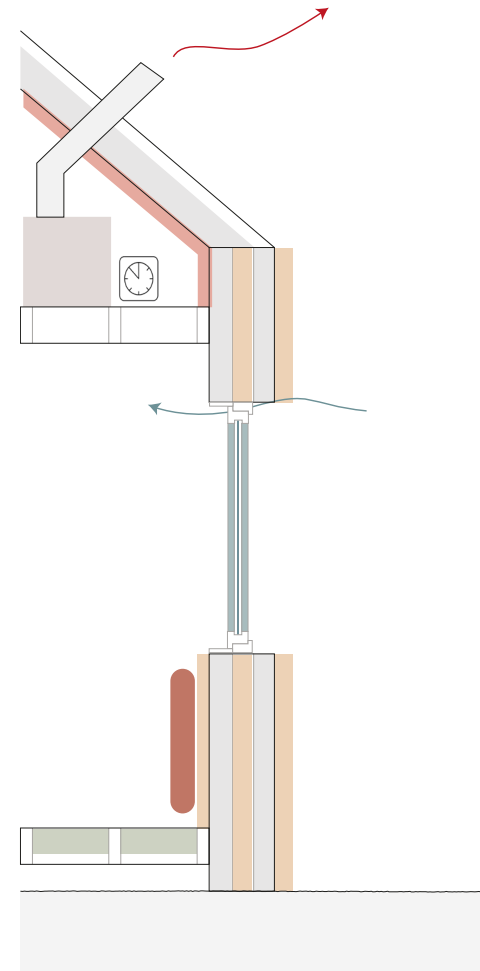
**10 – 18 kWh/m<sup>2</sup>**  
**< 300** hours too cold

Global cost: € **80,000 – 95,000**



# Results Discussion

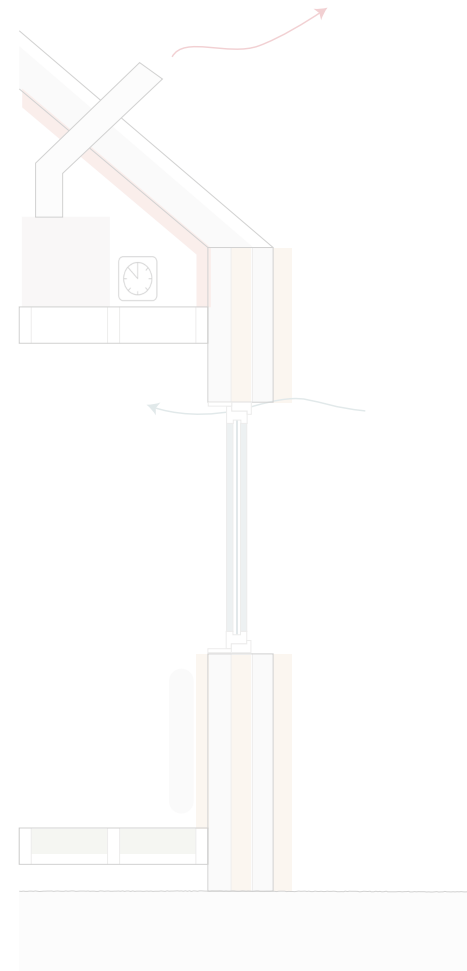
## Evaluation by Categories



### Category 3

#### Lowest Hours Too Cold

External wall 158mm EPS insulation  
Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
**Internal roof 74mm PIR insulation**  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
**Type C2 ventilation**  
**Comfort Radiator LT**

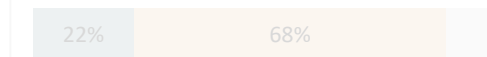


#### Best performing overall

External wall 158mm EPS insulation  
Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Original radiator

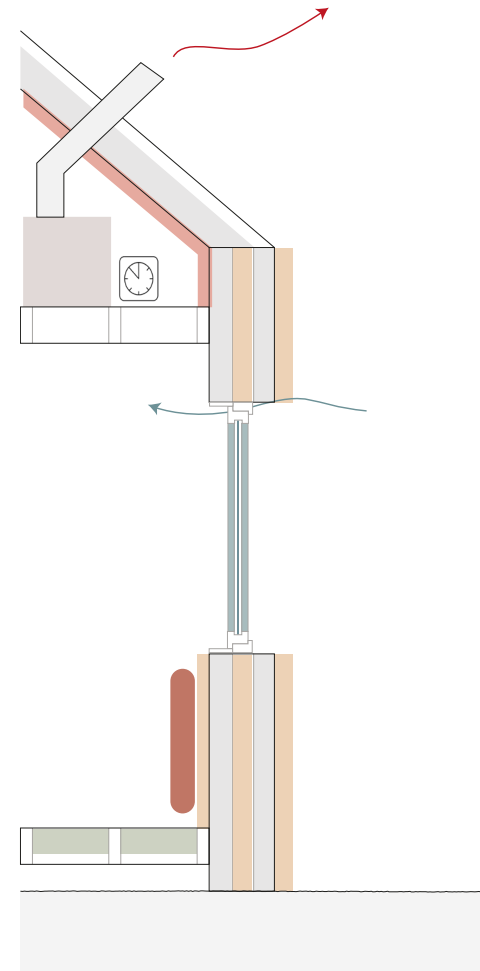
10 – 18 kWh/m<sup>2</sup>  
< 300 hours too cold

Global cost: € 80,000 – 95,000



# Results Discussion

## Evaluation by Categories



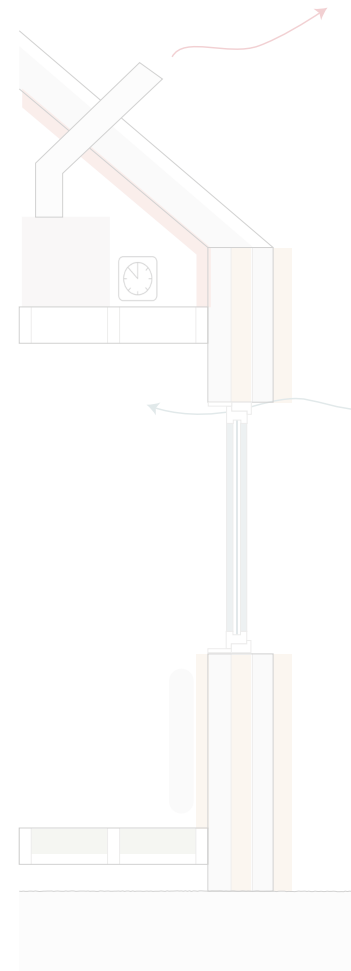
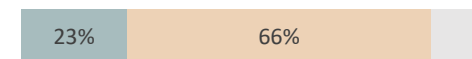
### Category 3

#### Lowest Hours Too Cold

External wall 158mm EPS insulation  
Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
**Internal roof 74mm PIR insulation**  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
**Type C2 ventilation**  
**Comfort Radiator LT**

**12 – 25 kWh/m<sup>2</sup>**  
**< 200 hours too cold**

Global cost: € **85,000 – 98,000**

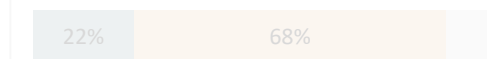


#### Best performing overall

External wall 158mm EPS insulation  
Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Original radiator

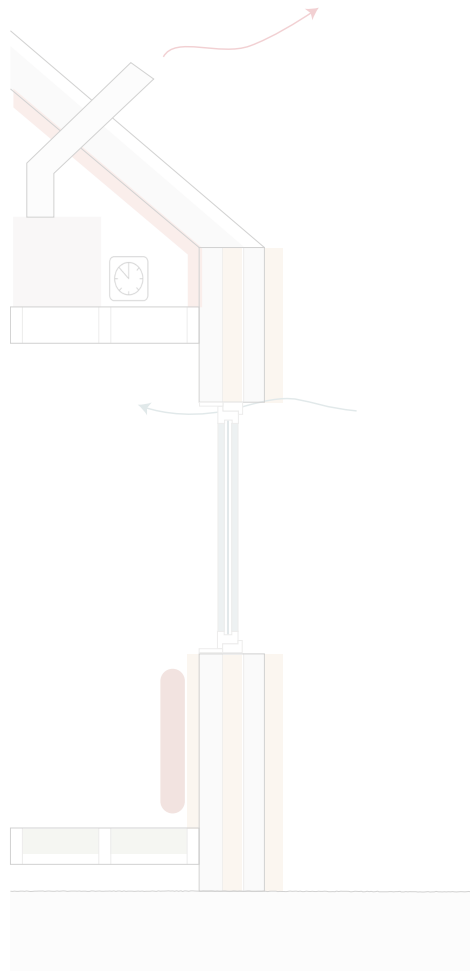
**10 – 18 kWh/m<sup>2</sup>**  
**< 300 hours too cold**

Global cost: € **80,000 – 95,000**



# Results Discussion

## Evaluation by Categories

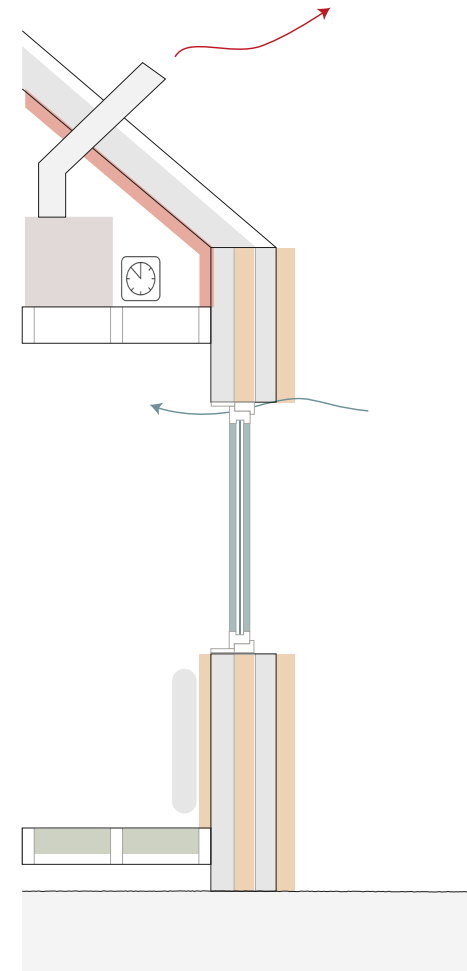


### Lowest Hours Too Cold

External wall 158mm EPS insulation  
Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Comfort Radiator LT

12 – 25 kWh/m<sup>2</sup>  
< 200 hours too cold

Global cost: € 85,000 – 98,000



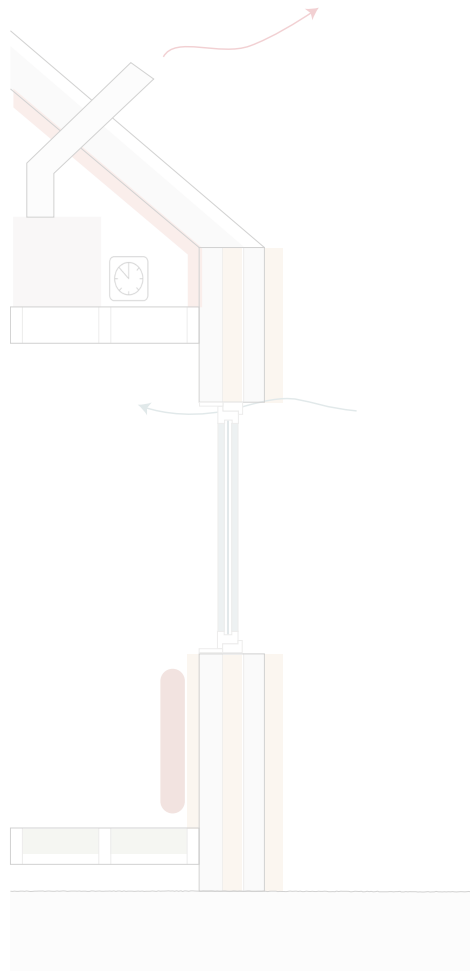
### Category 4

### Best performing overall

External wall 158mm EPS insulation  
Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Original radiator

# Results Discussion

## Evaluation by Categories

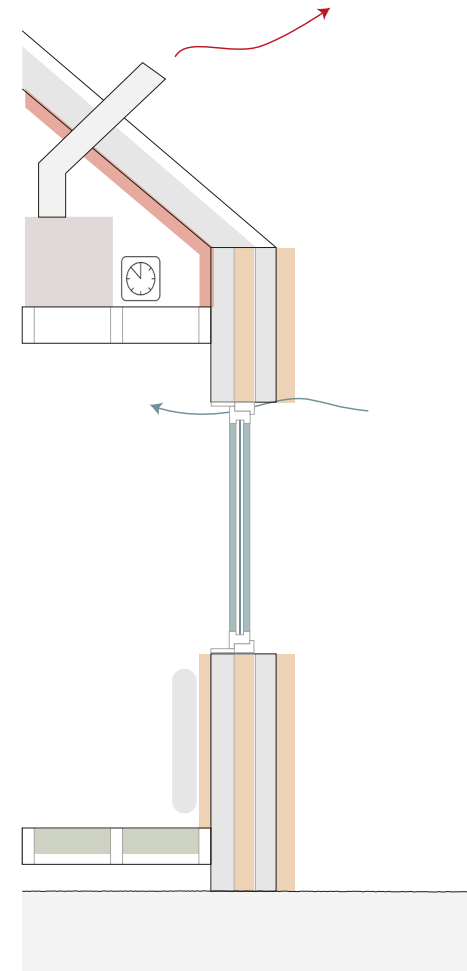


### Lowest Hours Too Cold

External wall 158mm EPS insulation  
Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Comfort Radiator LT

12 – 25 kWh/m<sup>2</sup>  
< 200 hours too cold

Global cost: € 85,000 – 98,000



### Category 4

### Best performing overall

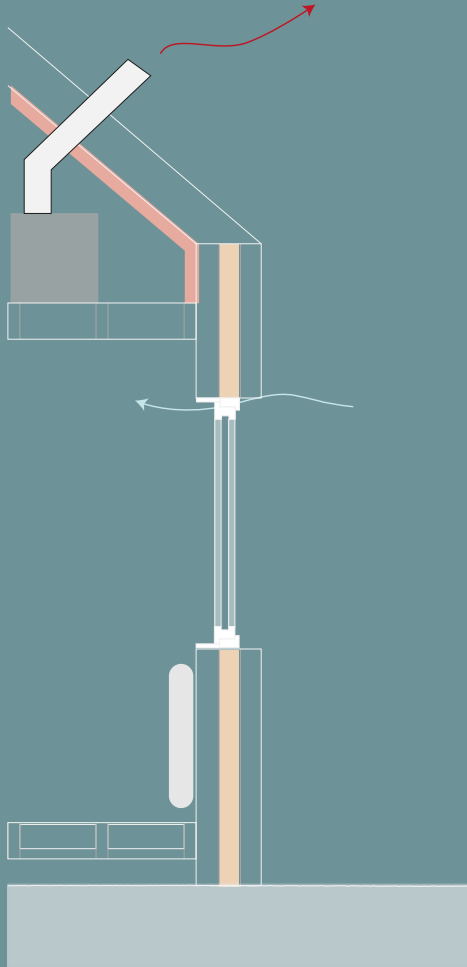
External wall 158mm EPS insulation  
Cavity wall 50mm foam beads insulation  
Internal wall 54mm Mineral wool insulation  
Internal roof 74mm PIR insulation  
Underfloor 70mm Mineral wool insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
**Original radiator**

10 – 18 kWh/m<sup>2</sup>  
< 300 hours too cold

Global cost: € 80,000 – 95,000



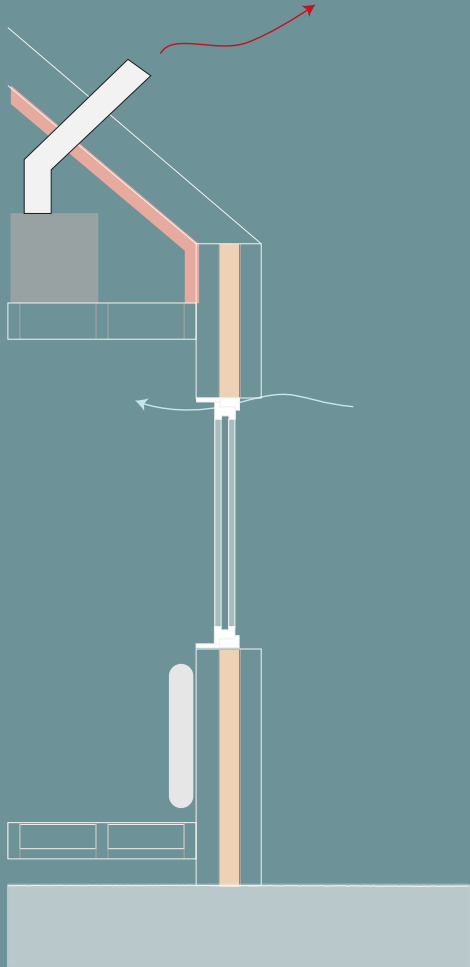
# Recap



## Most Impactful measures

Cavity wall insulation  
Internal roof 74mm PIR insulation  
Triple glazing  
Airtightness : High  
Type C2 ventilation  
Original Radiator LT

# Key Takeaways



## Most Impactful measures

1. Cavity wall insulation
2. Internal roof 74mm PIR insulation
3. Triple glazing
4. Airtightness : High
5. Type C2 ventilation
6. Original Radiator LT

- **Energy cost contribute significantly to global cost**
- **Intensive measures required**
- **Higher initial investment cost**
- **Particularly affects less compact housing archetypes**

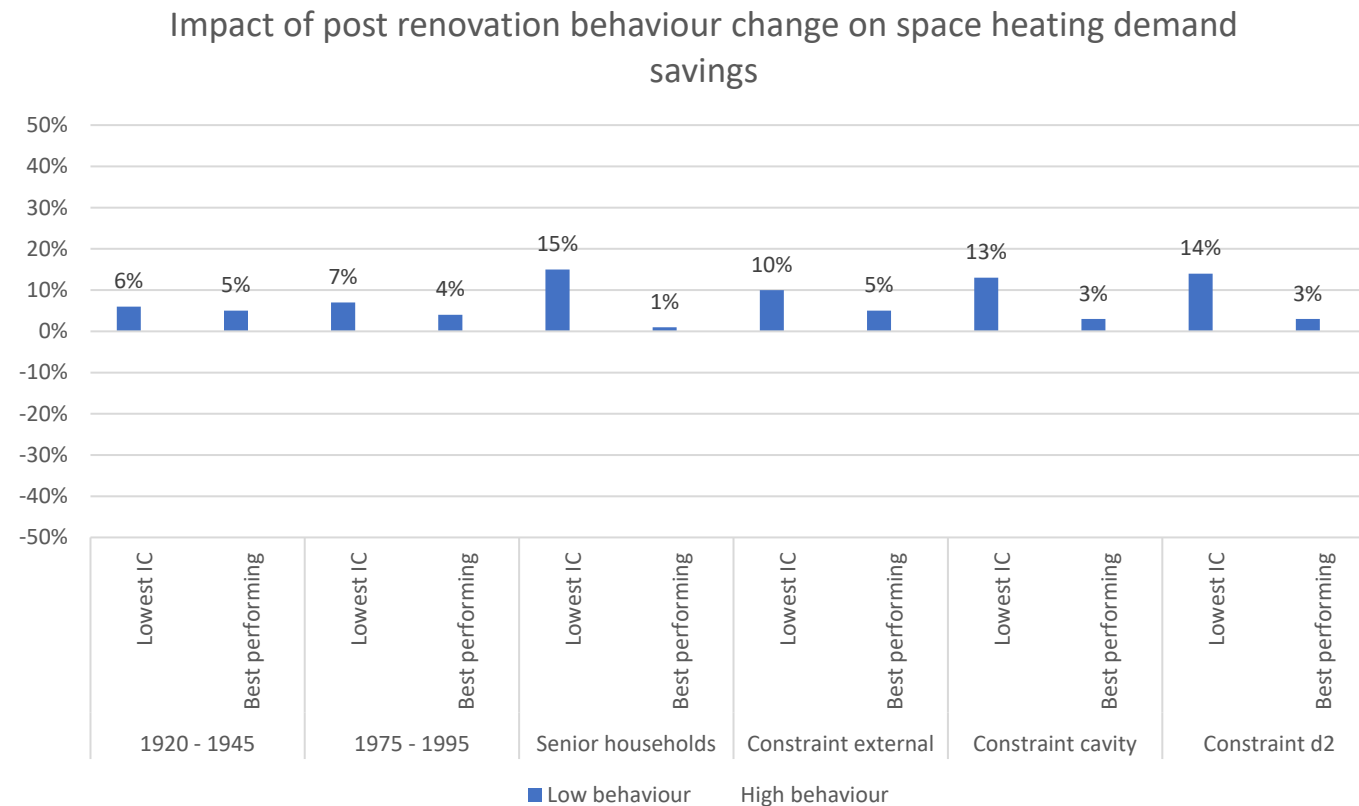


# Results Discussion

Impact of post occupancy behaviour change on space heating savings

# Results Discussion

## Lower behaviour post refurbishment

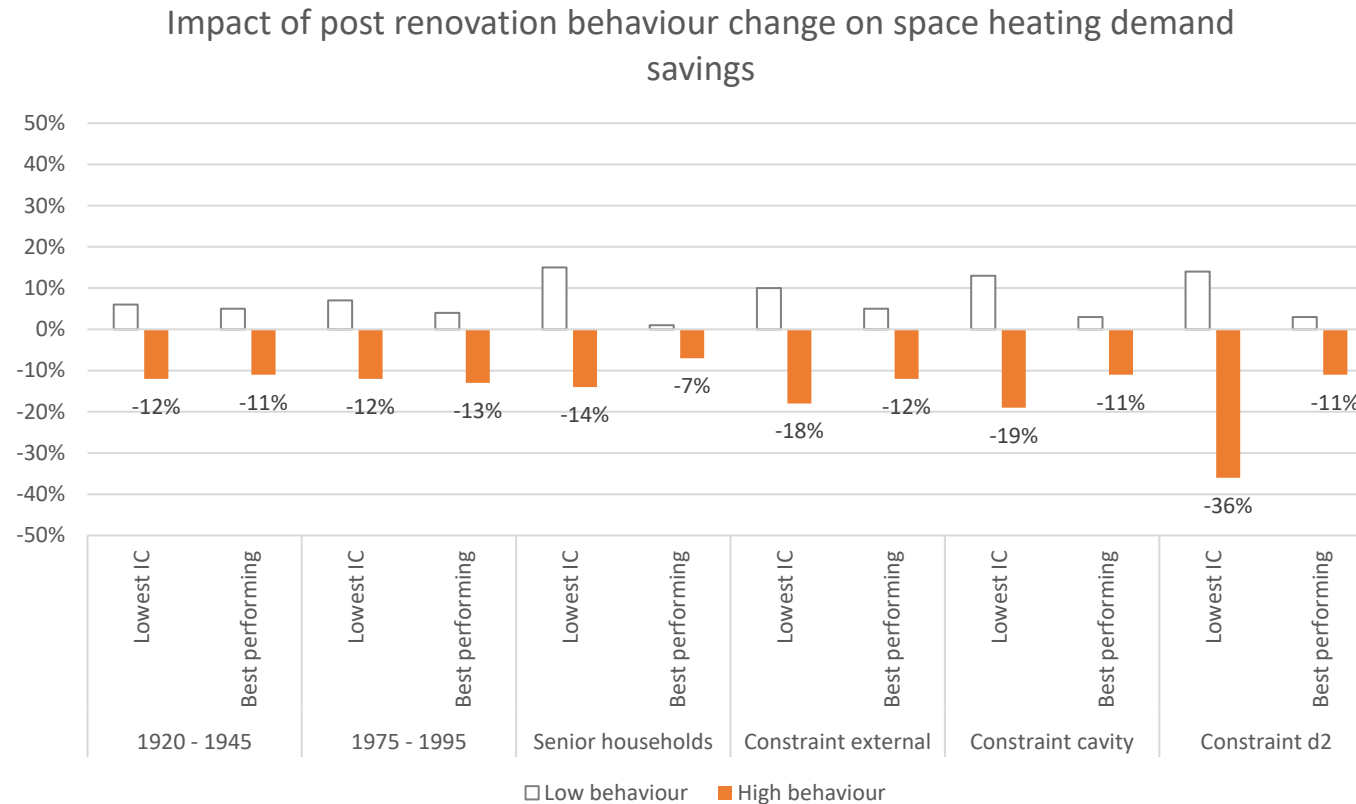


Low behaviour : average 7 % increase in savings



# Results Discussion

## High behaviour post refurbishment

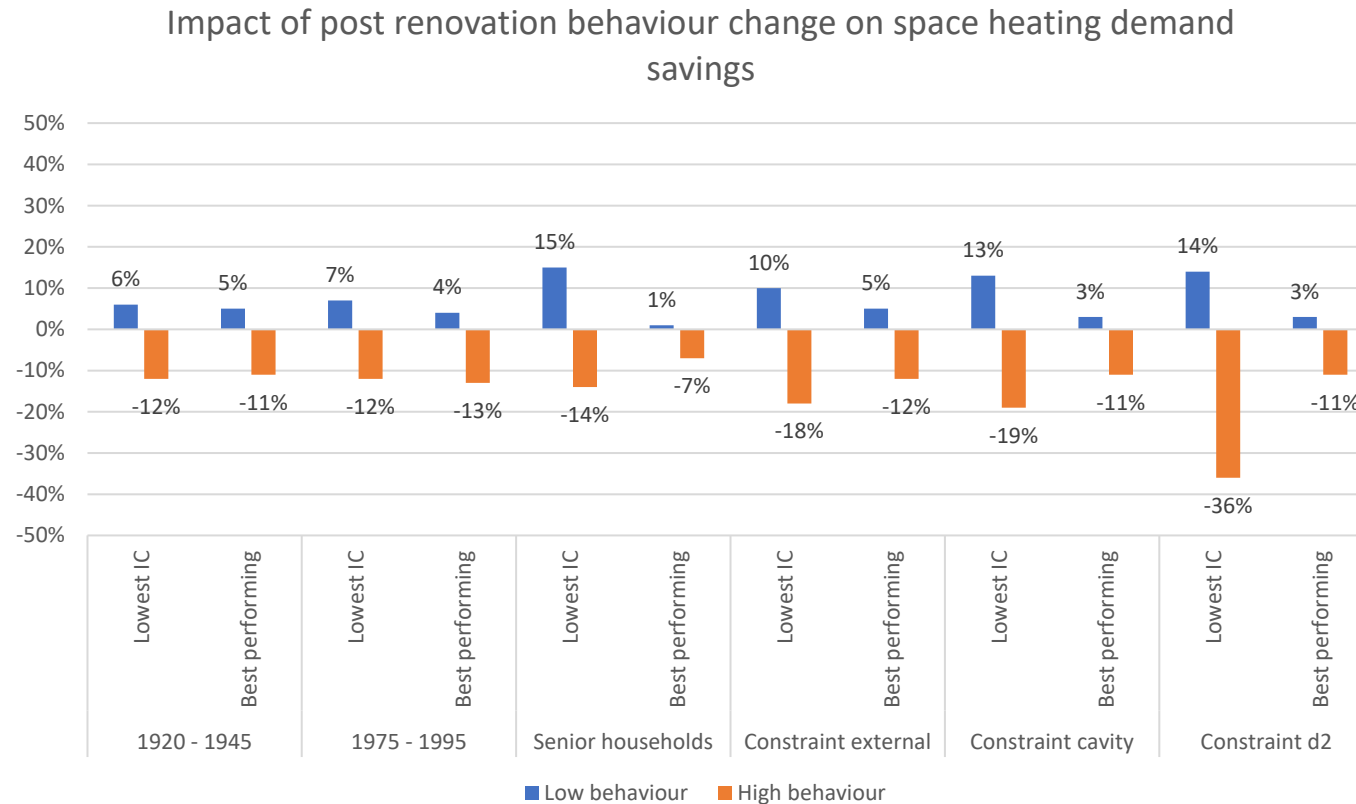


High behaviour : average **15 %** reduction in savings



# Results Discussion

## Impact of post occupancy behaviour change on space heating



Low behaviour : average 7 % increase in savings

High behaviour : average 15 % reduction in savings



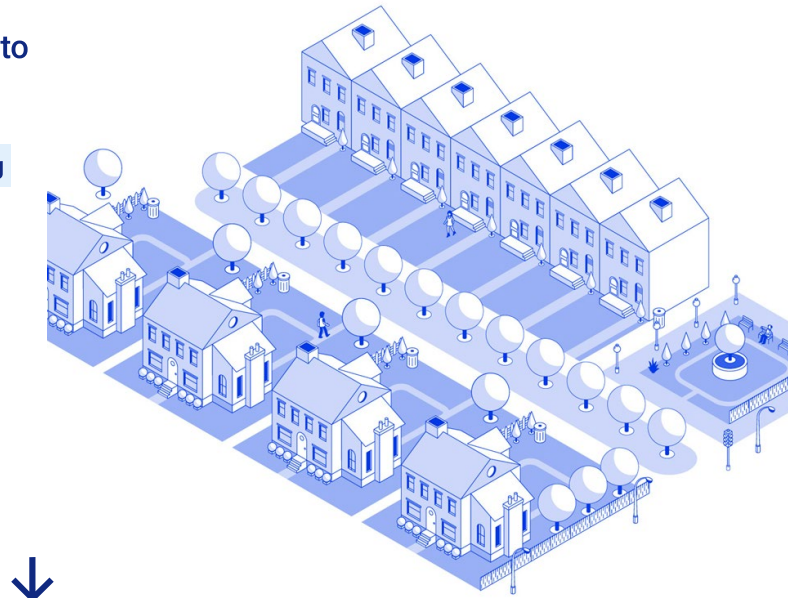
How to develop a **surrogate model-based decision-making** tool to select **combined, no-regret refurbishment measures** using **performance indicators** for **multiple Dutch housing typologies** considering **occupancy behaviour** and **lifecycle cost** to transition to **low-temperature** district heating?



## Why should you consider transitioning to low Temperature District heating?

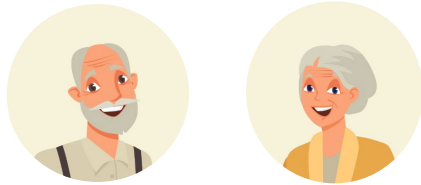
Transitioning to a **Low Temperature District Heating** can offer you many benefits:

- Energy Efficiency
- Sustainable Heating
- Enhanced Comfort
- Lowered Energy Bills



# Personas

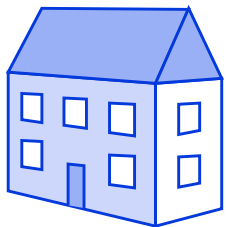
Senior couple



Filipo, 65

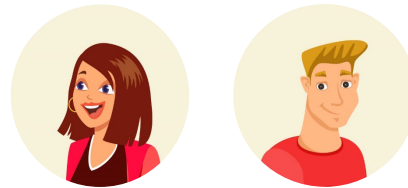
Dalila, 65

Retired elderly couple living it up in Amsterdam.



1965

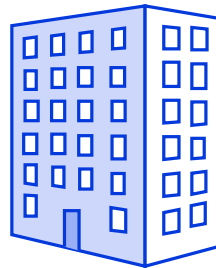
Adult Couple



Simona, 25

Ricardo, 25

Young professionals living in the Hague



1985

Nuclear family



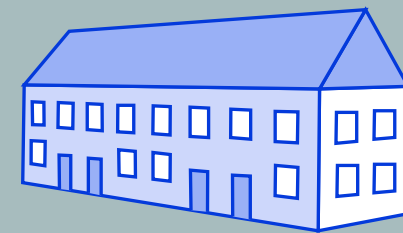
Luis, 30

Sara, 30

Revy, 30

Ariele, 30

A loving and caring family in Delft, that always there for you.

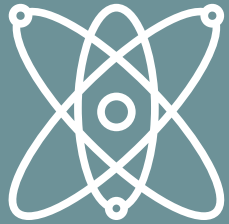


1940





# Conclusion



Integrated **behaviour** and **lifecycle** perspective into a refurbishment decision making framework using **surrogate** models



Examine variations of methods to set up **optimization objectives**



Helped a **diverse range of homeowners** address the need to refurbish their dwellings to transition to an **LT-set** future!

