

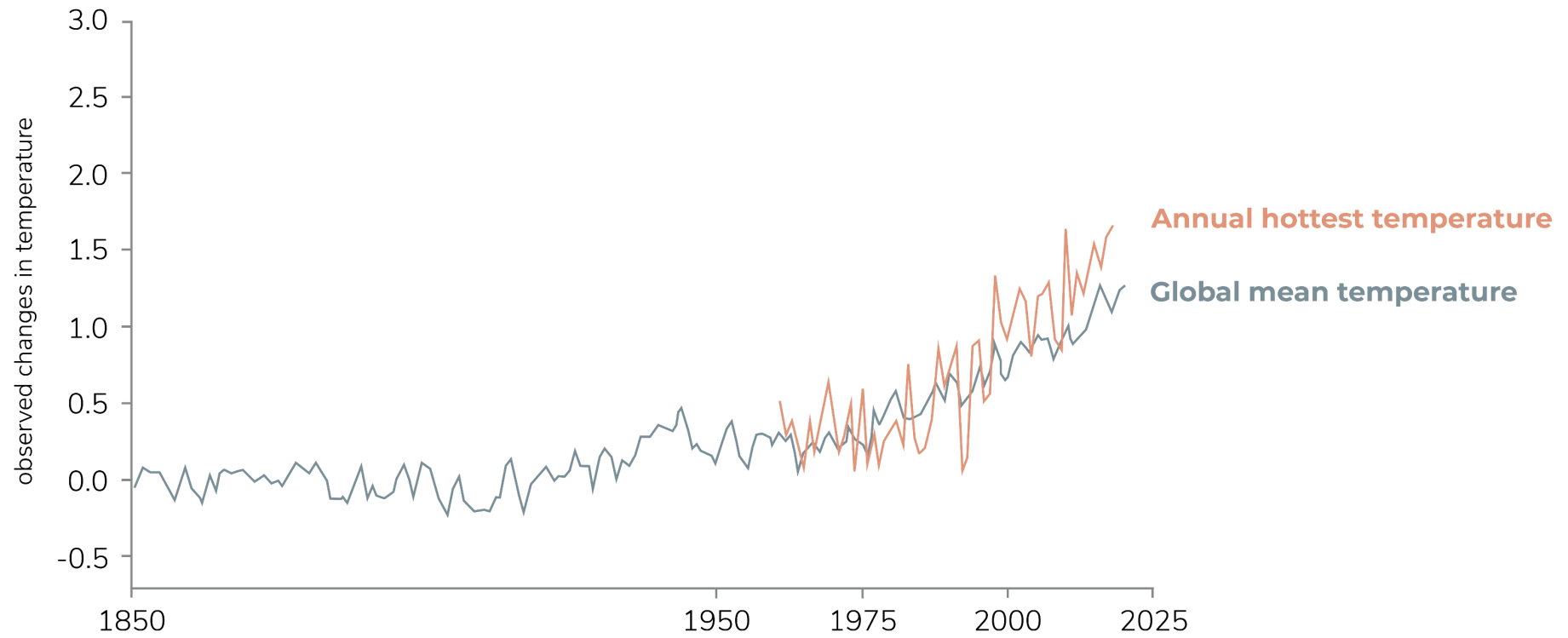




Aiming to improve the design process of retrofit options  
increasing thermal indoor comfort during heat waves  
and enhancing long-term building thermal resilience.

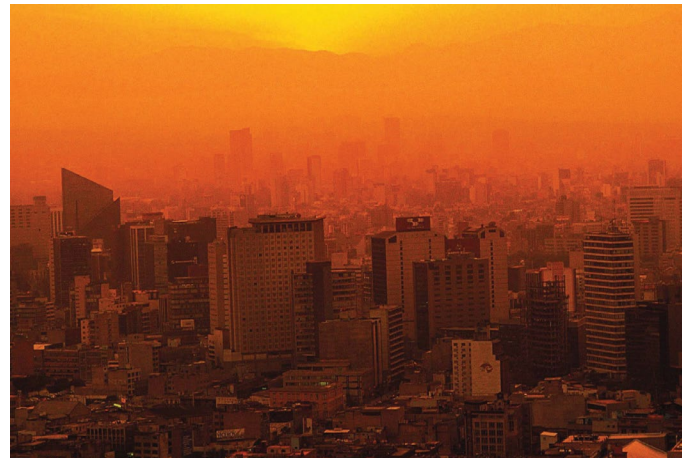
# Introduction

increased frequency and intensity of future heat waves



# Introduction

heat stress on the ecosystem, the built environment and humankind



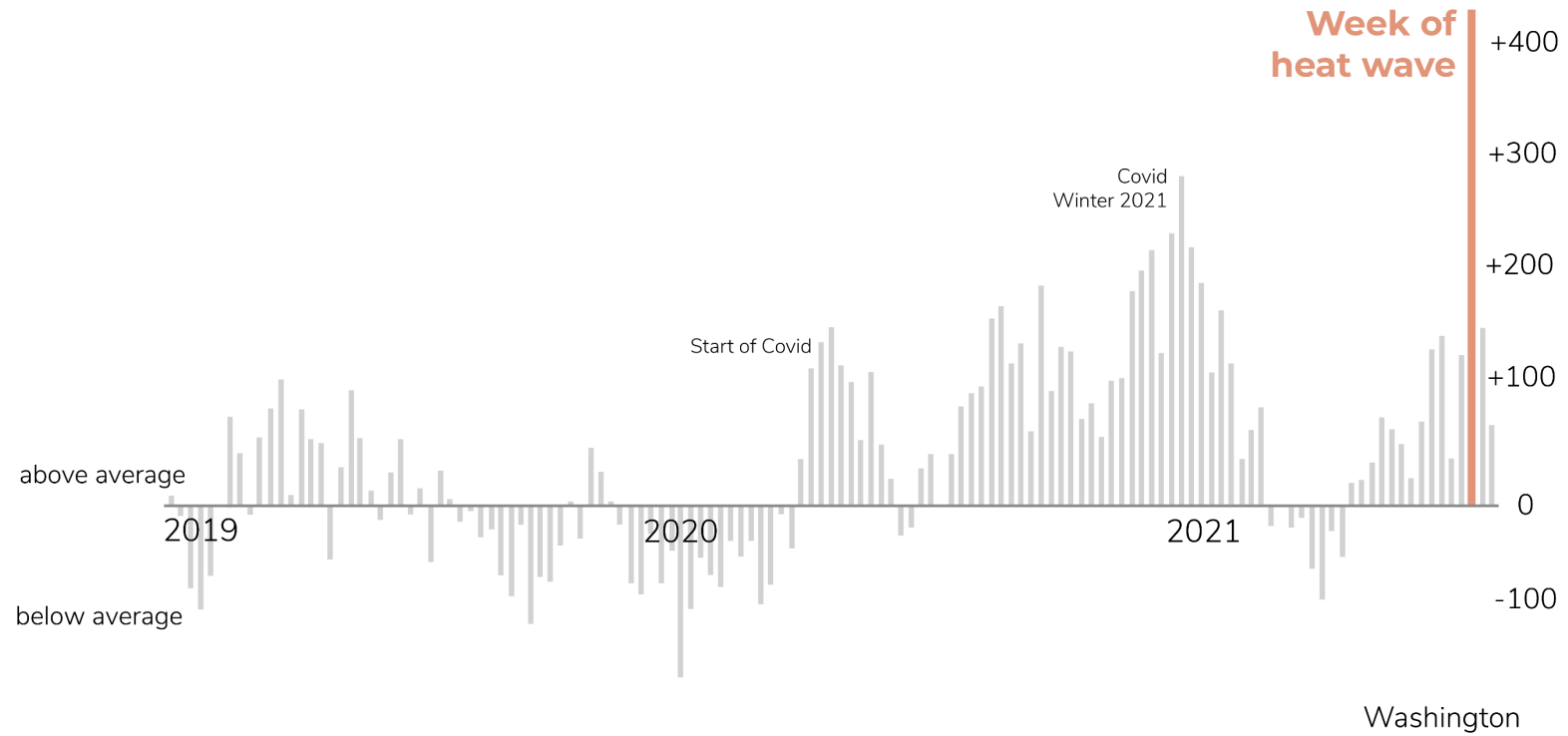
# Introduction

heat stress on the ecosystem, the built environment and humankind



# Introduction

heat stress on occupants



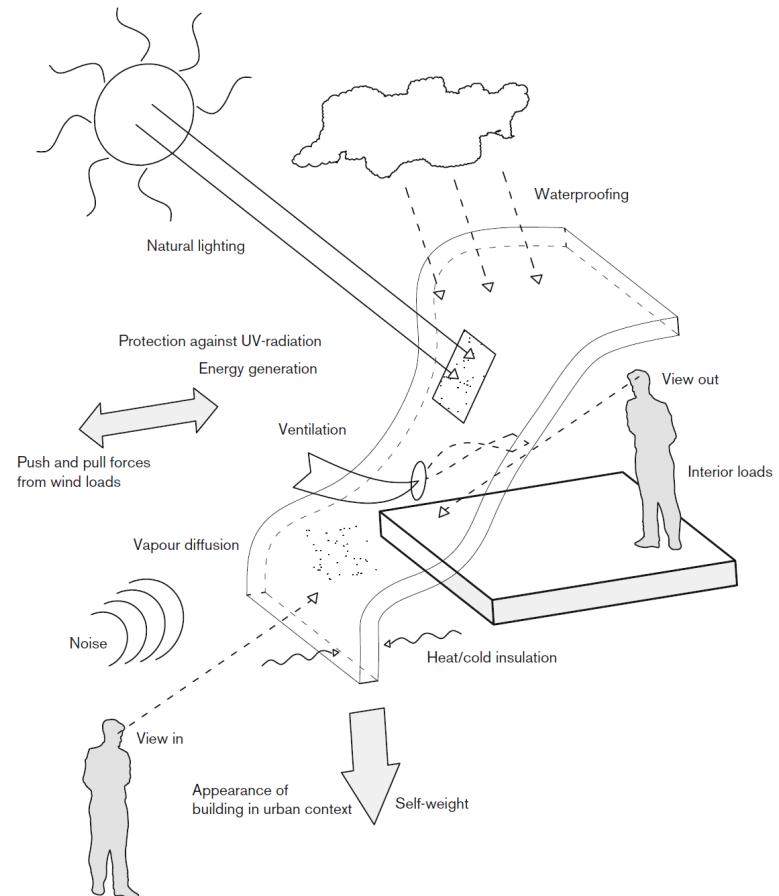
# Introduction

heat stress on occupants



# Research relevance

facade functions



# Relevance

UN goals

“inclusive, safe, **resilient** and sustainable cities and human settlements”

## **Problem statement**

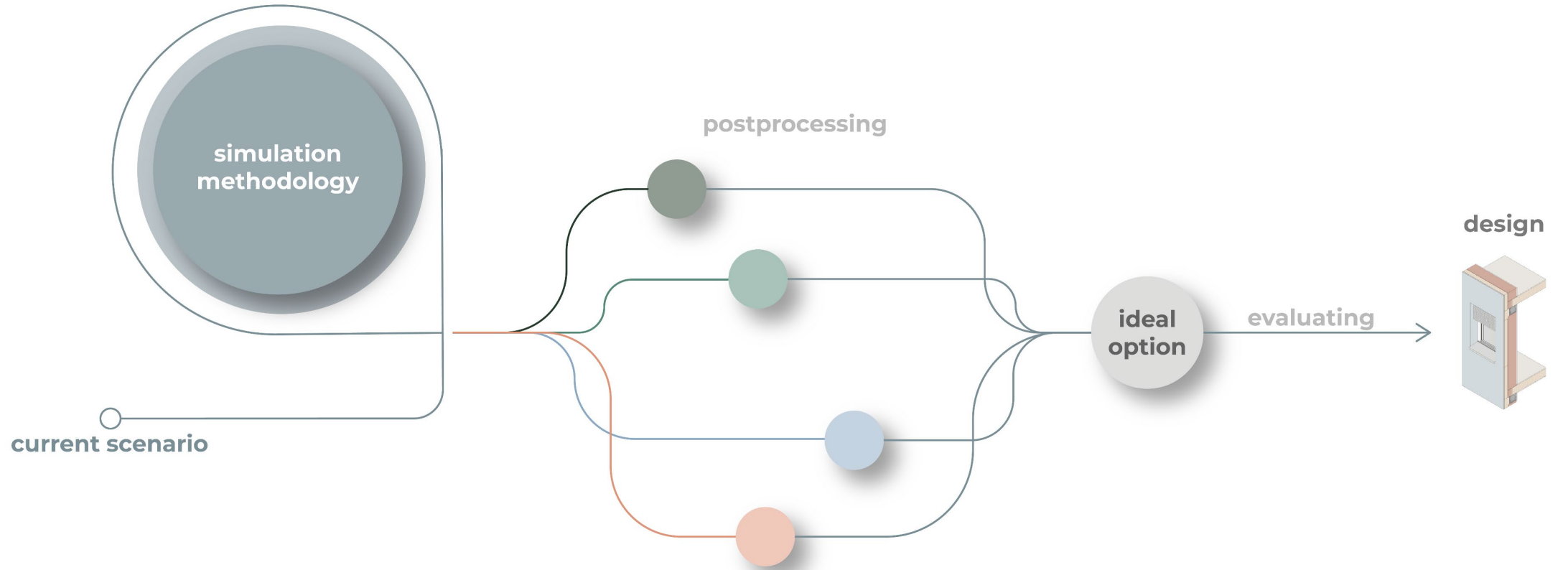
missing standards and regulations

but...

**guidelines and methods  
for the design of  
thermal resilient façades  
are not existing.**

# Research objectives

decision-making process



# Research questions

main research question

“How can we **evaluate** the **influence of façades** on **building thermal resilience** during heat waves?”

# Research questions

sub questions

- 1 How do **future climate-related heat waves** change **building requirements** for **façade** constructions?

# Research questions

sub questions

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What are **commonly** used **metrics**?

# Research questions

sub questions

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- 3 How could current **assessment methodologies** of building thermal resilience be **improved**?

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What are **commonly** used **metrics**?
- 3 How could current **assessment methodologies** of building thermal resilience be **improved**?
- 4 What are **relevant façade parameters** to be **considered** for **retrofitting improving occupants' thermal comfort** during **extreme heat events**?

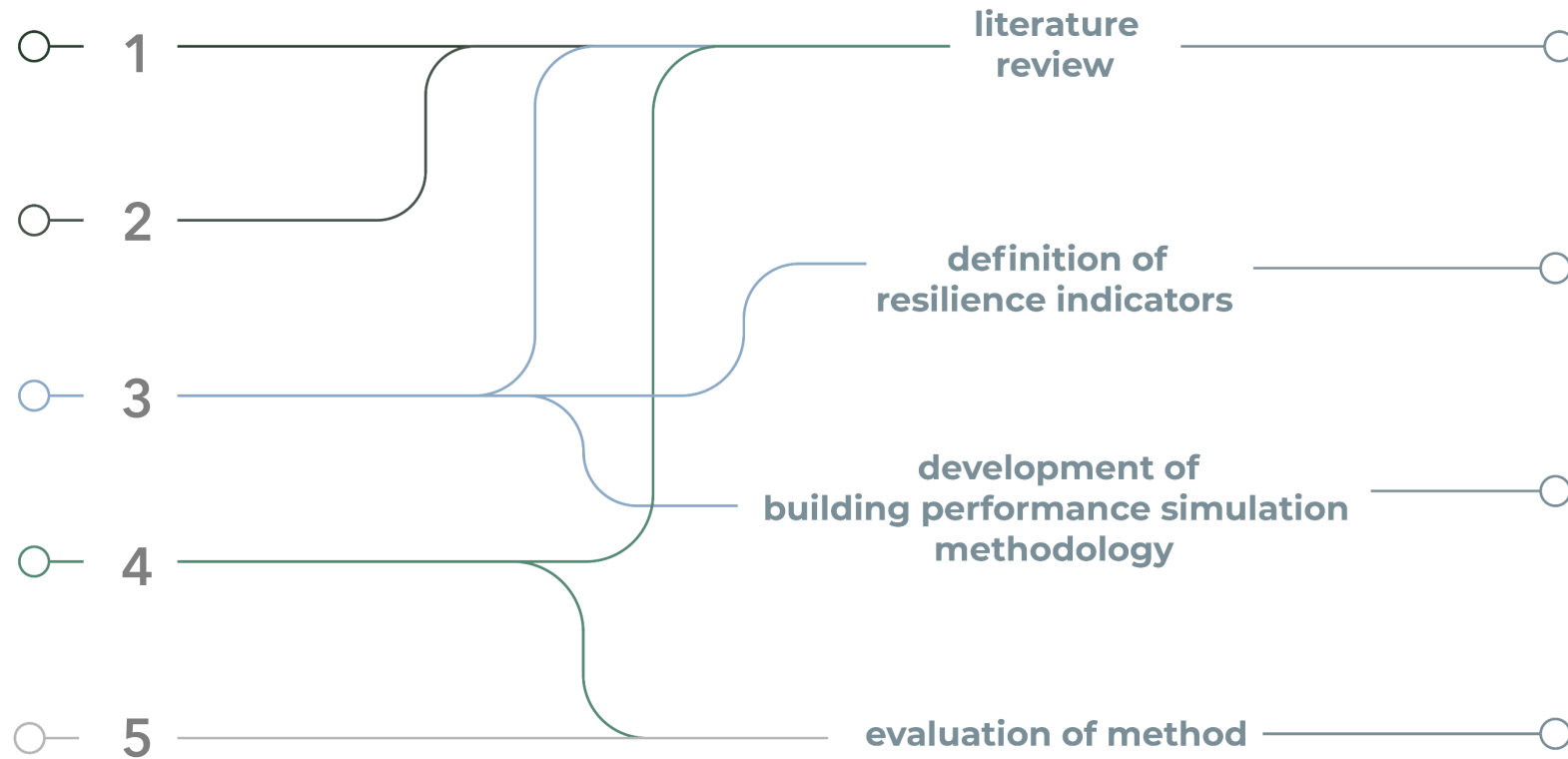
# Research questions

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What are **commonly** used **metrics**?
- 3 How could current **assessment methodologies** of building thermal resilience be **improved**?
- 4 What are **relevant façade parameters** to be **considered** for **retrofitting** improving occupants' **thermal comfort** during **extreme heat events**?
- 5 What are the most important **façade parameters influencing resilience indicators**?

# Research questions

sub questions



# Research outline

- literature review **1**
- definition of resilience indicators **2**
- development of simulation methodology **3**
- simulation set up and definition of case study **4**
- sensitivity analysis **5**
- postprocessing **6**
- final evaluation **7**
- design **8**
- conclusion **9**

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literature review

**1**

definition of resilience indicators

**2**

development of simulation methodology

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simulation set up and definition of case study

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sensitivity analysis

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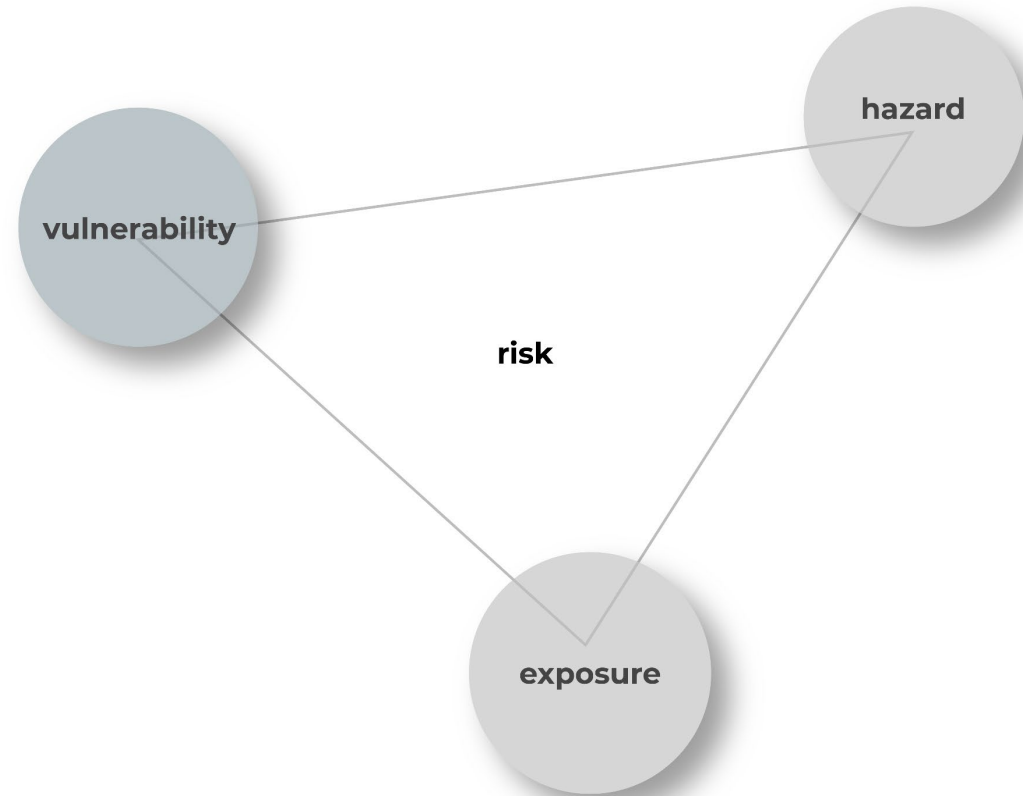
**9**



**What is „resilience“?**

# Resilience definition

terminology



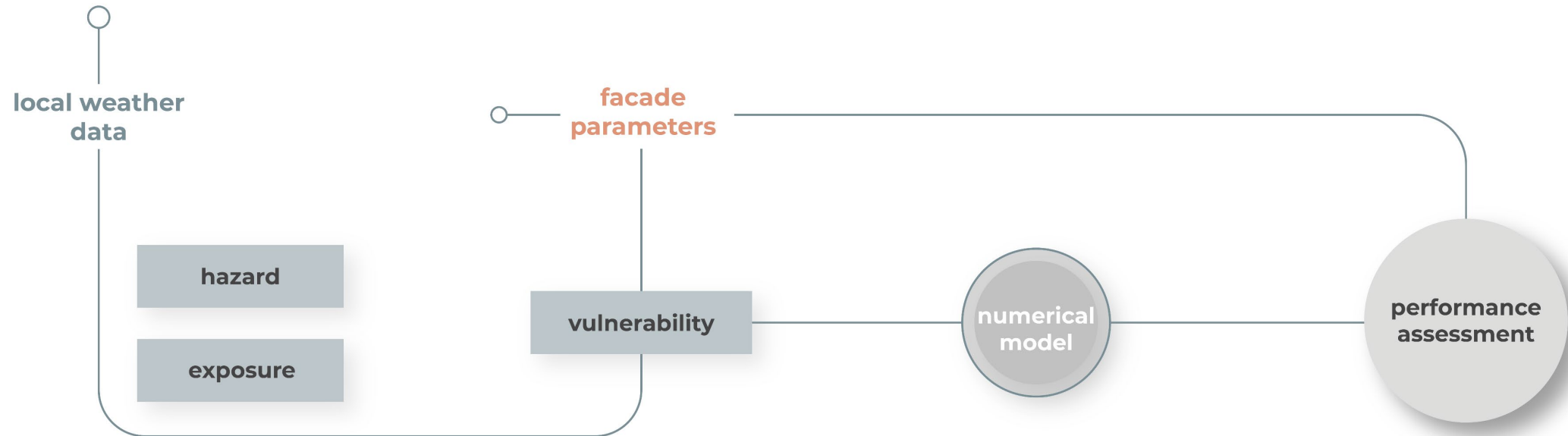
# Resilience definition

terminology



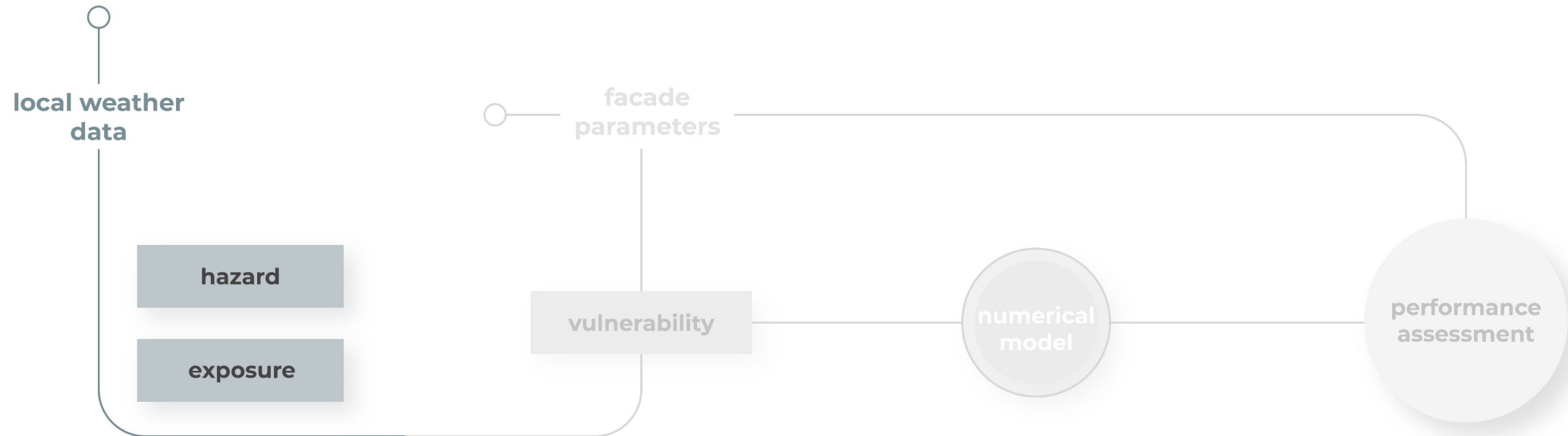
# Assessment methodology

quantitative



# Assessment methodology

heat wave hazard



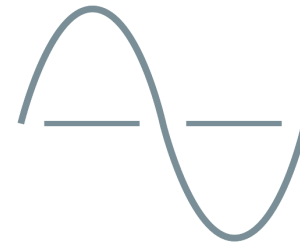
# Heat wave definition

**heat waves are periods consecutive days with excessively hotter conditions than normal**

Pattenden, 2003; Trigo, 2005

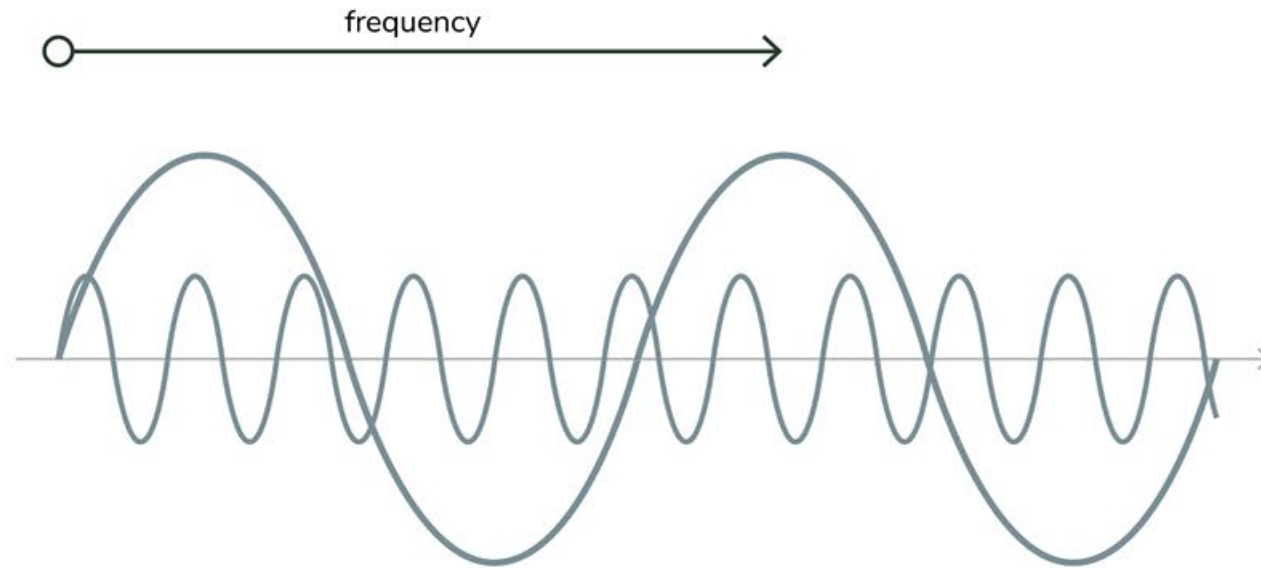
# Heat wave definition

characteristics of waves



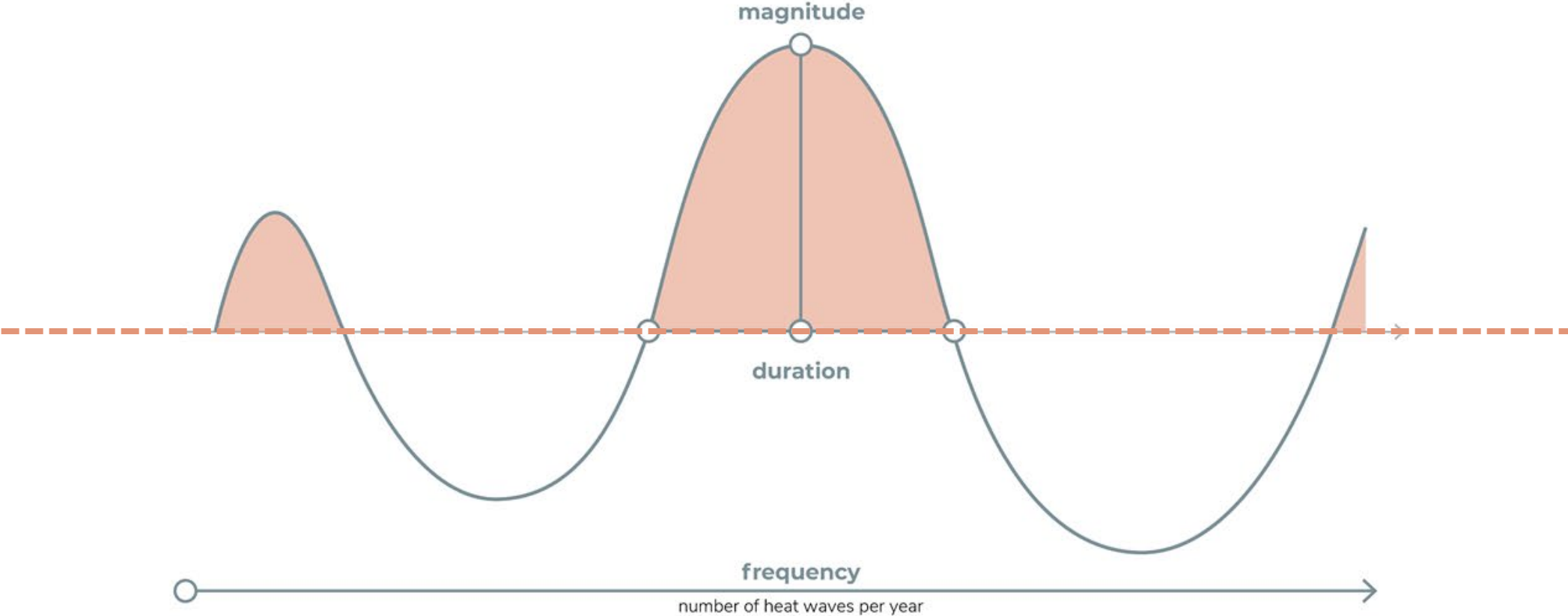
# Heat wave definition

characteristics of waves



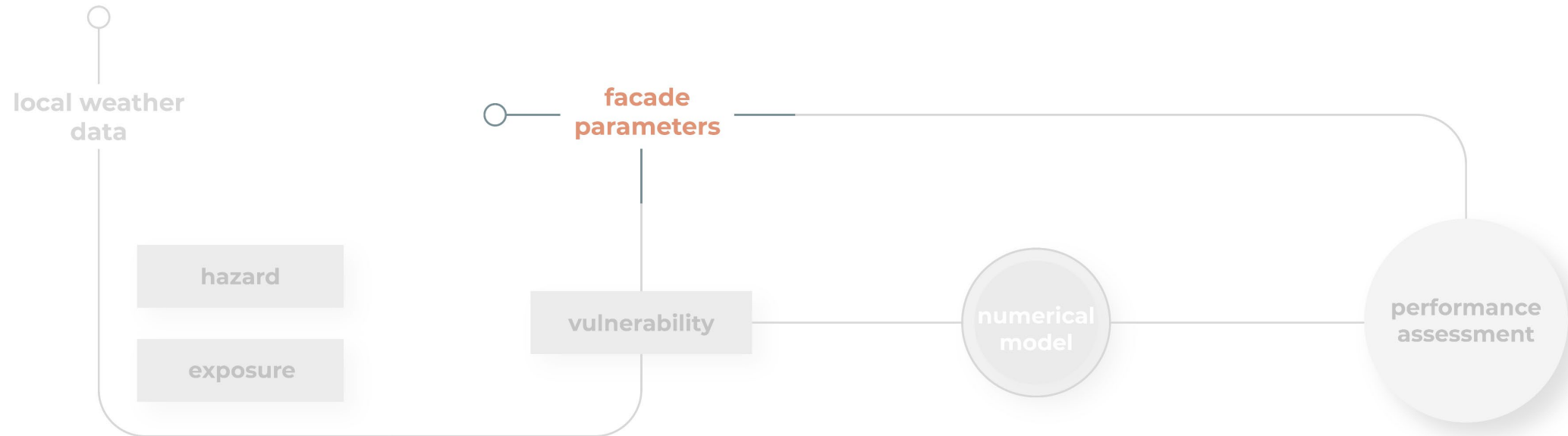
# Heat wave definition

heat wave indices



# Assessment methodology

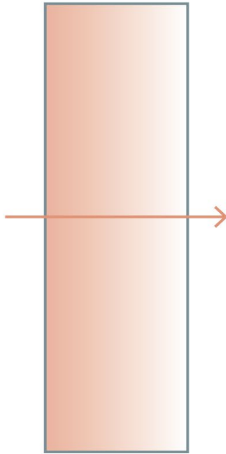
identification of facade parameters



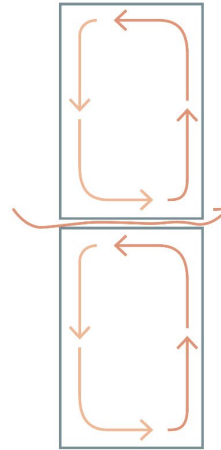
# Heat transfer

three principles

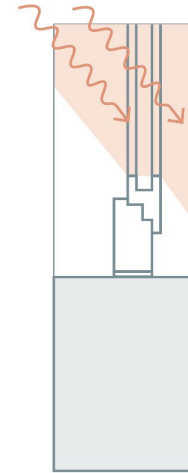
**conduction**



**convection**



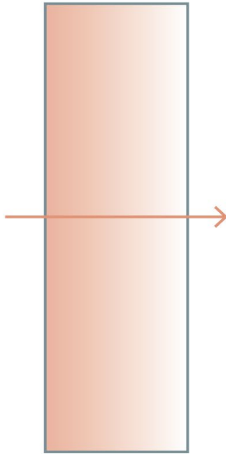
**radiation**



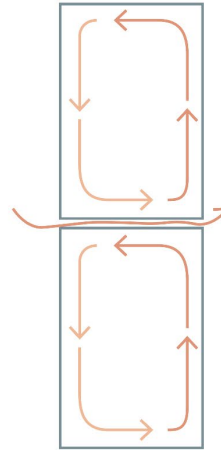
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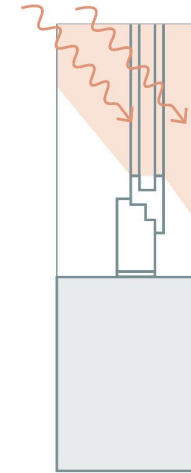
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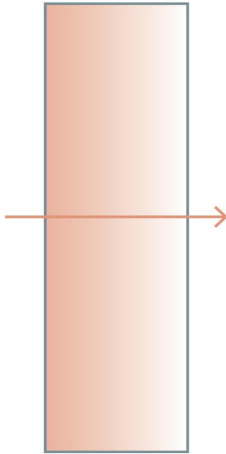
**radiation**



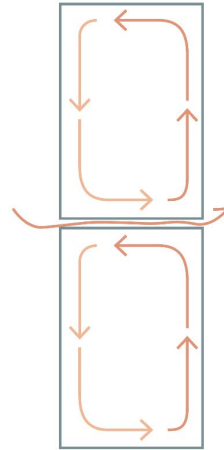
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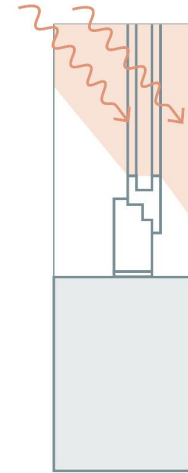
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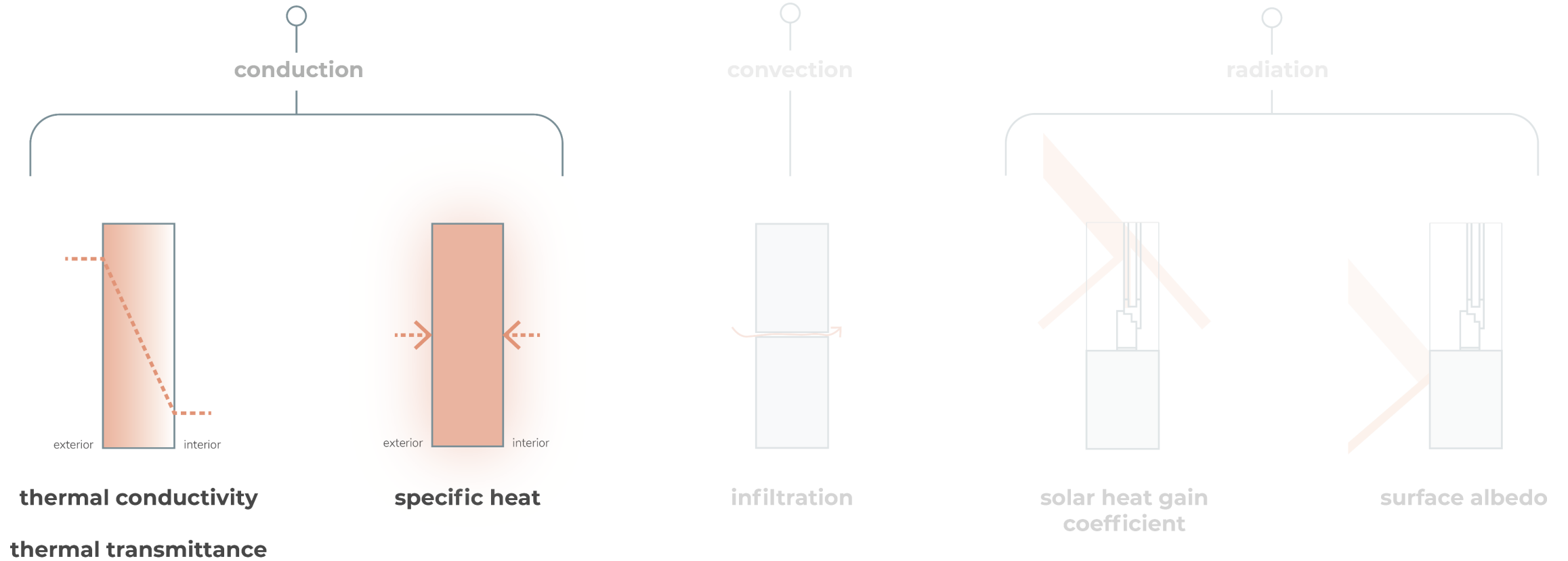


**radiation**



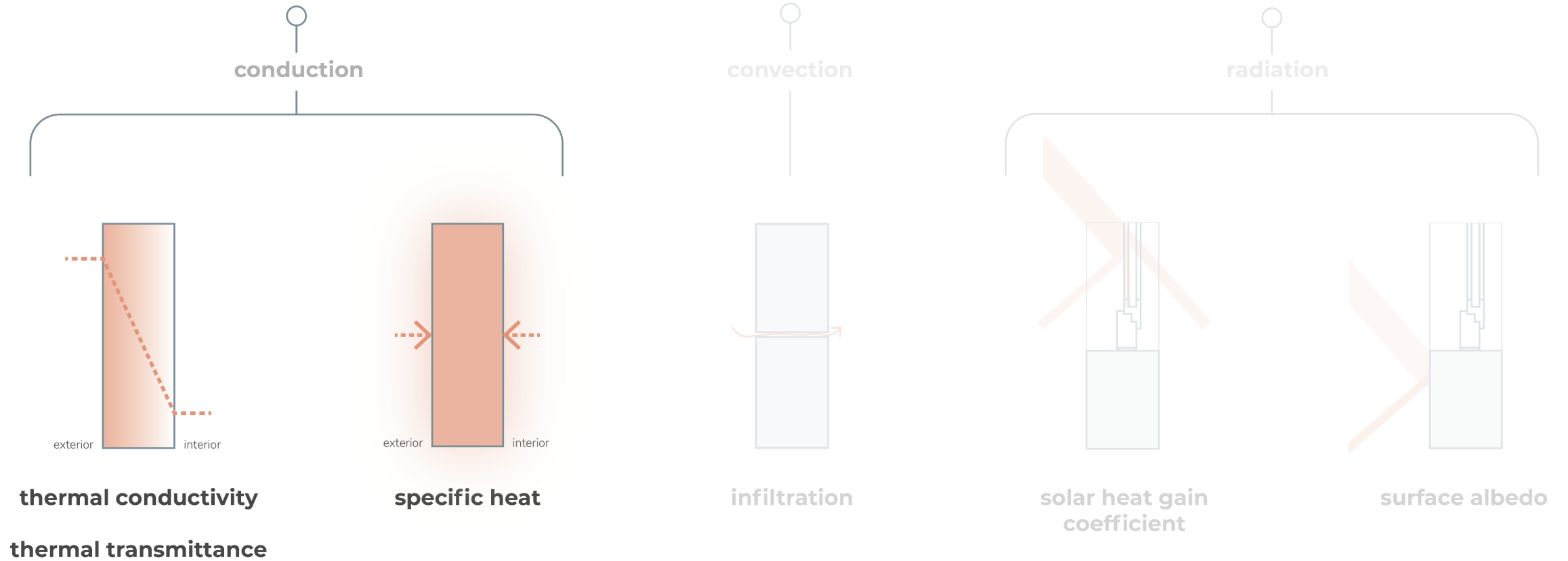
# Heat transfer

relevant facade parameters



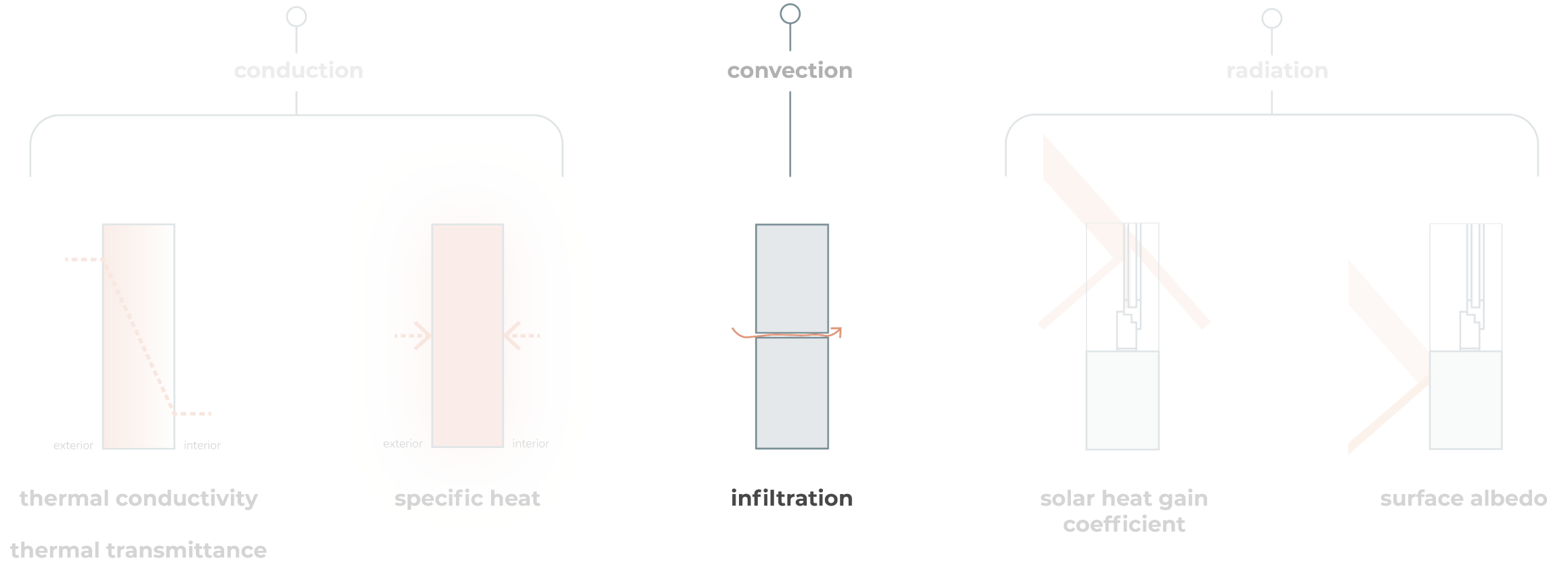
# Heat transfer

relevant facade parameters



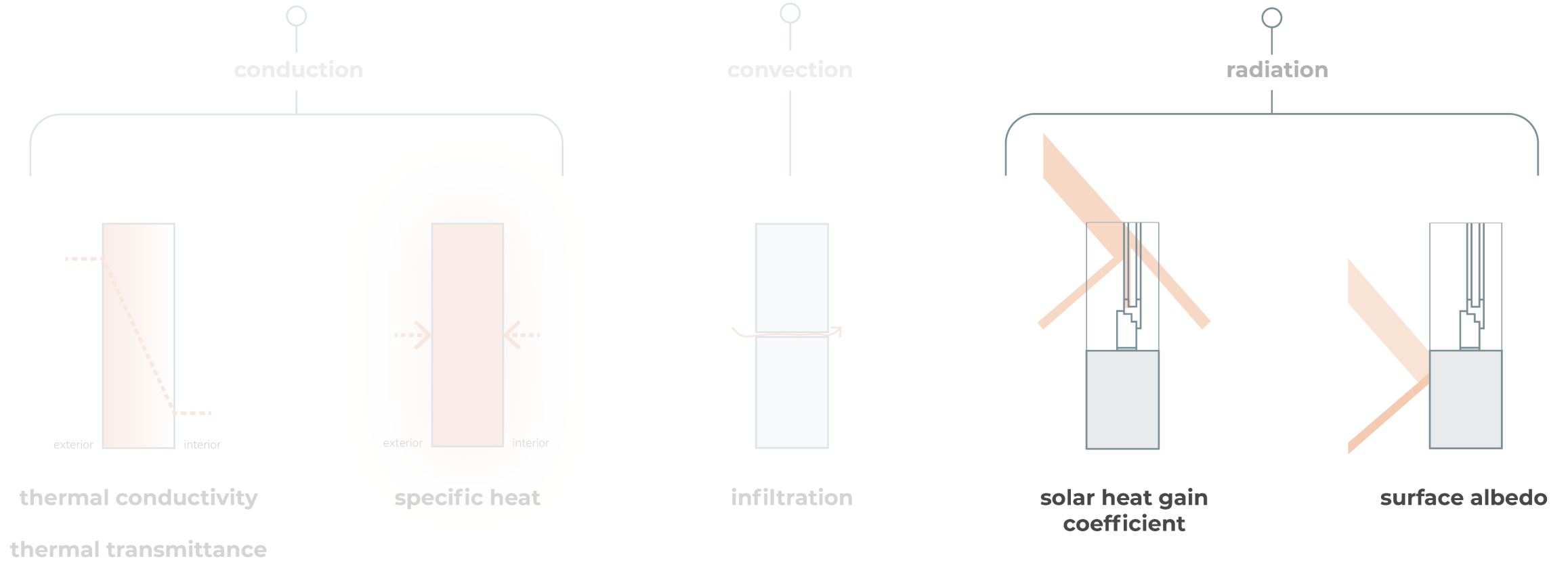
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relevant facade parameters



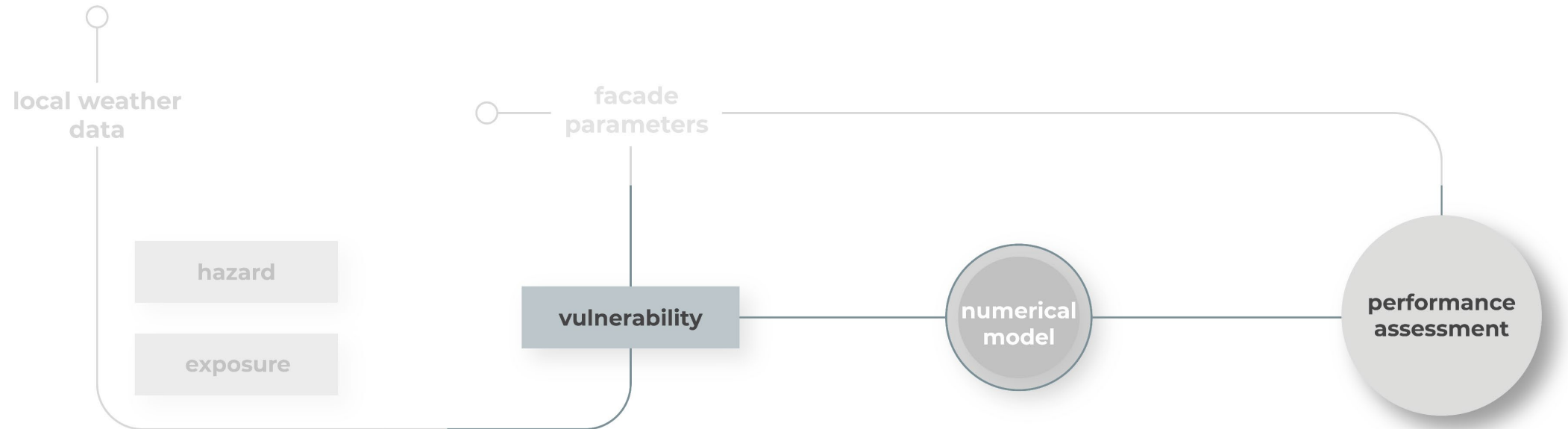
# Heat transfer

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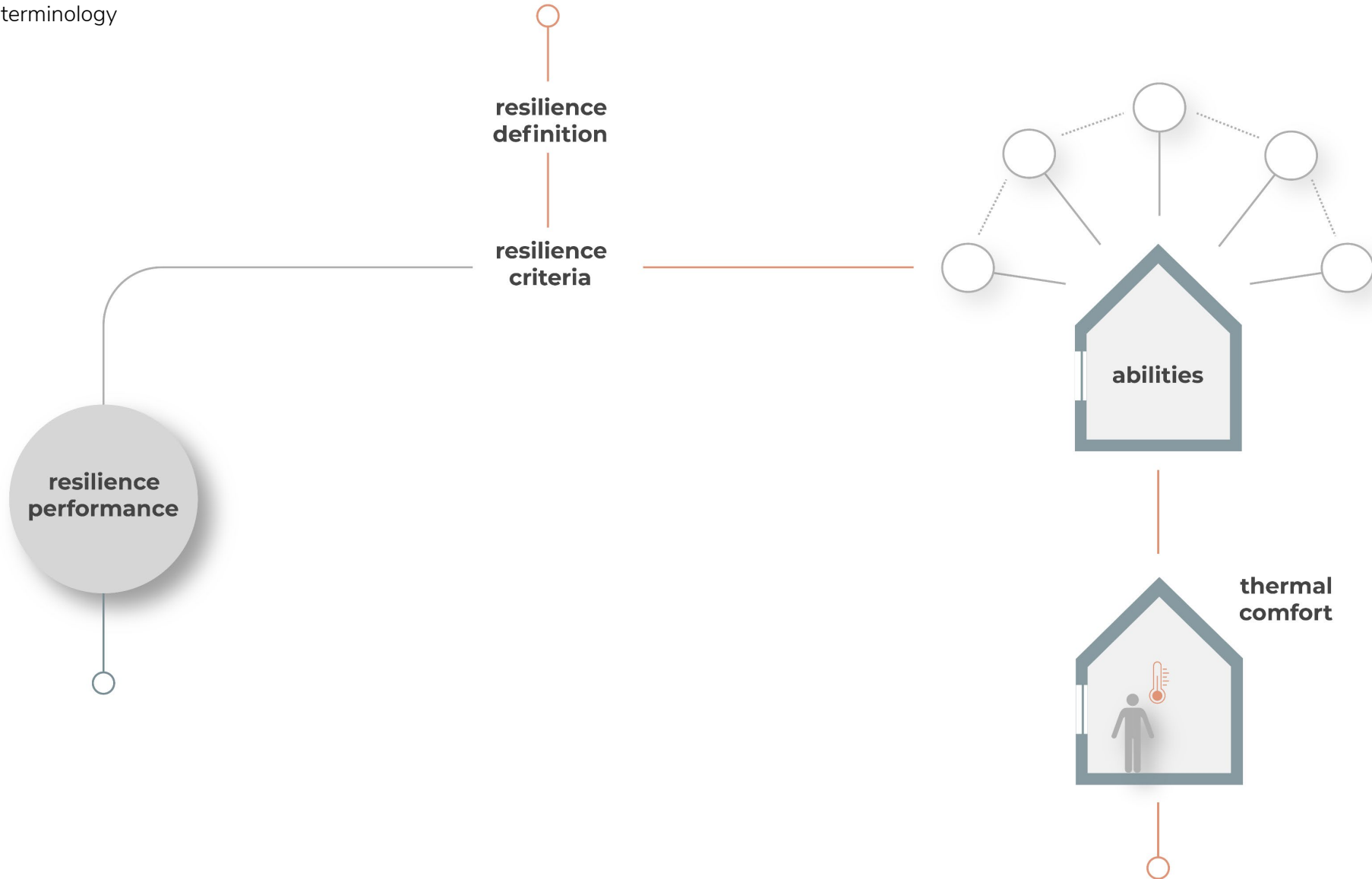
# Assessment methodology

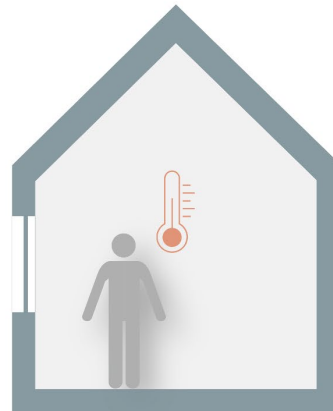
performance assessment



# Assessment methodology

resilience terminology

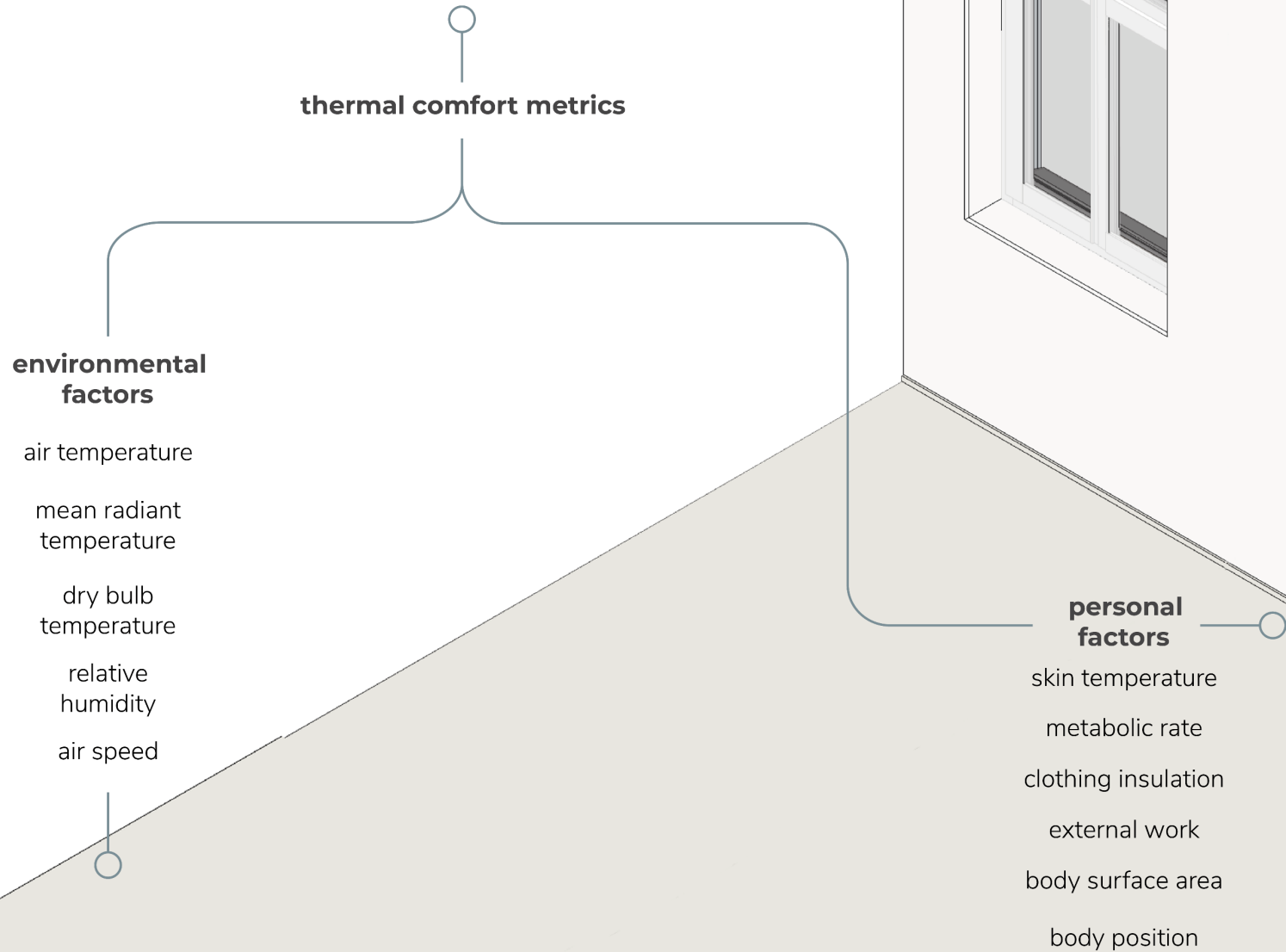




**thermal comfort**


# Literature review

important findings – thermal comfort metrics



# Literature review

important findings – SET



**Standard effective temperature (SET)**

mean radiant temperature

dry bulb temperature

relative humidity

air speed


metabolic rate

clothing insulation

external work

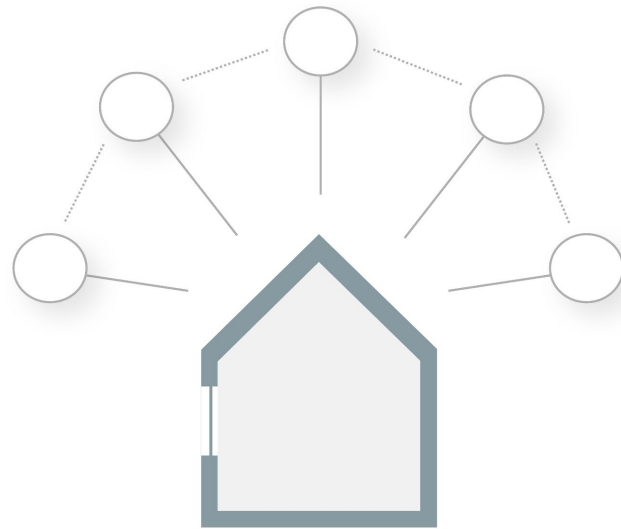
body surface area

body position



**equivalent temperature** which **hypothesizes** a standard environment to embody **multi-factor effects** comprehensively

(Ji et al., 2022)



**abilities**

# Resilience criteria

translation of resilience criteria to indices

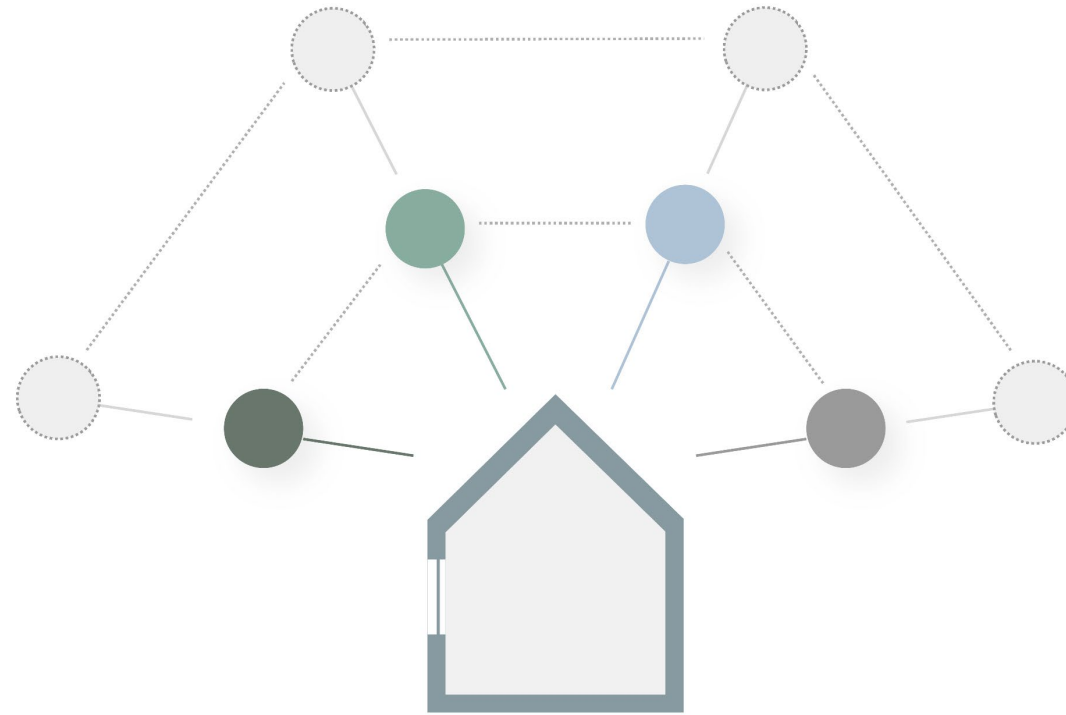
preparation

absorption

adaptability

recovery

durability



**proposal**

literature review **1**

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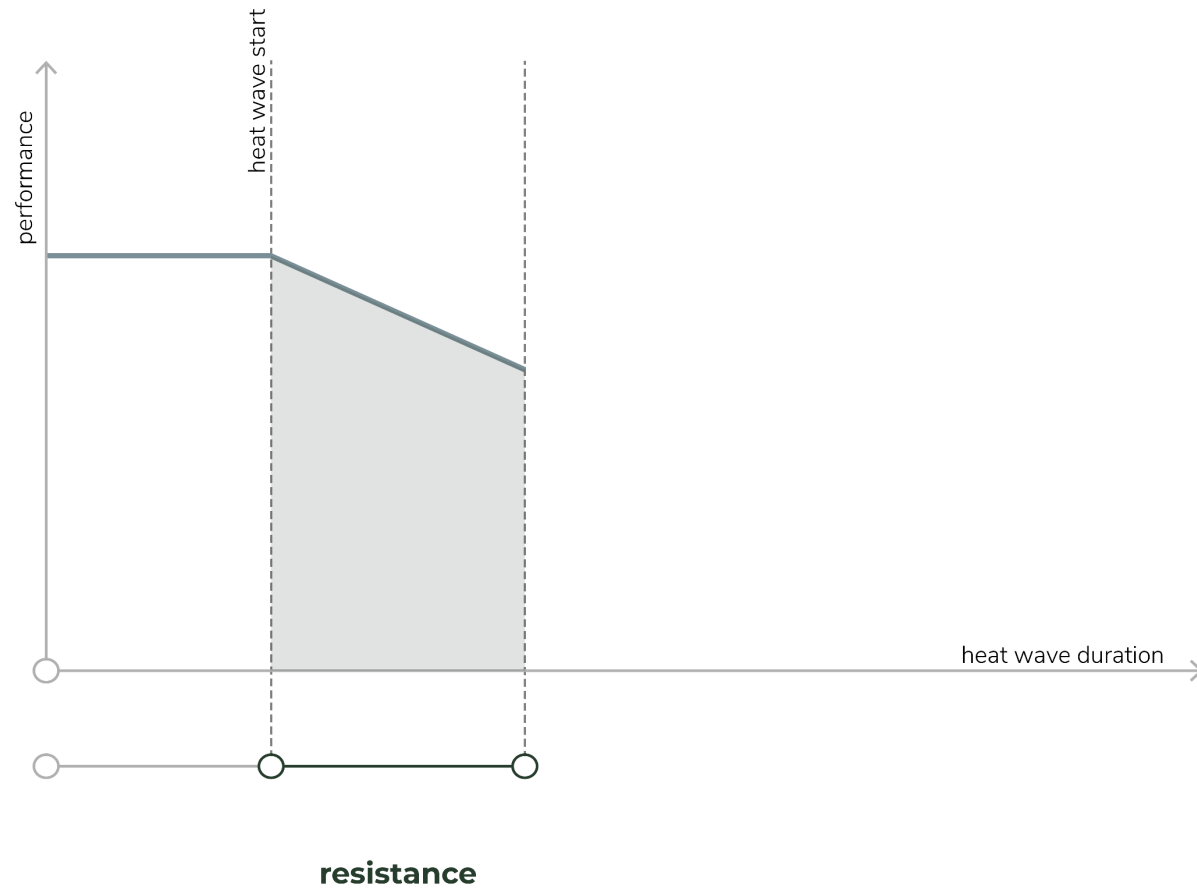
design **8**

conclusion **9**



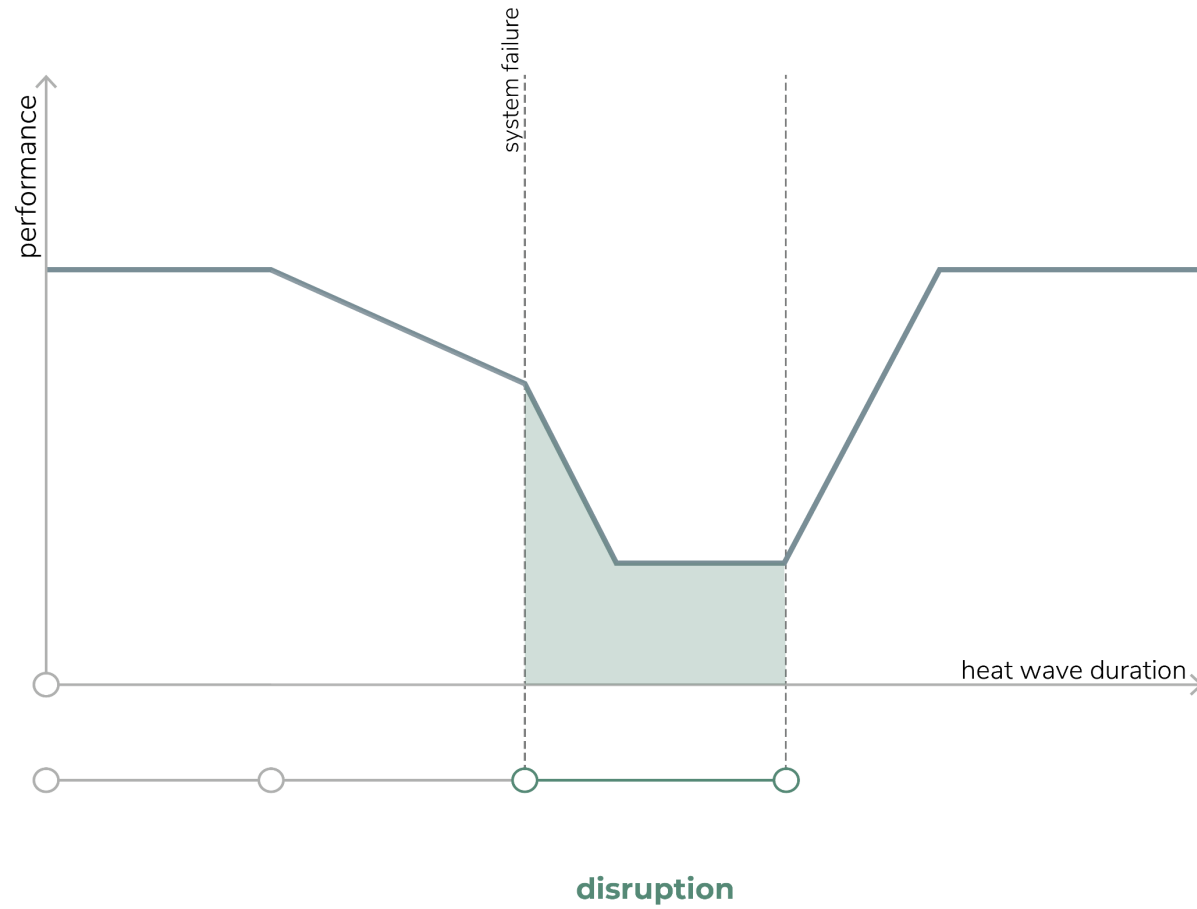
# Resilience performance graph

incl. resilience stages



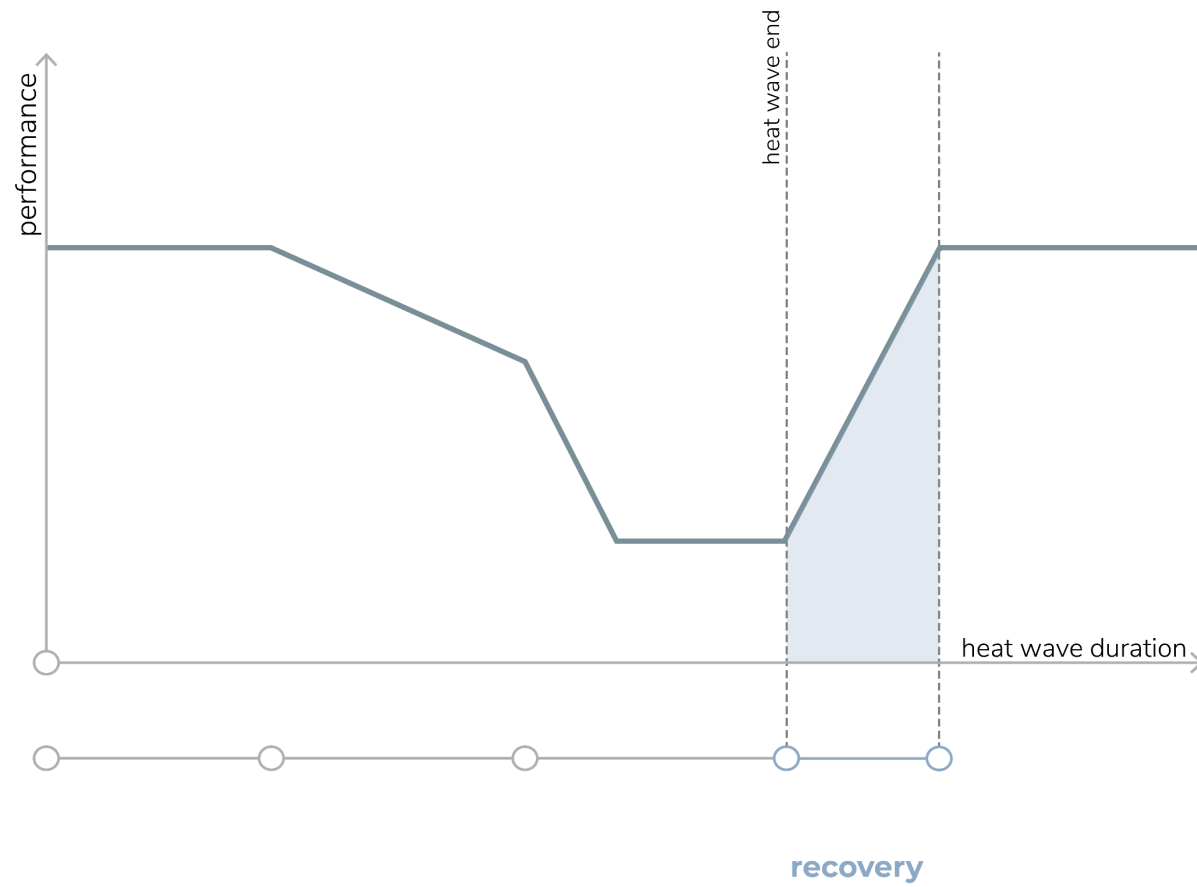
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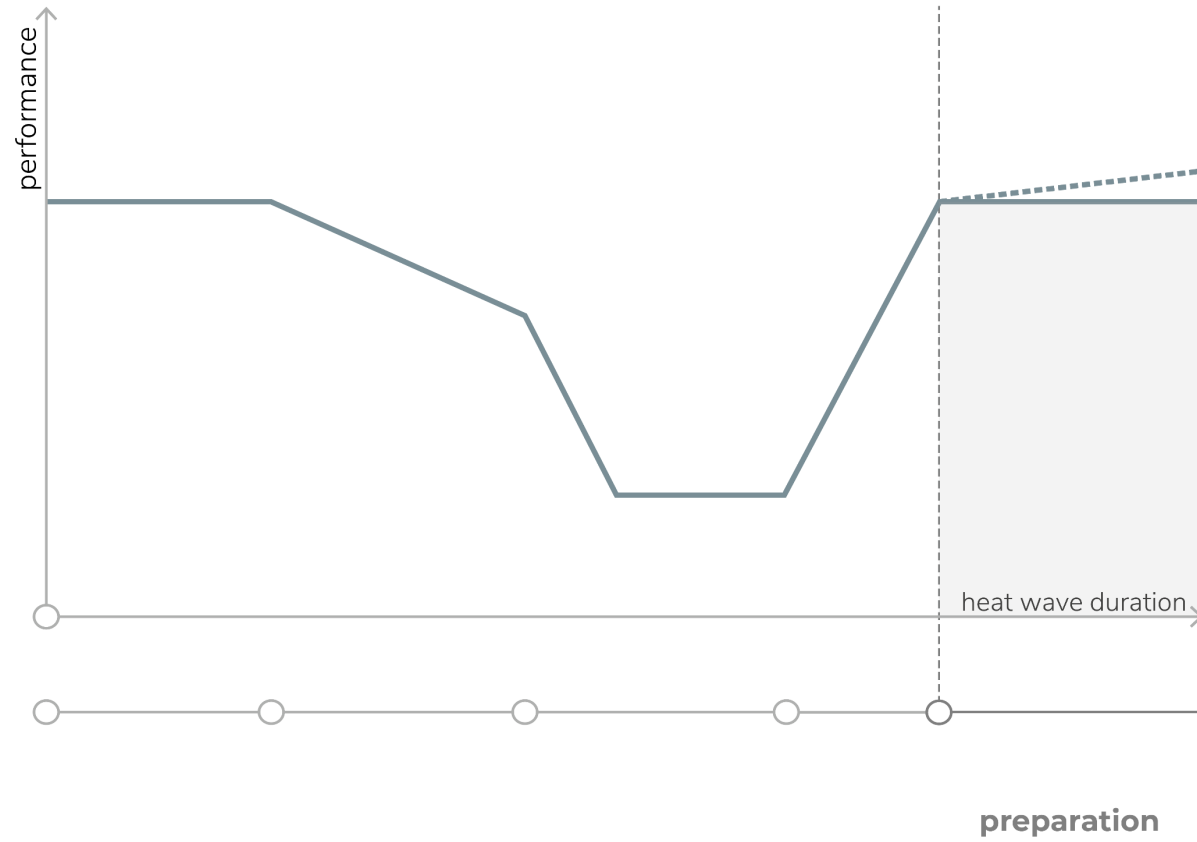
# Resilience performance graph

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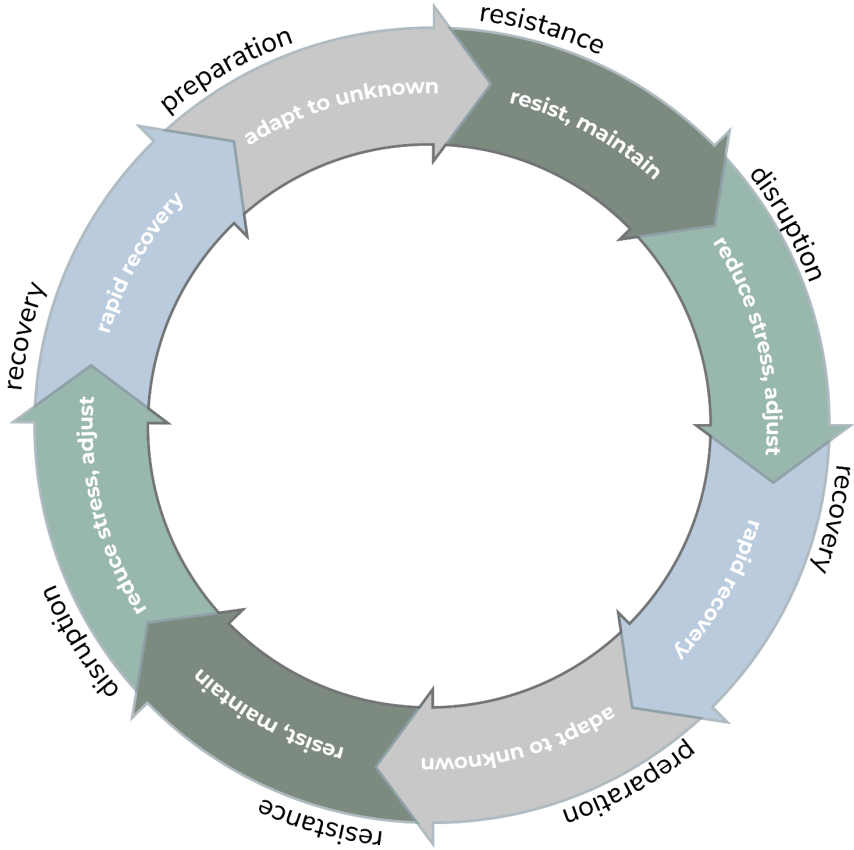
# Resilience performance graph

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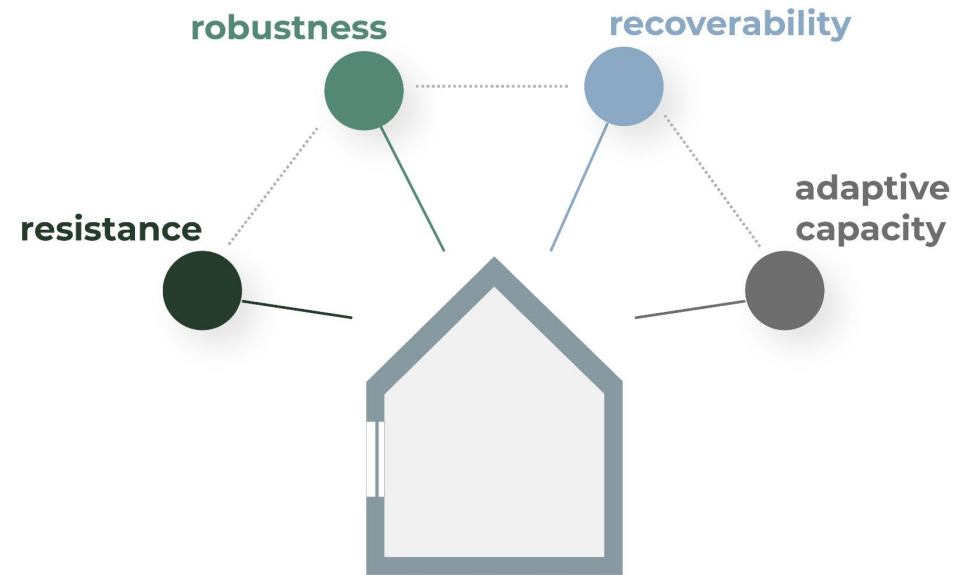
# Resilience definition

cyclic



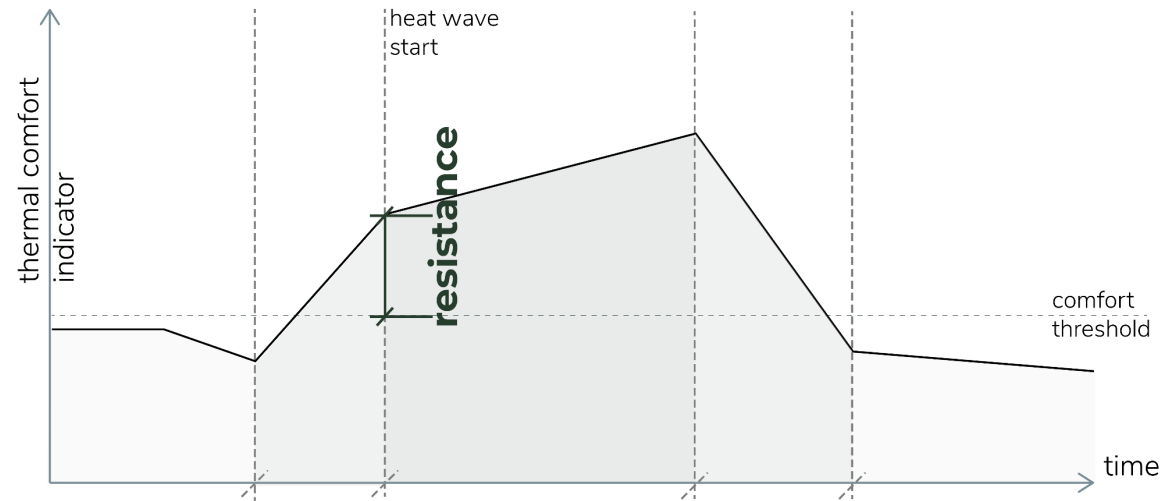
# Resilience definition

resilience indicators



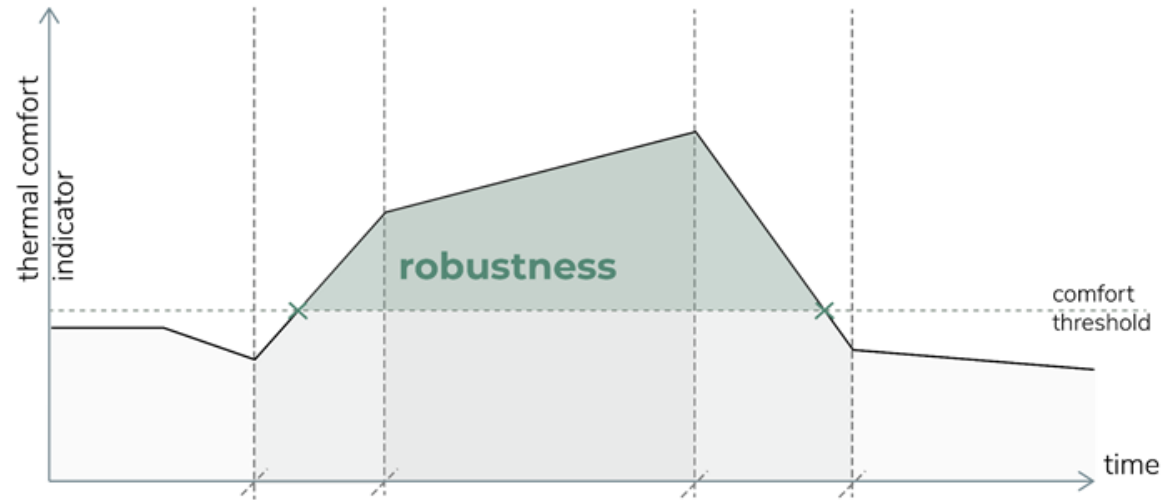
# Resilience indicators

resistance



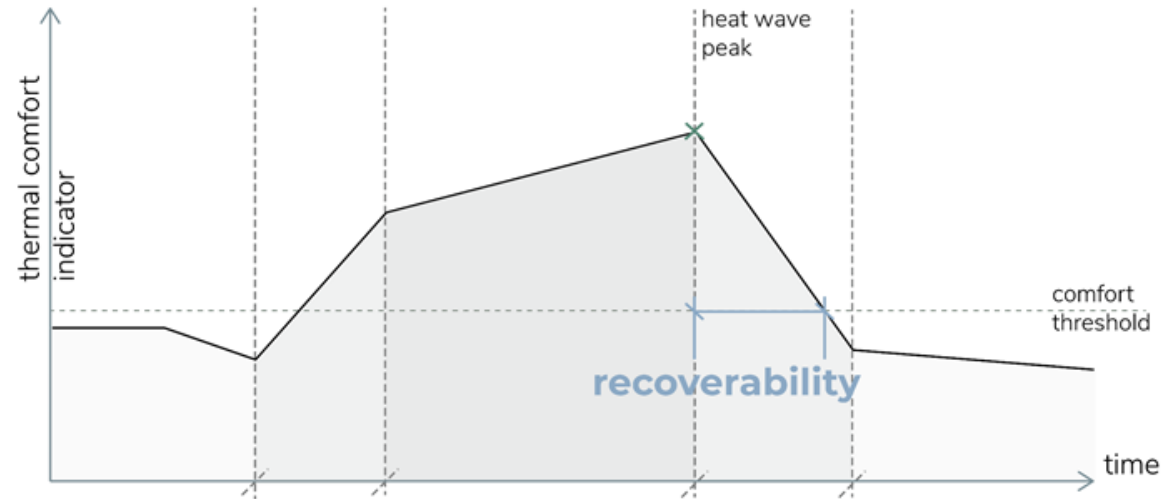
# Resilience indicators

robustness



# Resilience indicators

recoverability



# Resilience indicators

adaptive capacity

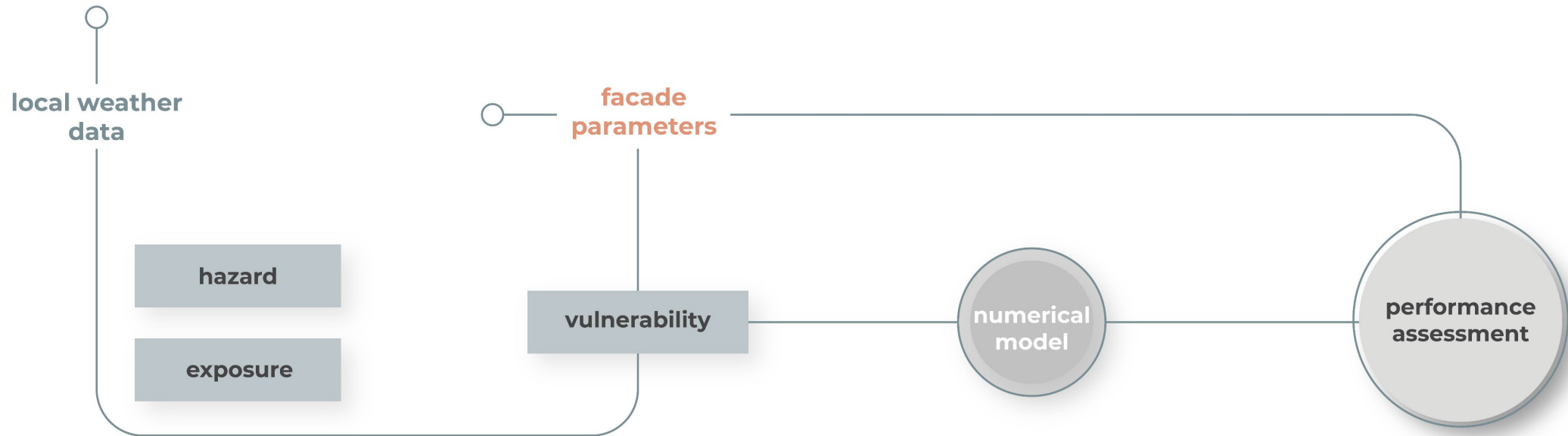


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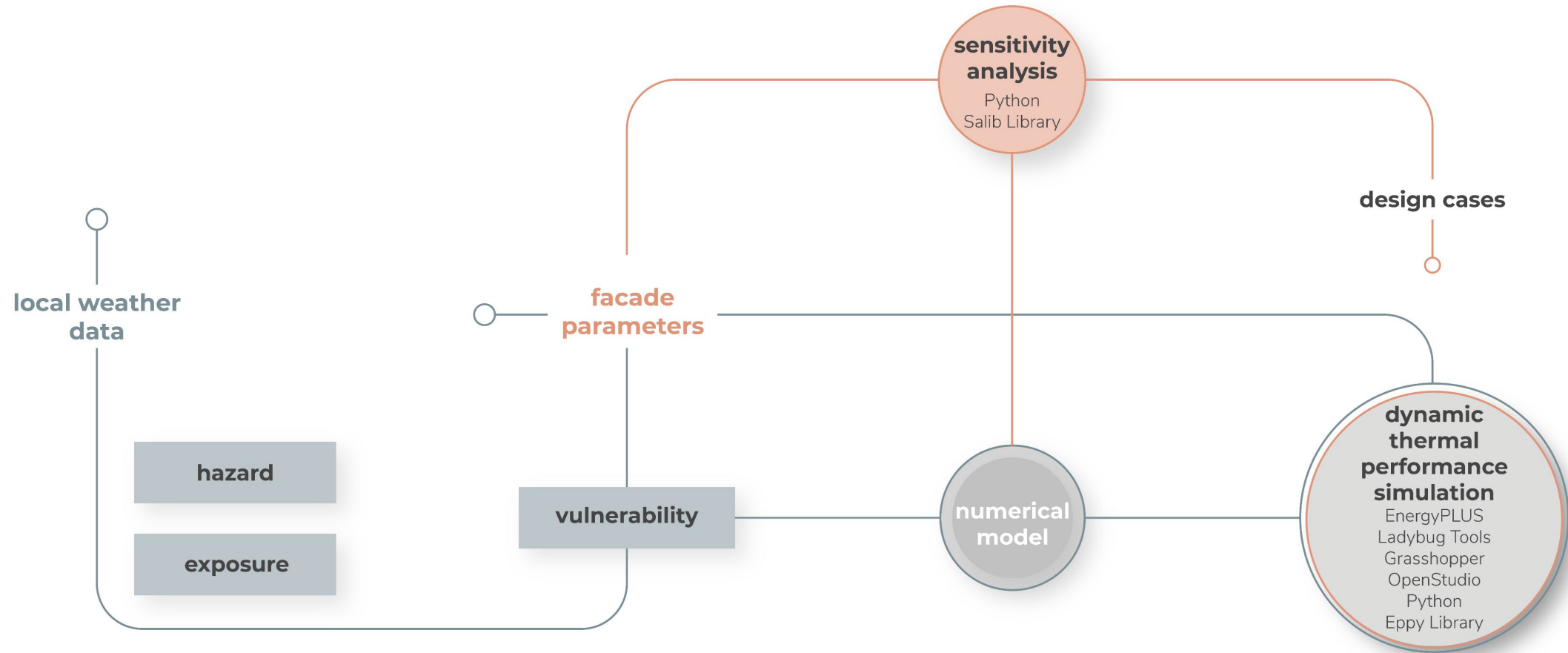


# Assessment methodology

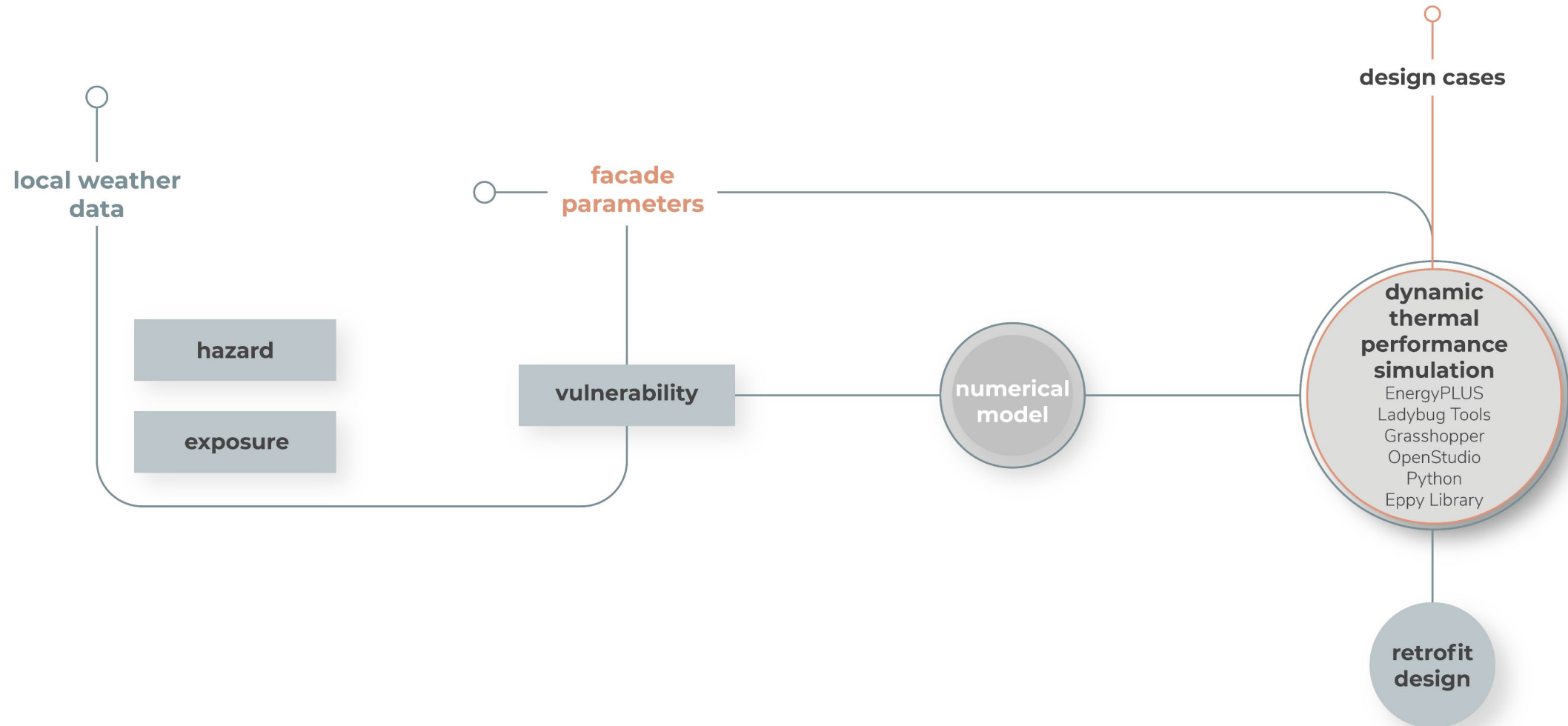
quantitative



# Simulation methodology



# Simulation methodology



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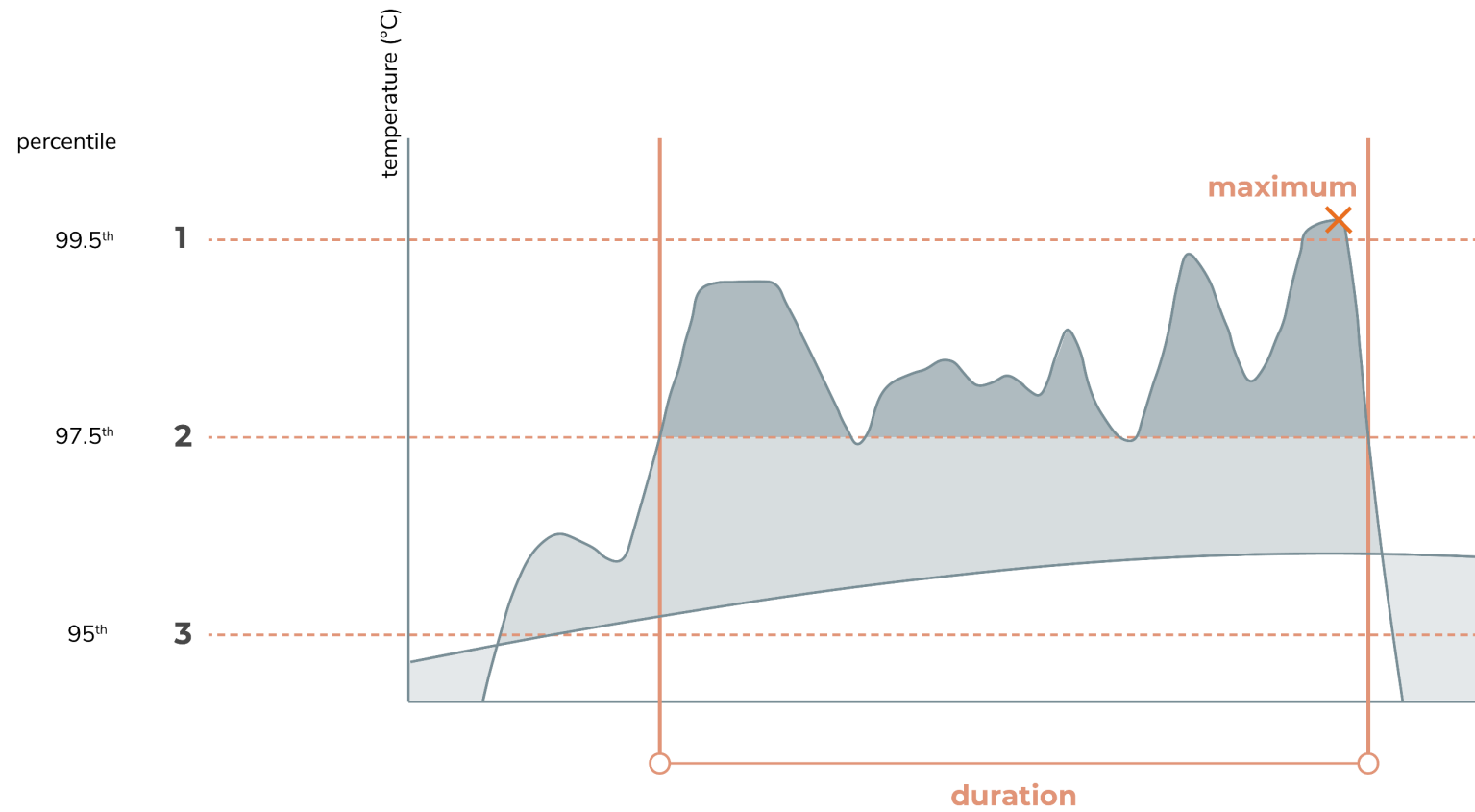


## Case study location



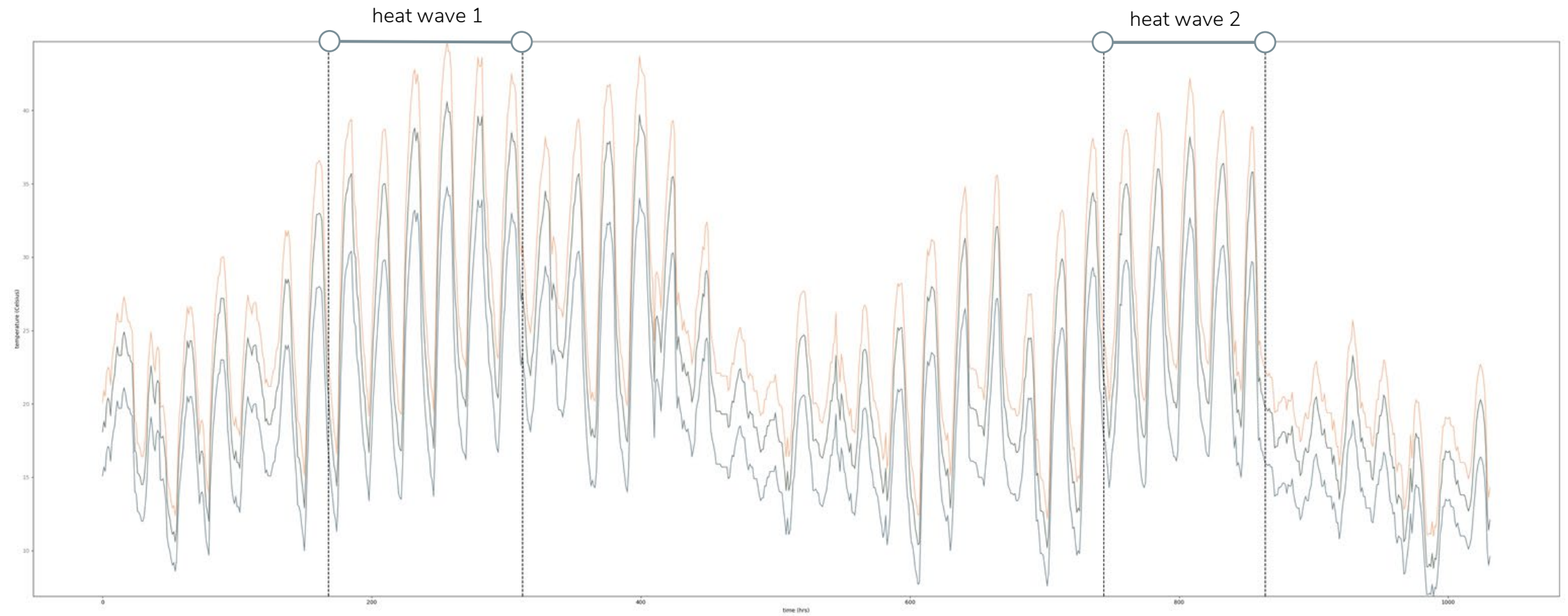
# Heat wave

threshold definition



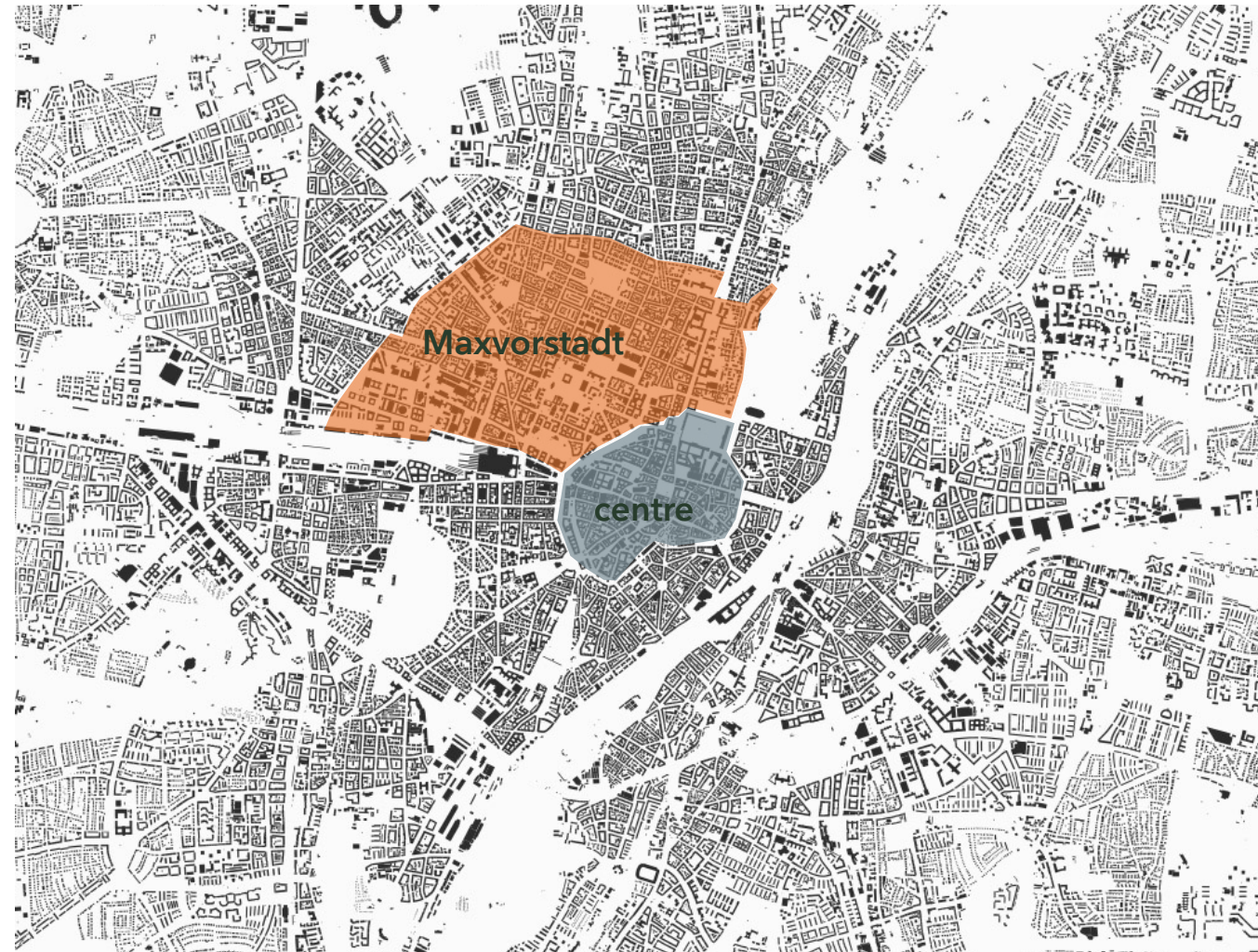
# Weather data

development of EPW



# Introduction case study

Location in Munich



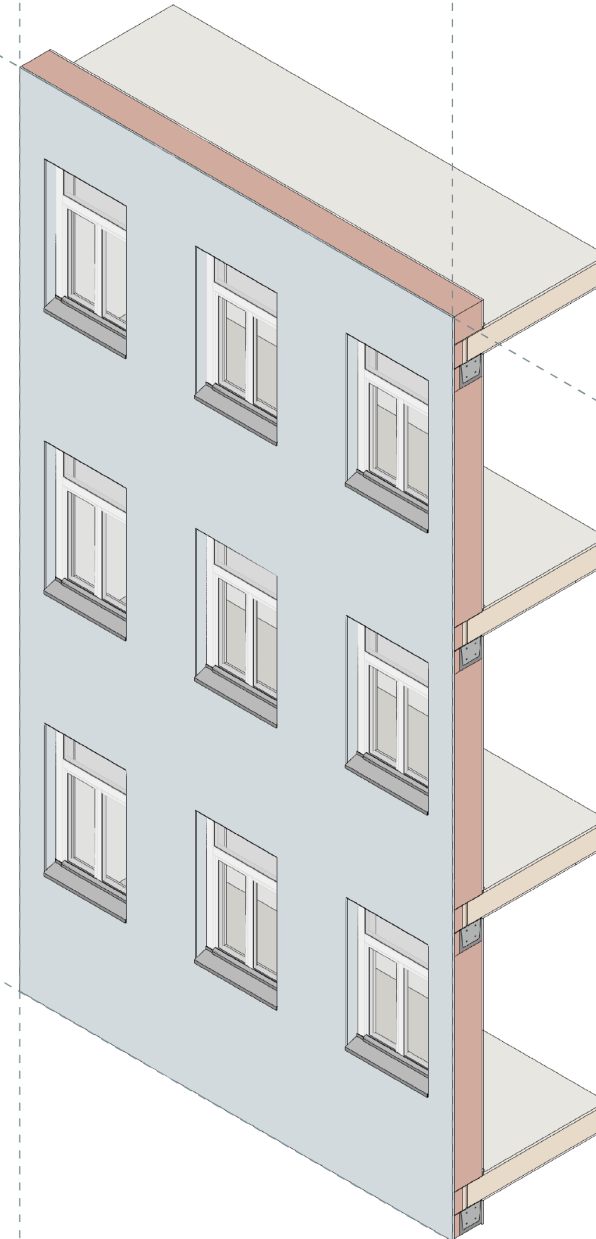
# Introduction case study

Location Maxvorstadt



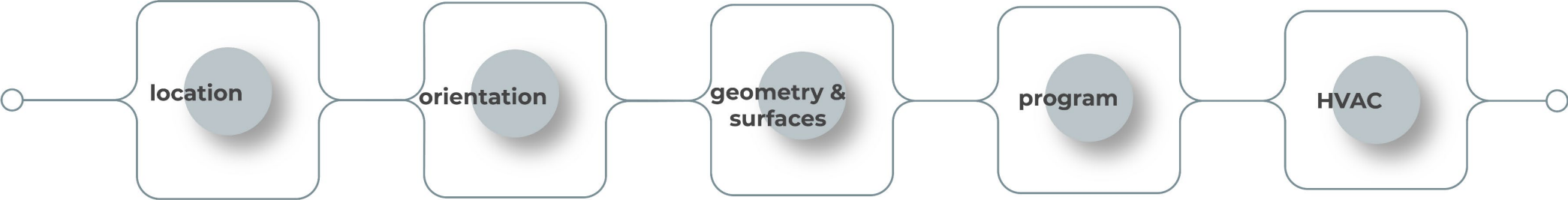
# Introduction case study

Archetype facade



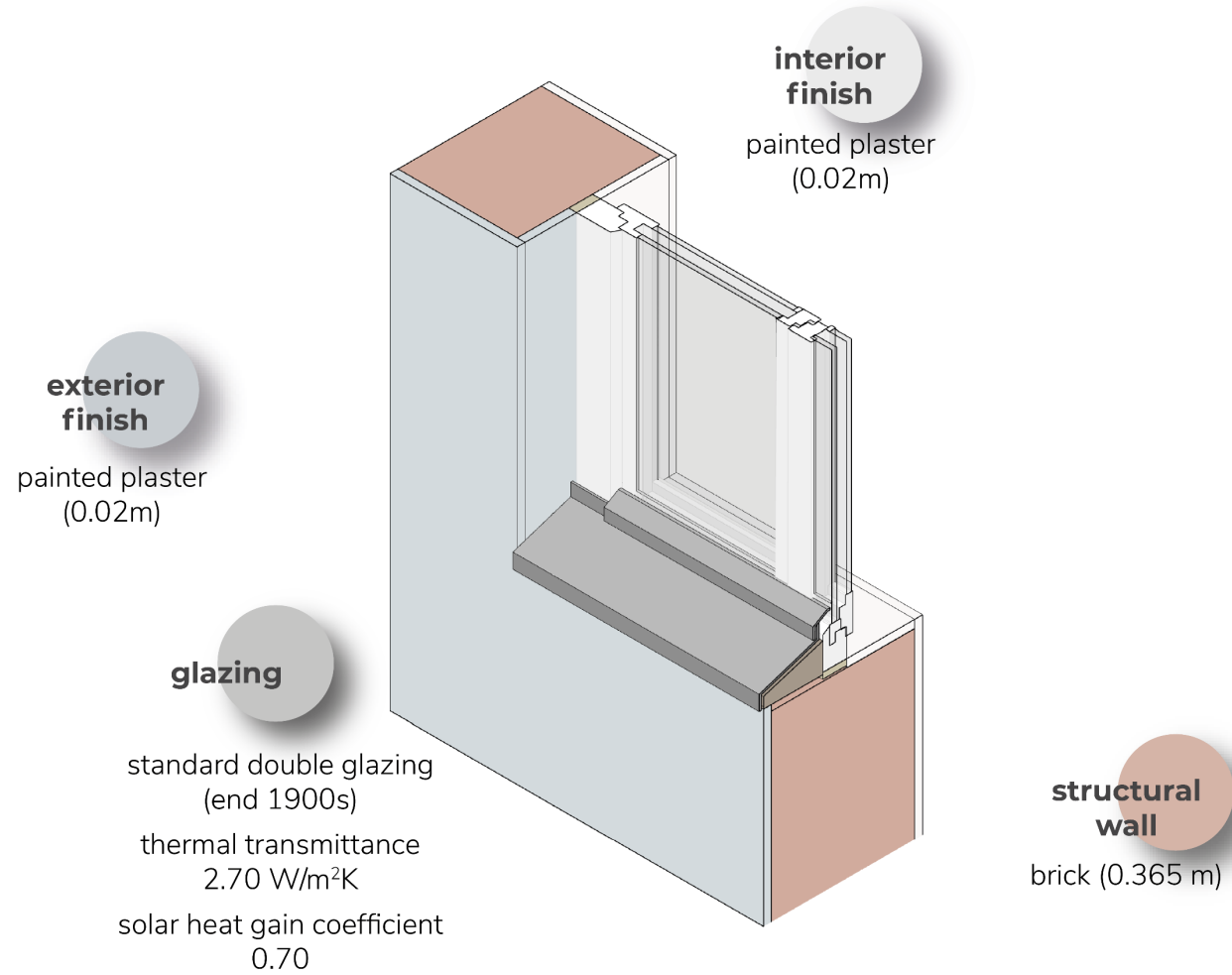
# Base case simulation set up

Fixed parameters



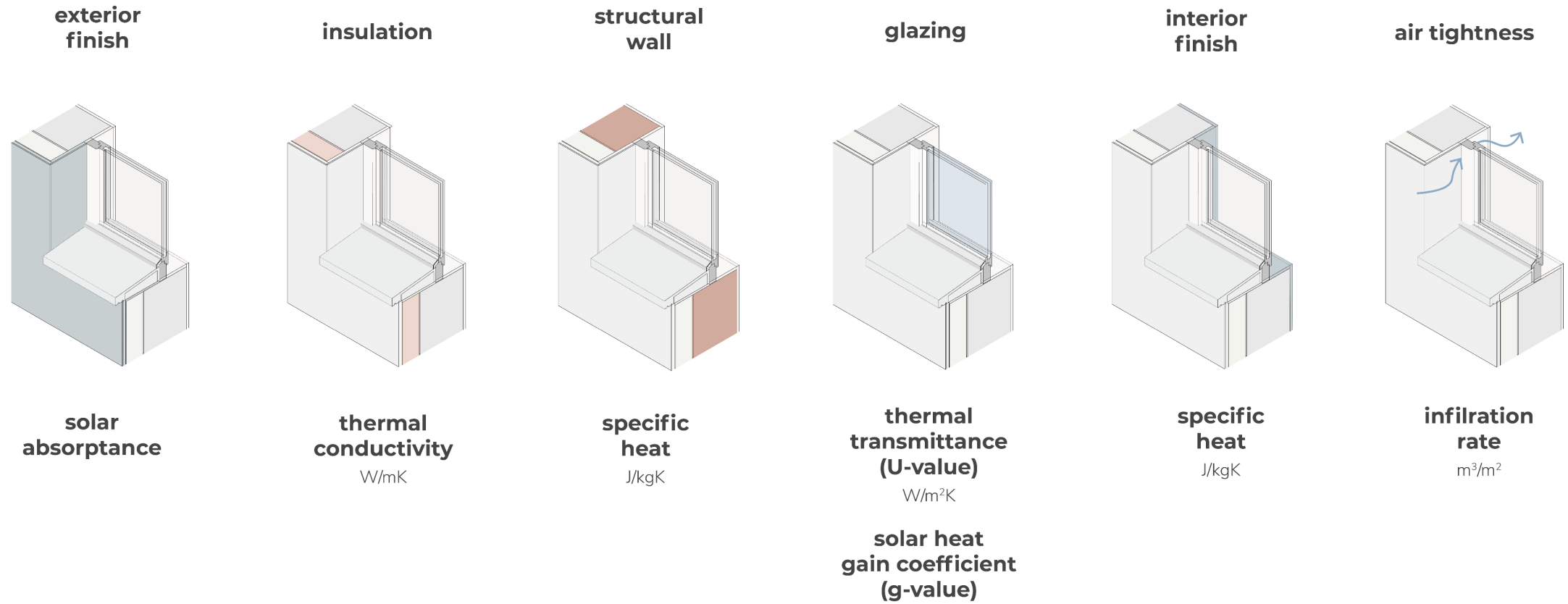
# Base case simulation set up

Exterior wall construction - material properties



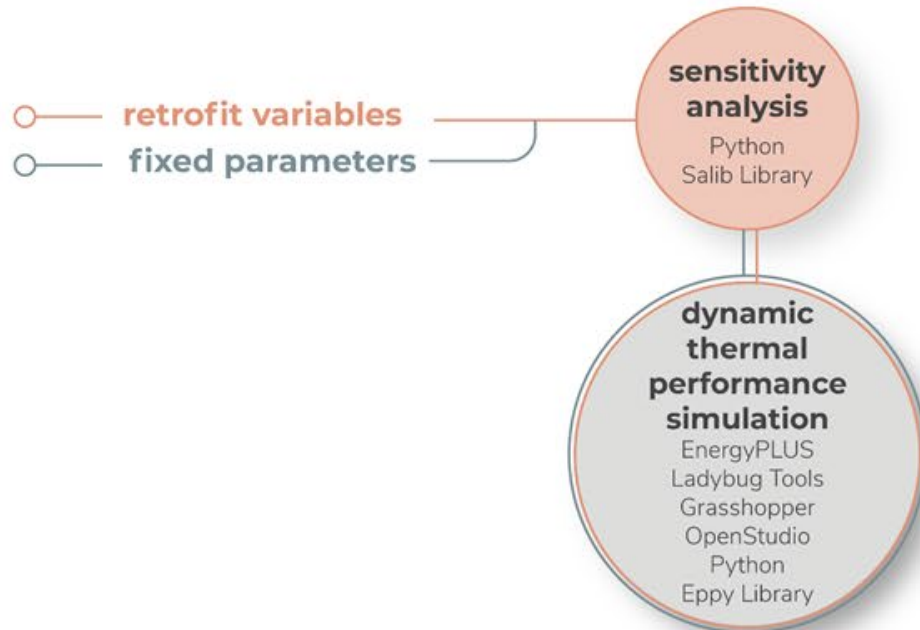
# Base case simulation set up

Choice of parameters for retrofit

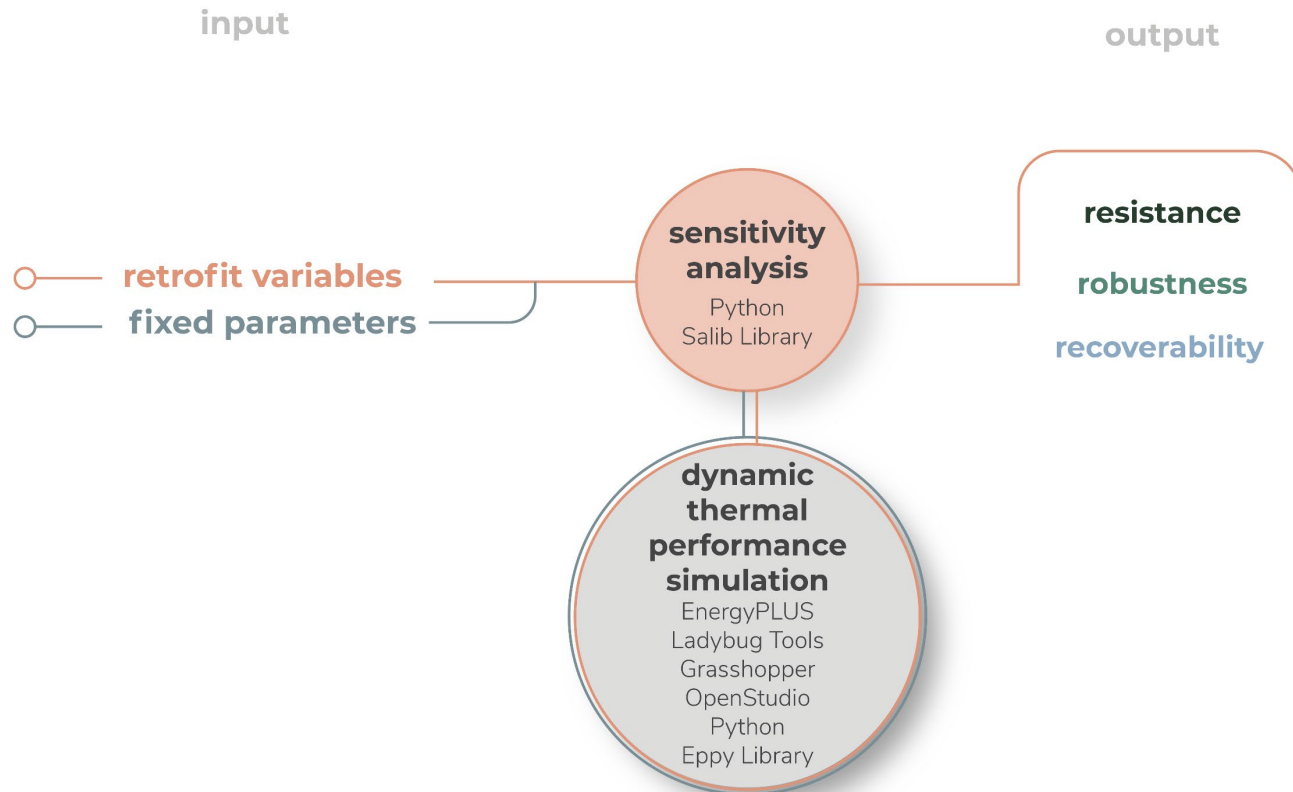


# Sensitivity analysis workflow

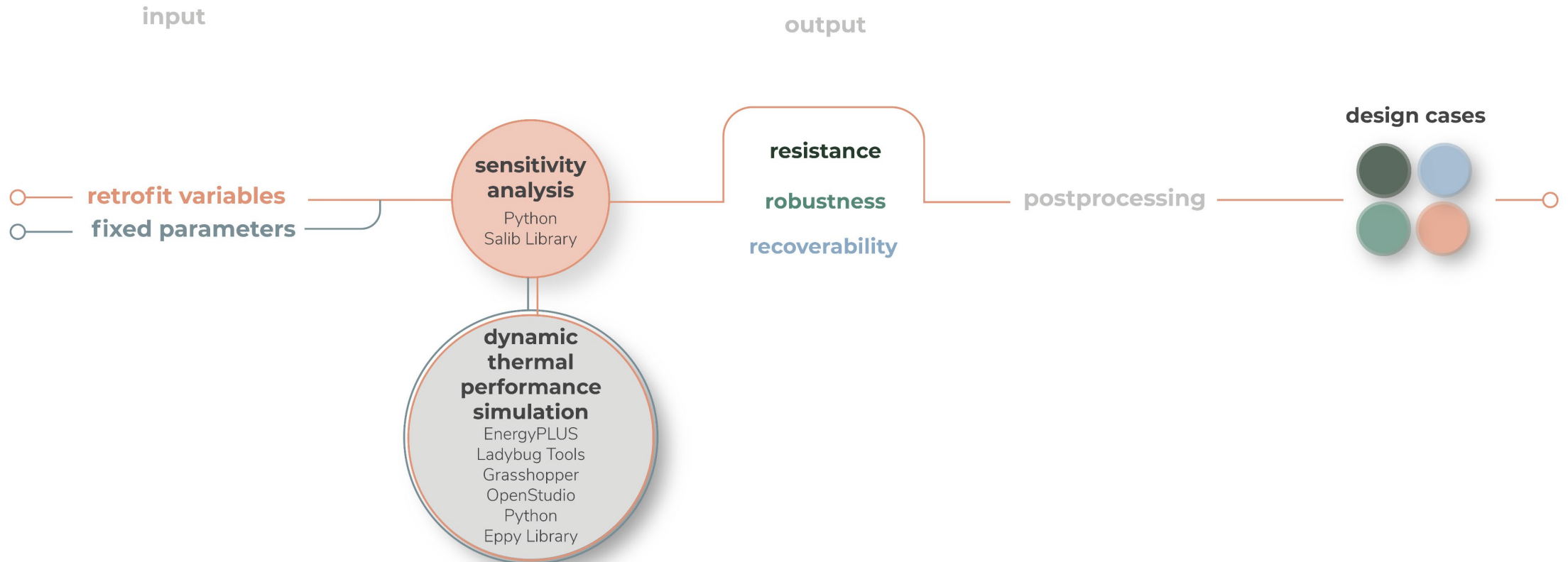
input



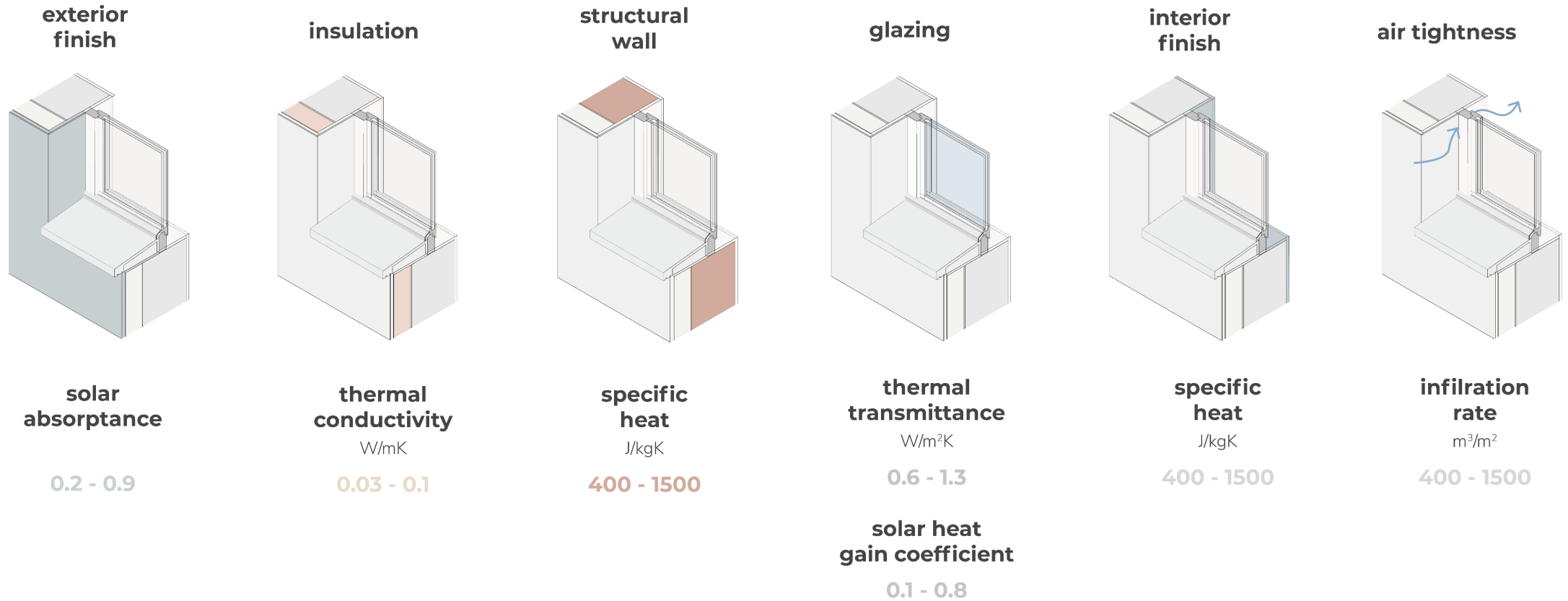
# Sensitivity analysis workflow



# Sensitivity analysis workflow

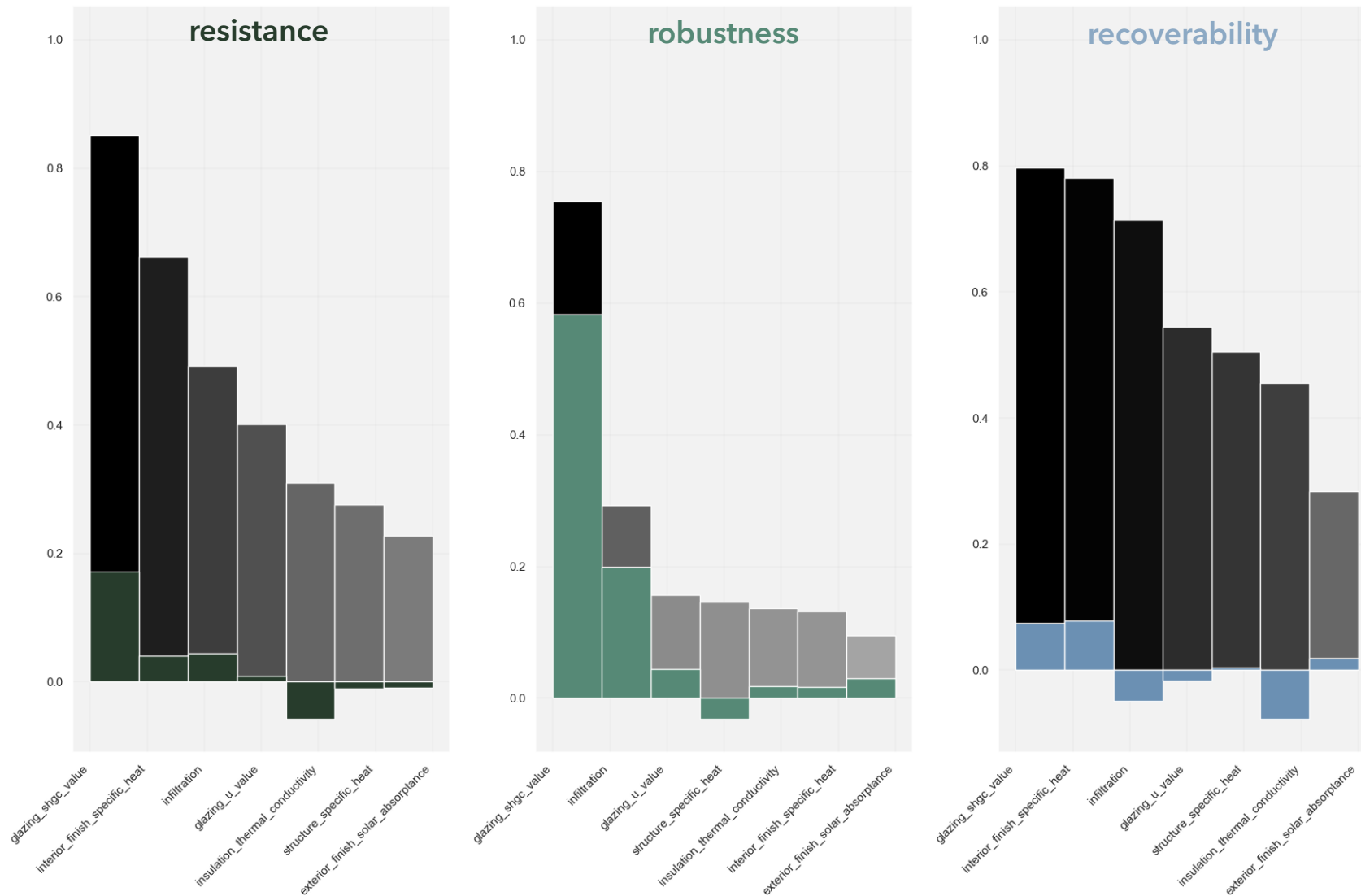


# Sensitivity analysis variables



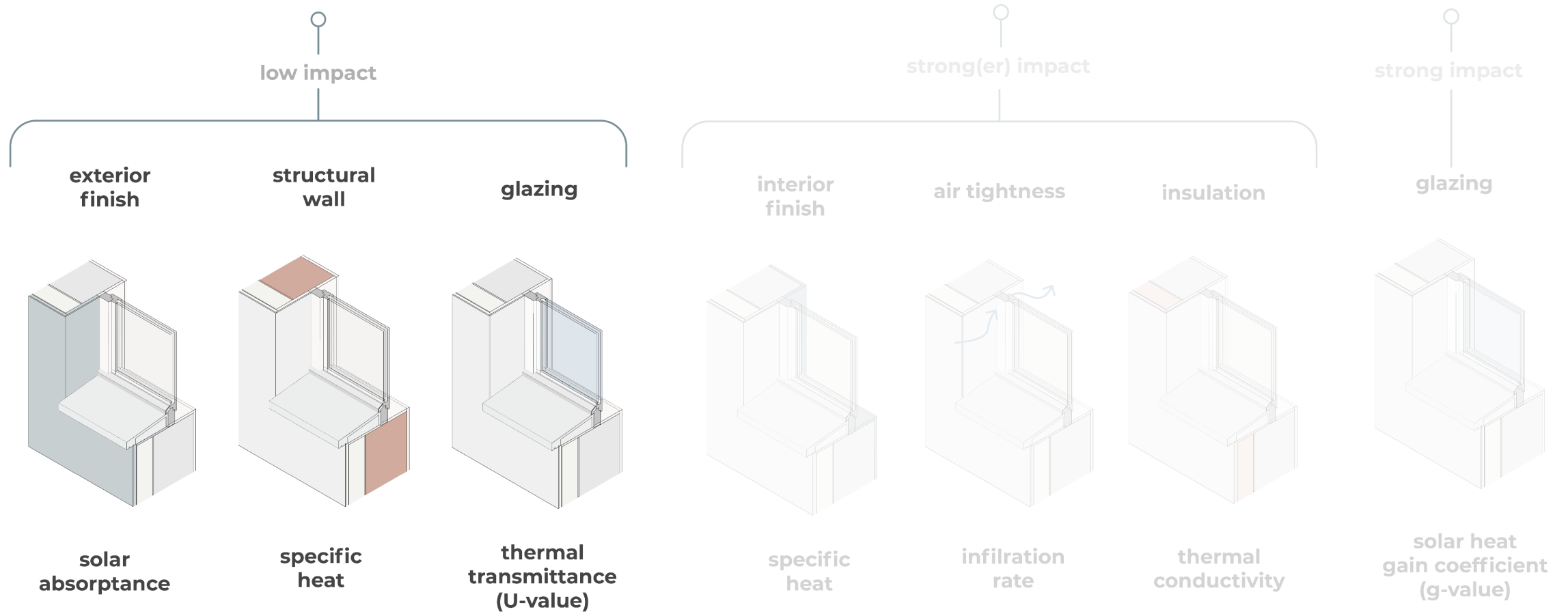
# Sensitivity analysis outcome

$S_{total}$ ,  $S_{direct}$  per index outcome



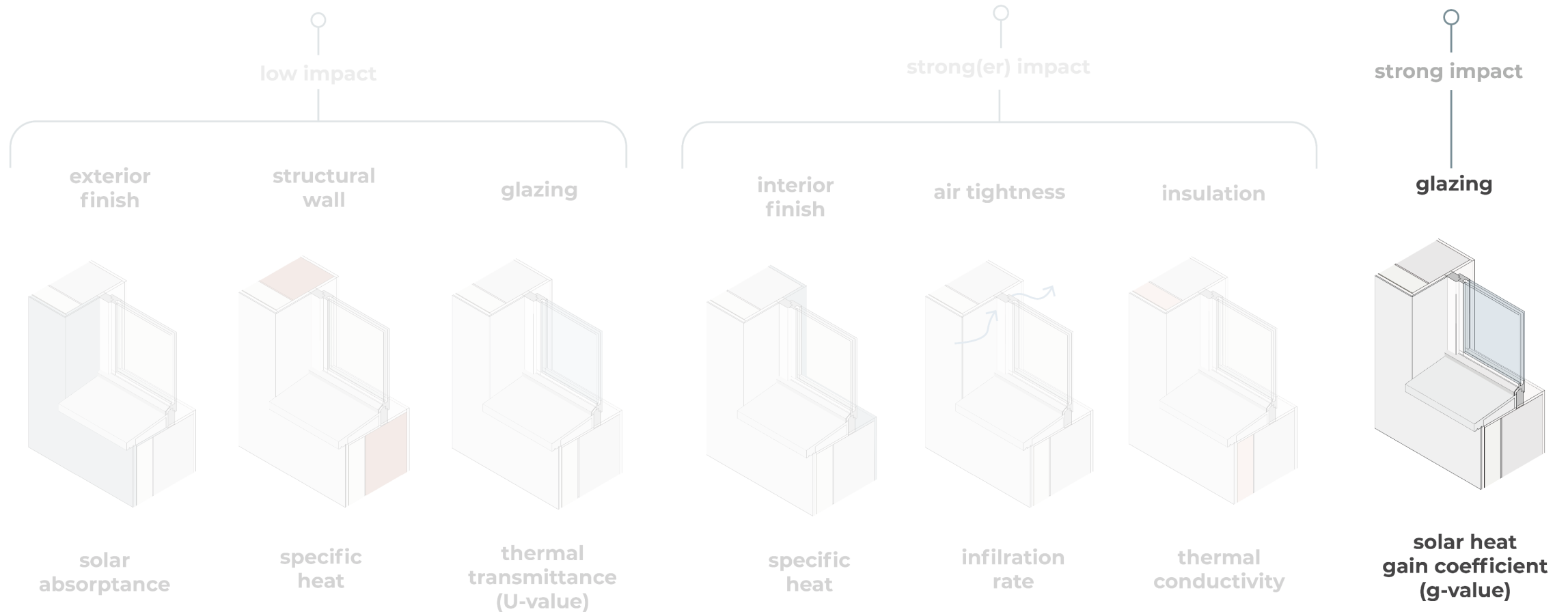
# Sensitivity analysis outcome

Sorted variables



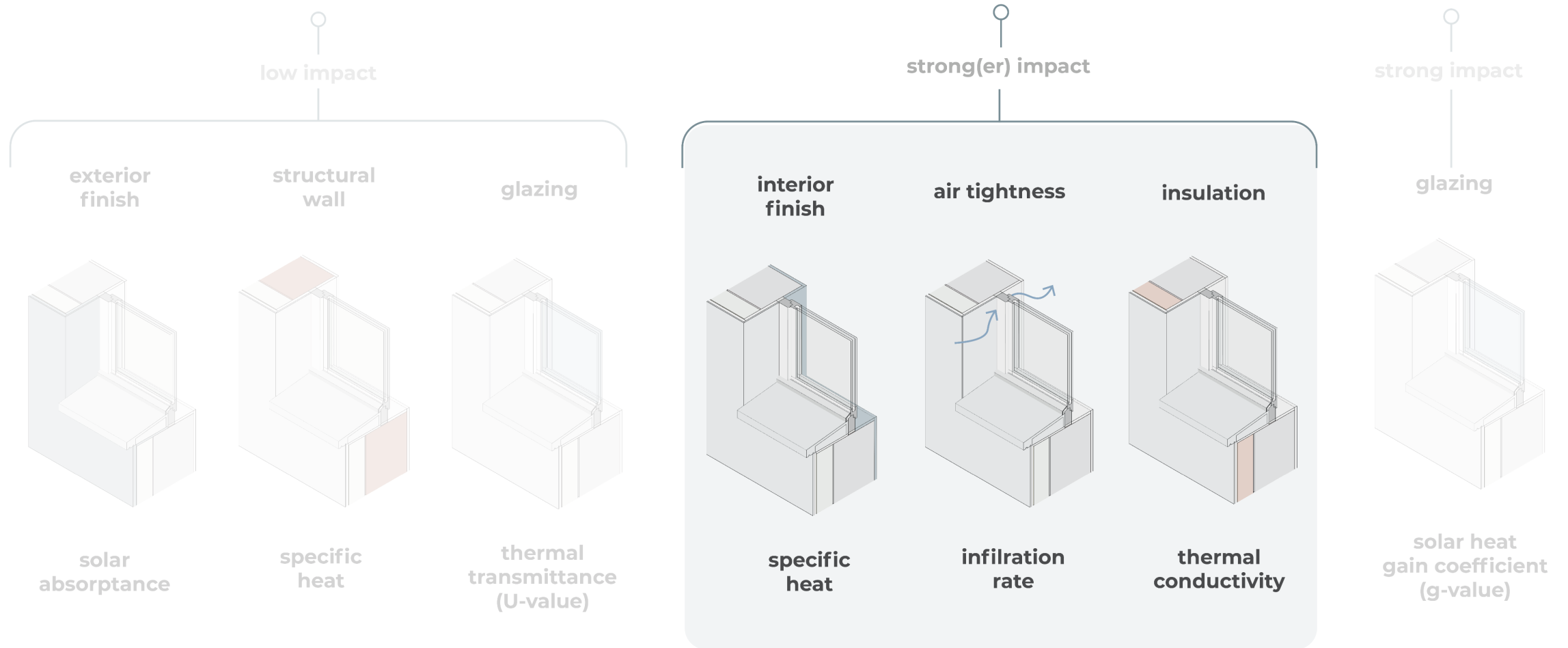
# Sensitivity analysis outcome

sorted variables



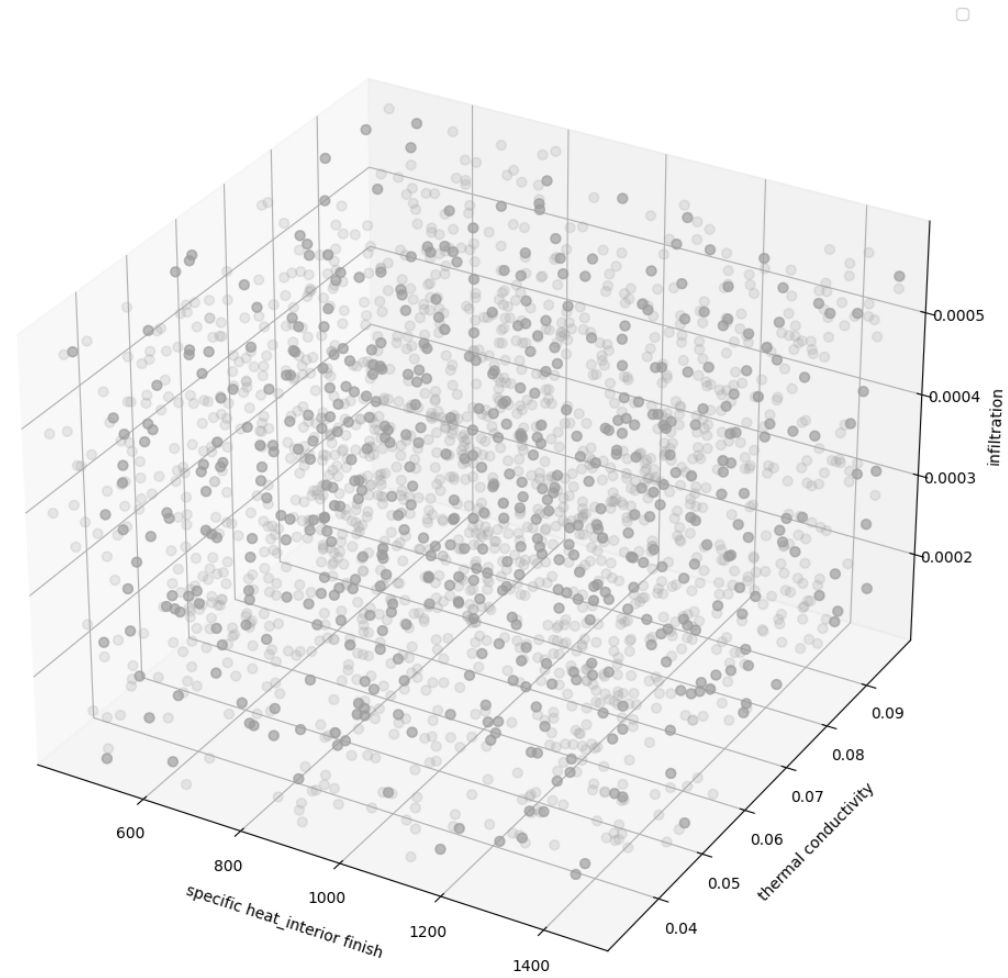
# Sensitivity analysis outcome

sorted variables



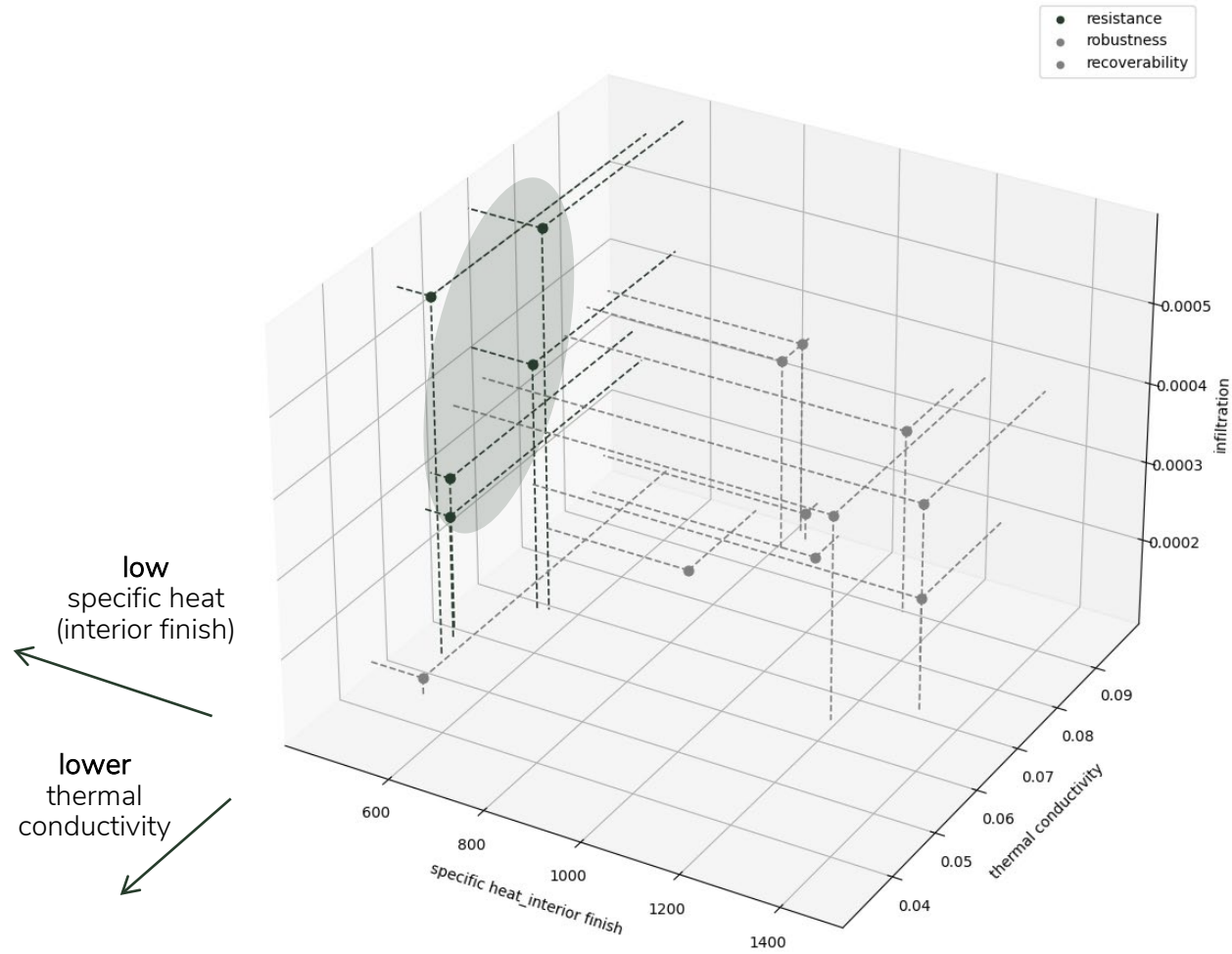
# Sensitivity analysis outcome

variables values – best performing scenarios



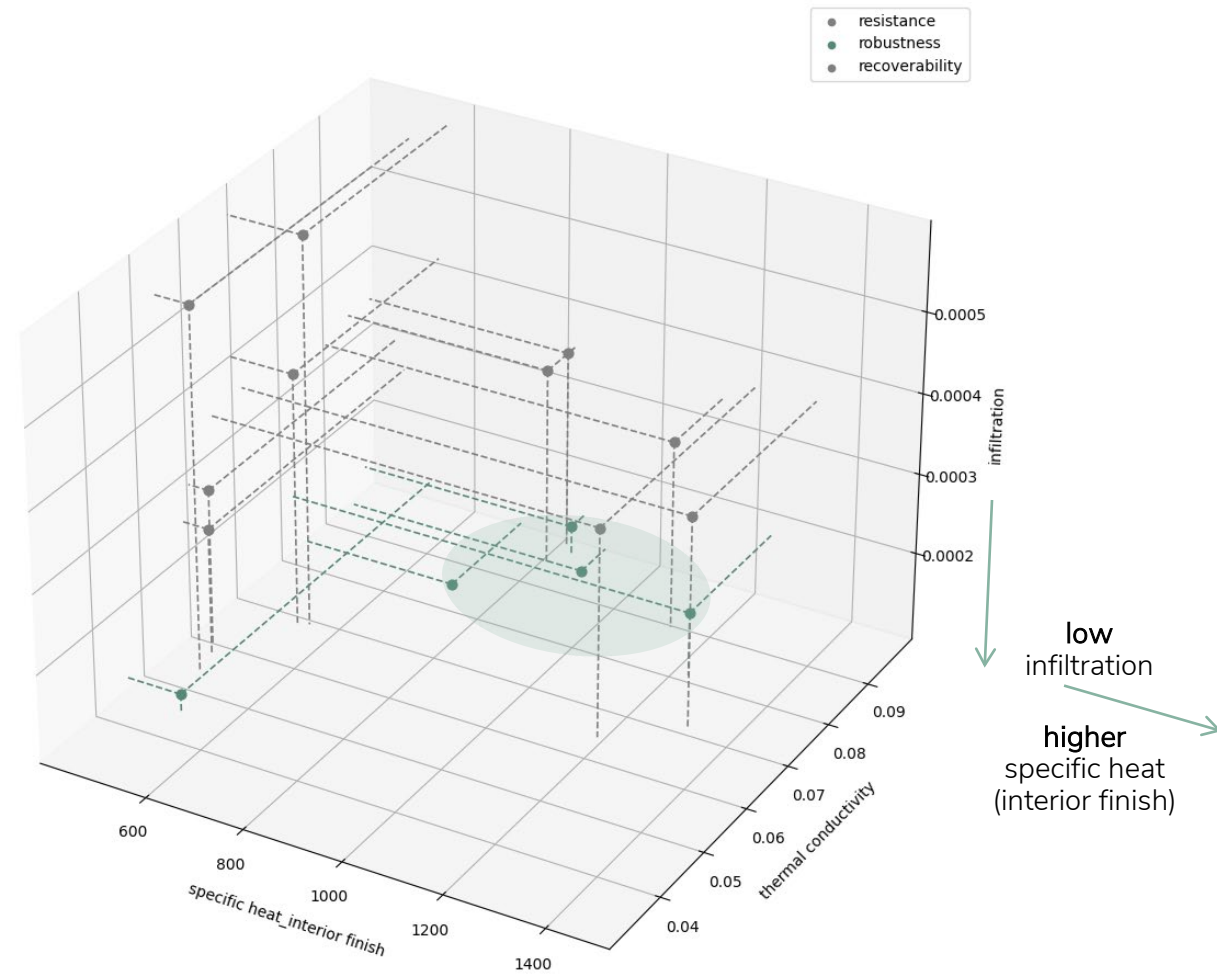
# Sensitivity analysis outcome

variables values – best performing scenarios



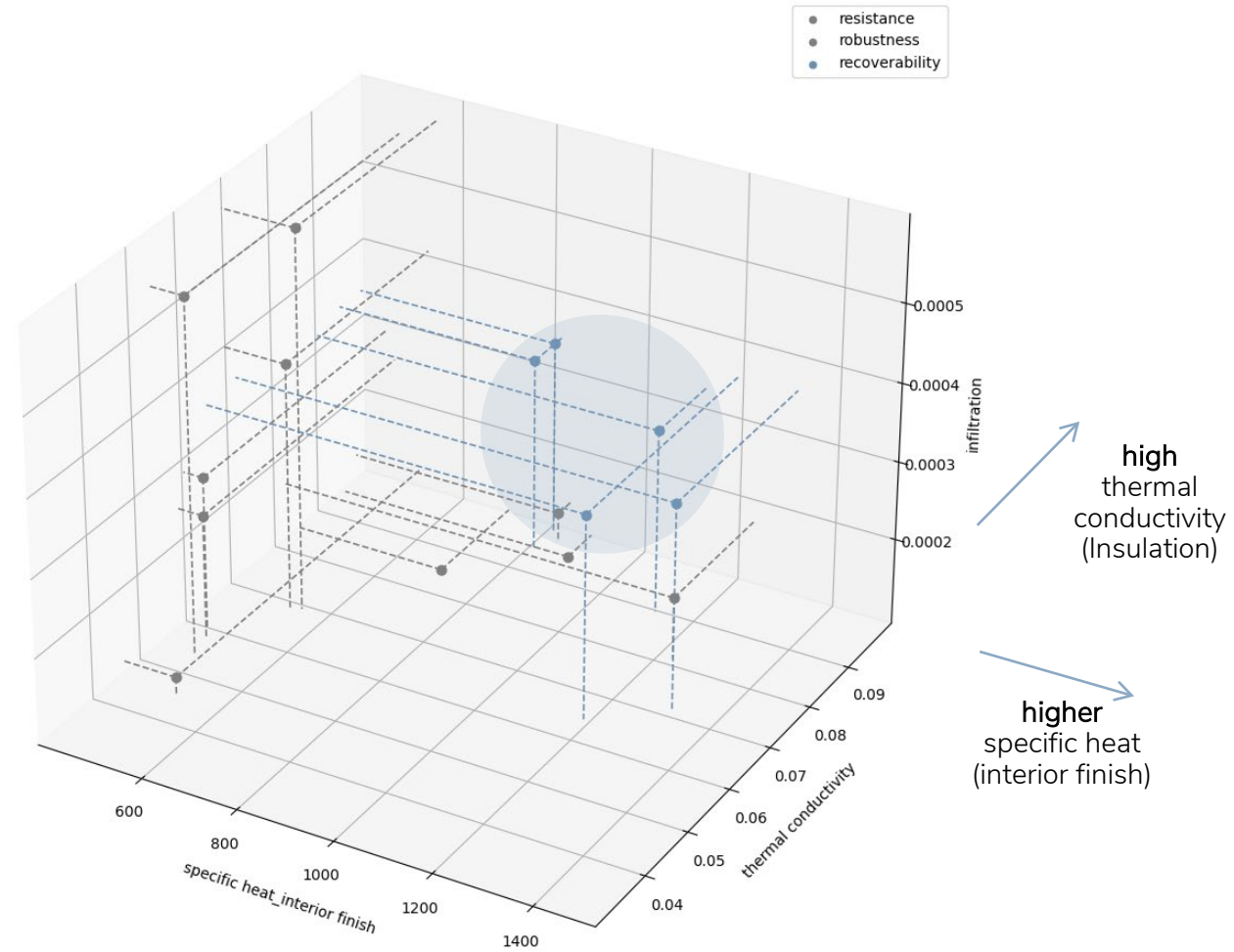
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variables values – best performing scenarios



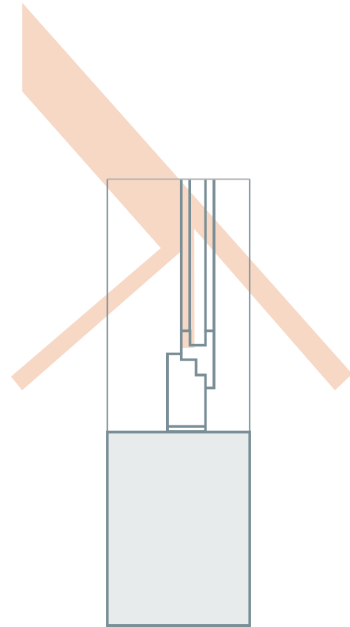
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variables values – best performing scenarios

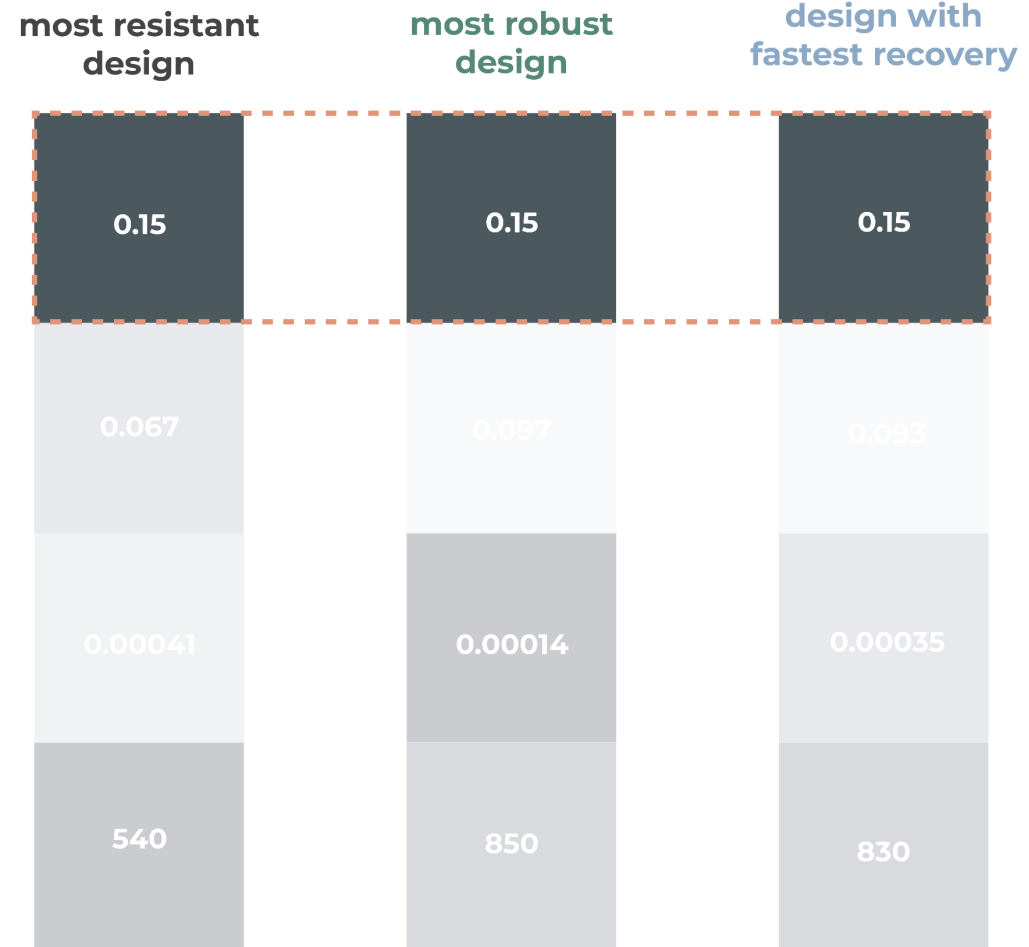


# Sensitivity analysis outcome

Variable values

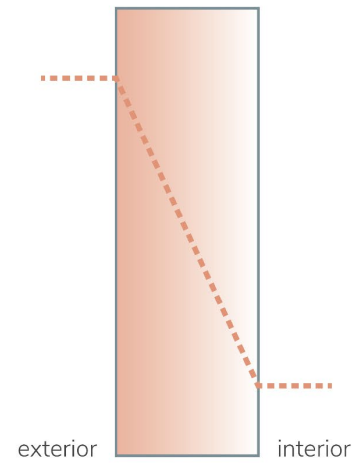


**solar heat gain coefficient**



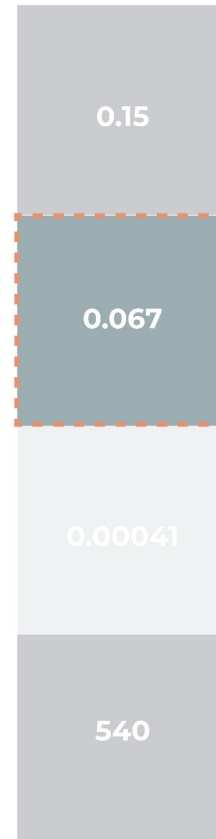
# Sensitivity analysis outcome

Variable values

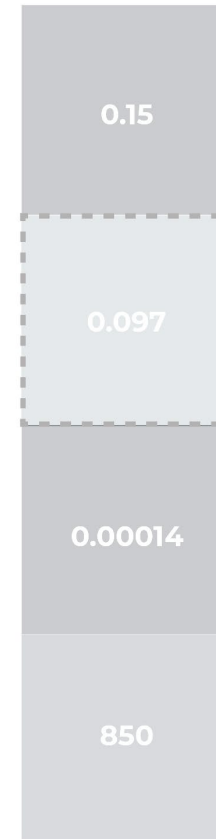


**thermal conductivity**

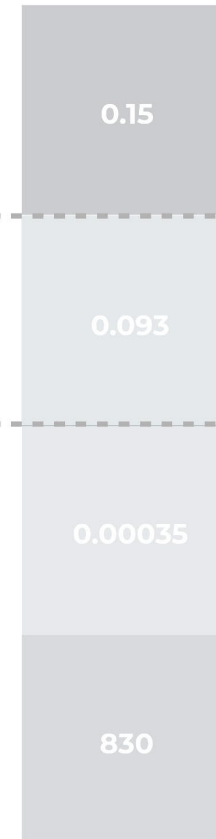
**most resistant design**



**most robust design**

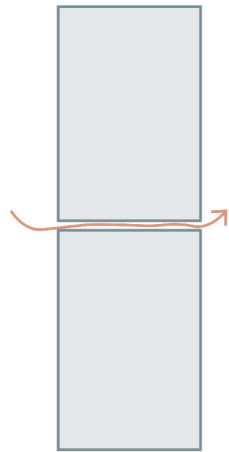


**design with fastest recovery**



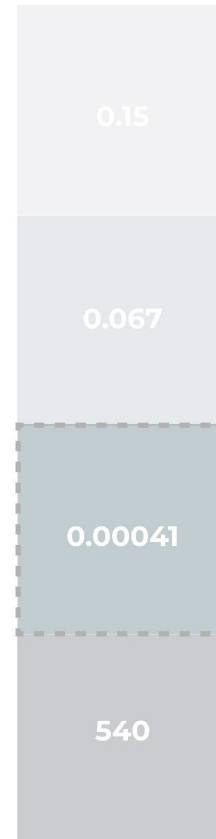
# Sensitivity analysis outcome

Variable values



**infiltration**

**most resistant design**



**most robust design**

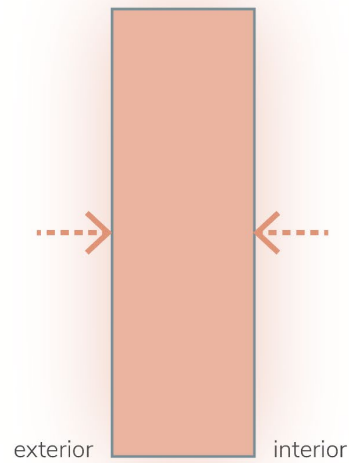


**design with fastest recovery**



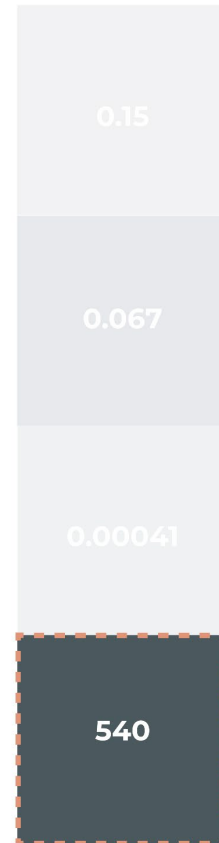
# Sensitivity analysis outcome

Variable values

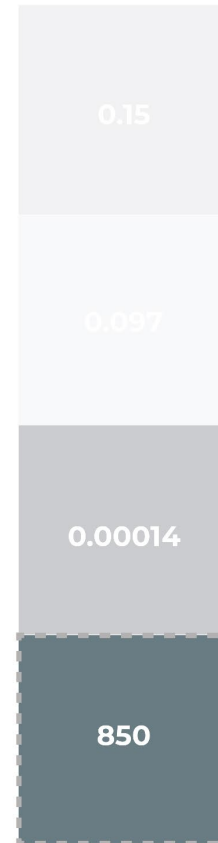


**specific heat**

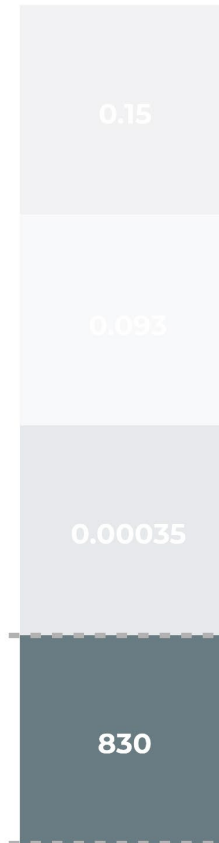
**most resistant design**



**most robust design**

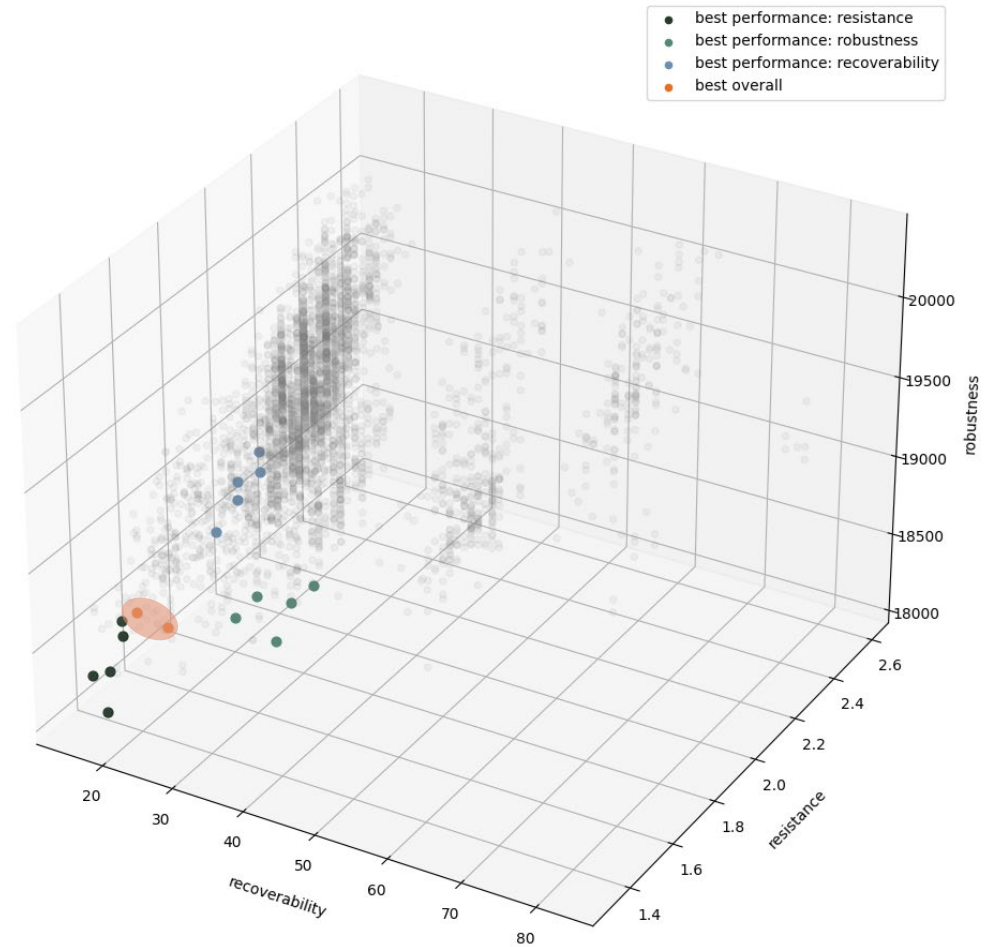


**design with fastest recovery**



# Sensitivity analysis outcome

performance per resilience index



# Sensitivity analysis outcome

variables sensitivities – direct impact

resistance



robustness



recoverability

# Sensitivity analysis outcome

variables sensitivities – direct impact

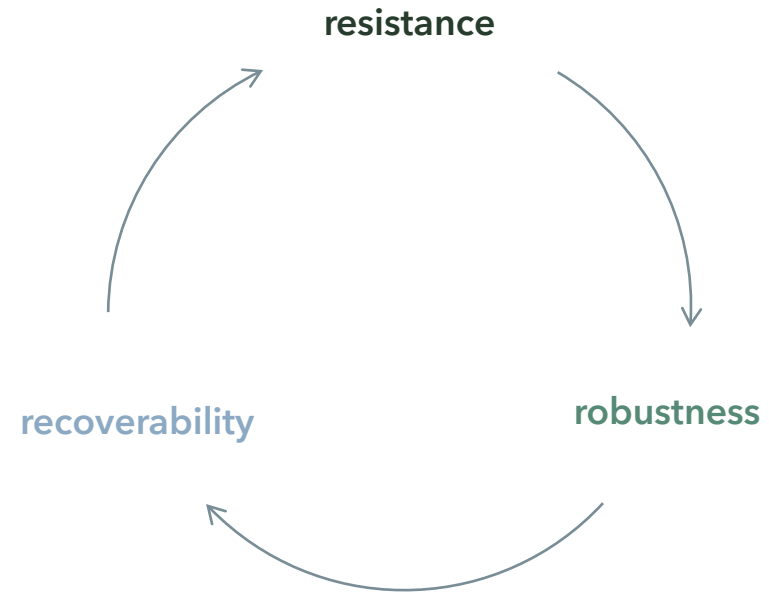


# Sensitivity analysis outcome

variables sensitivities – direct impact

overall best performing

=

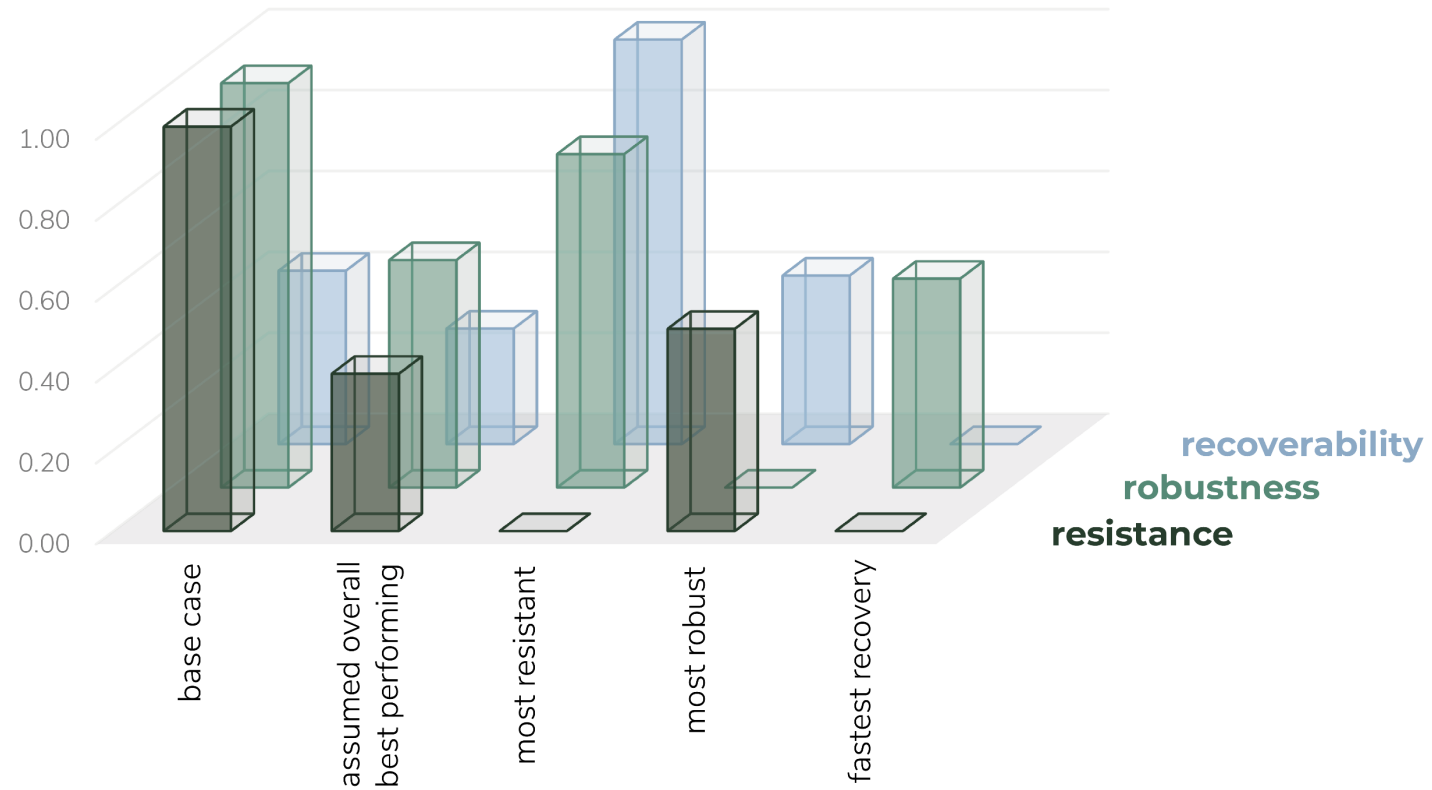


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- design 8
- conclusion 9



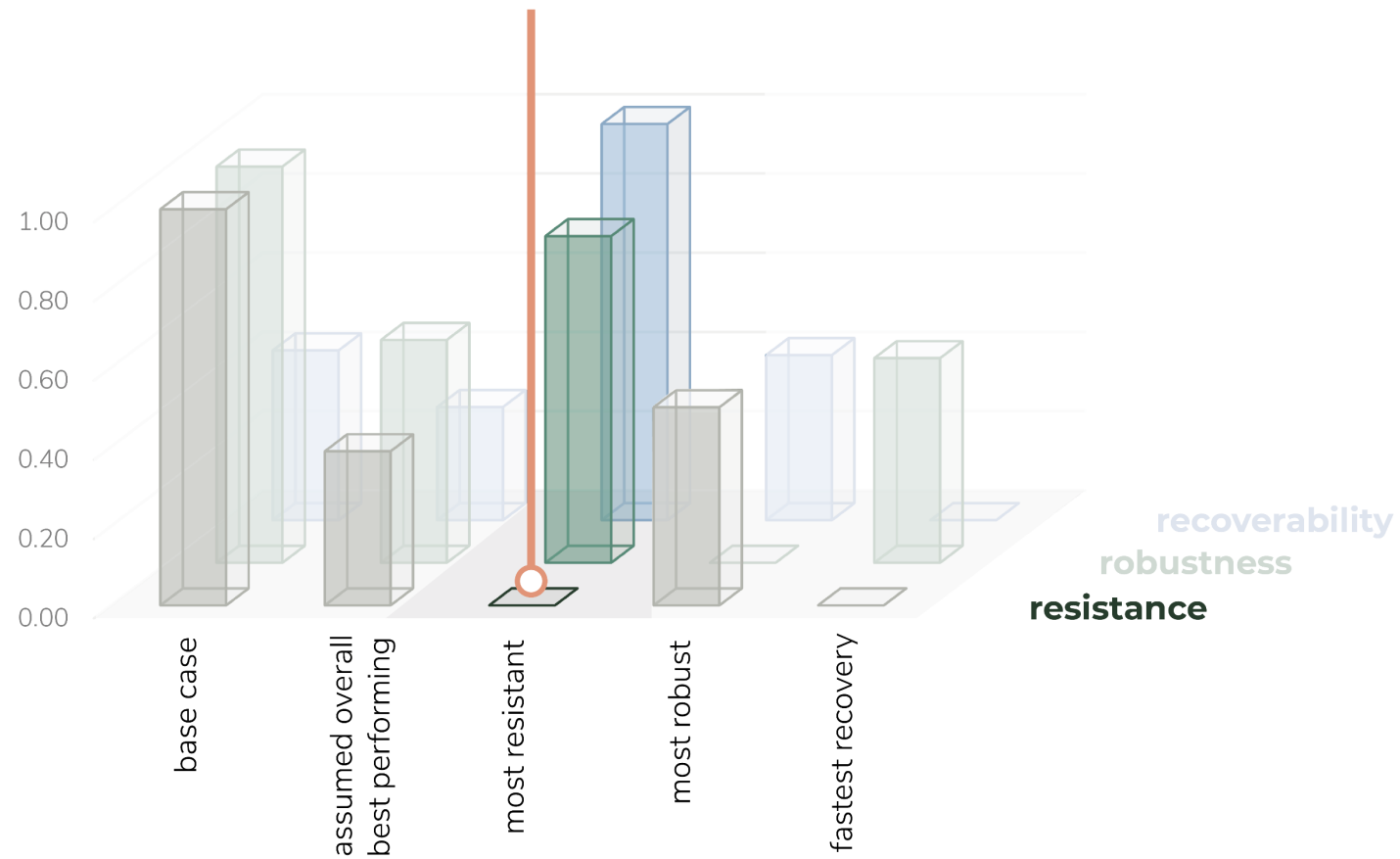
# Final evaluation

Future resilience index



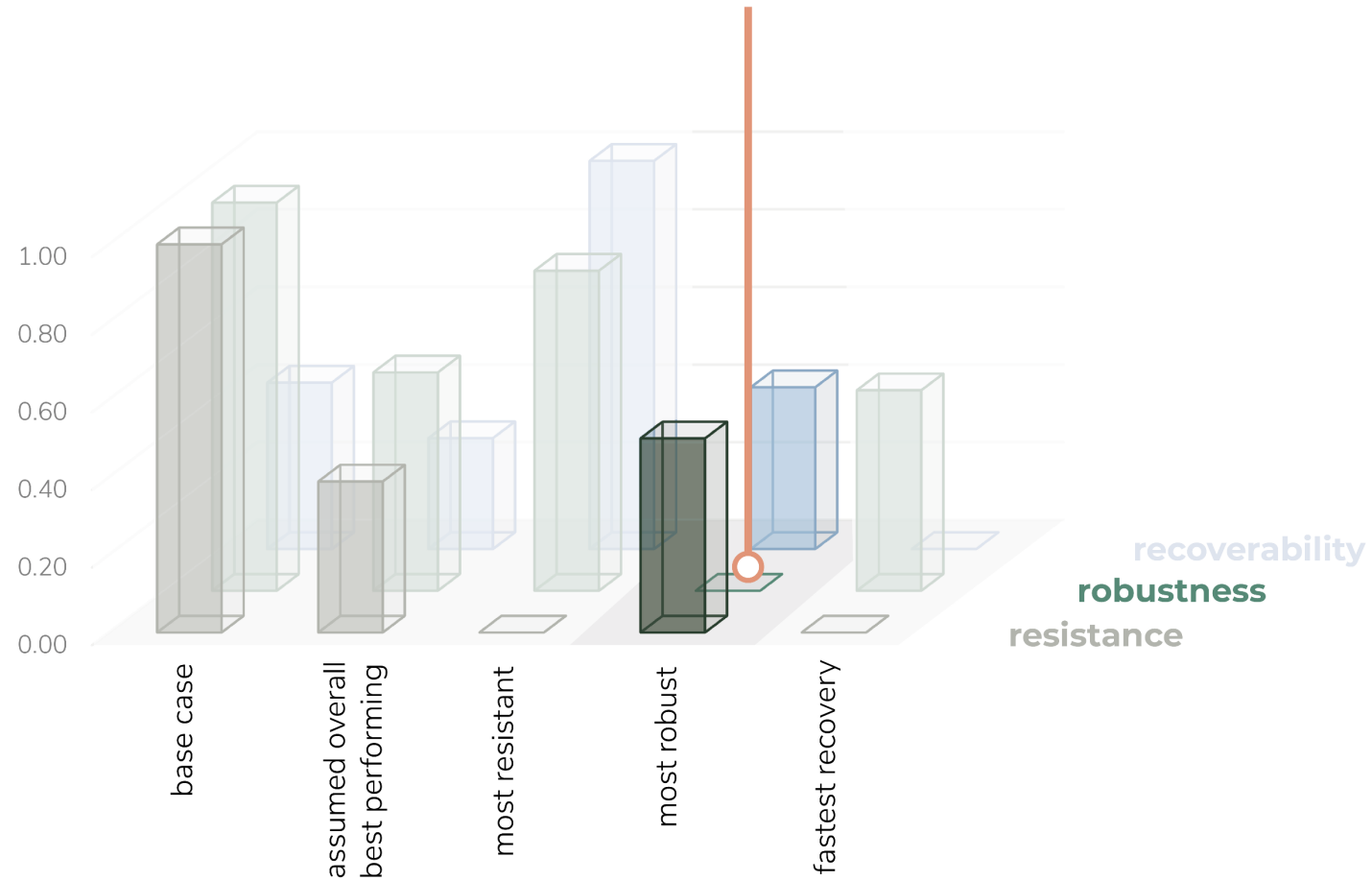
# Final evaluation

Future resilience index



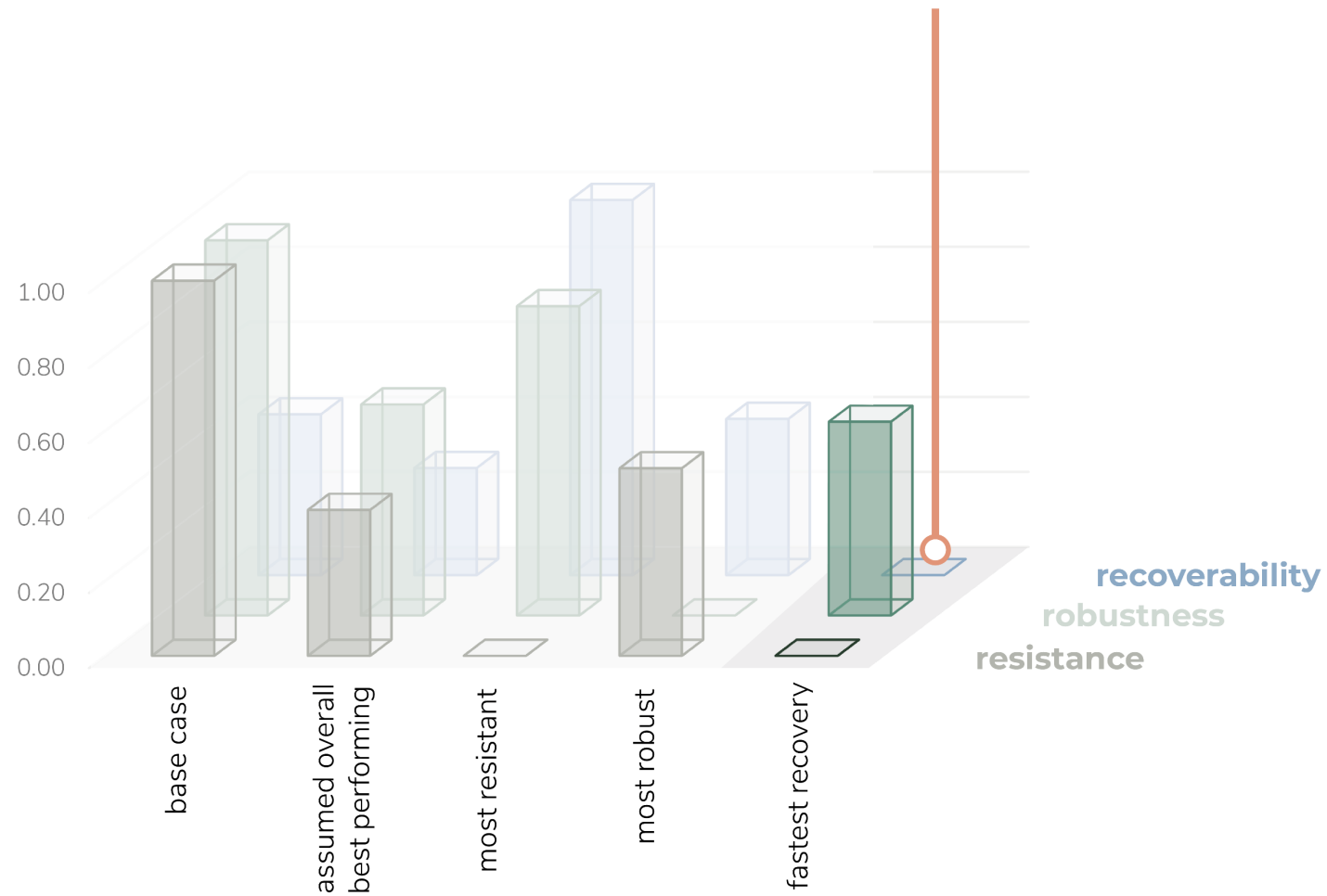
# Final evaluation

Future resilience index



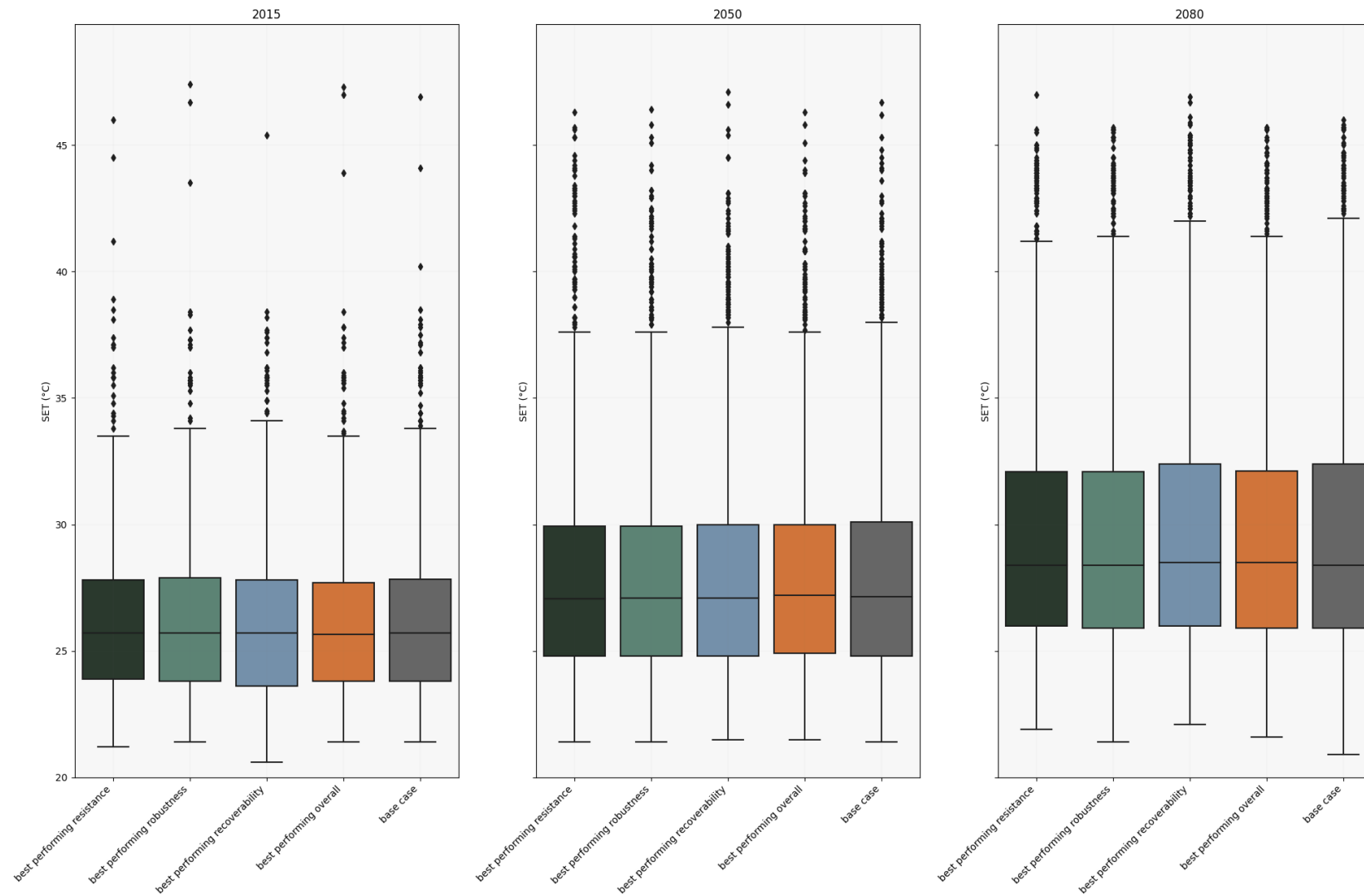
# Final evaluation

Future resilience index



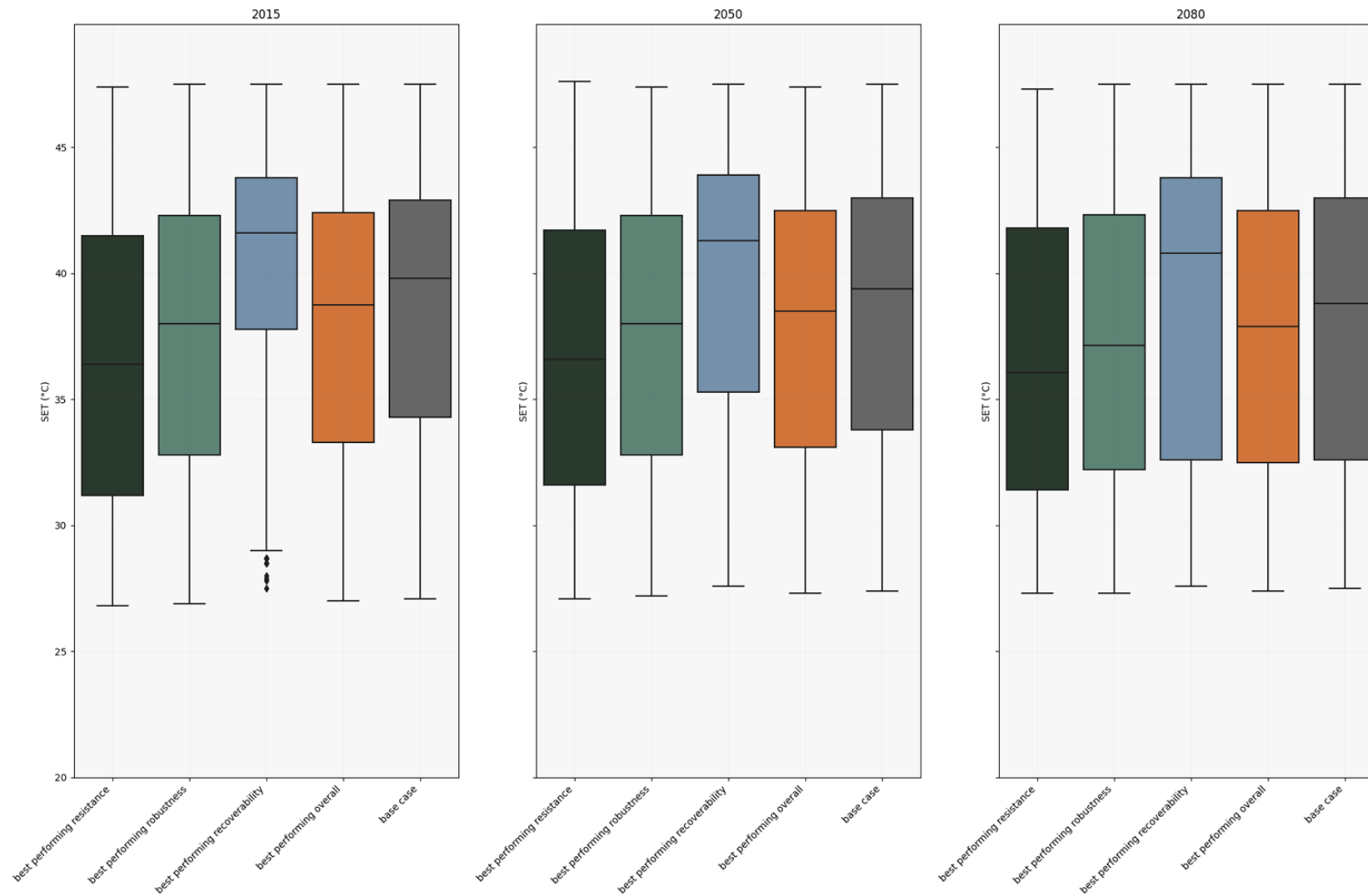
# Final evaluation

SET hourly data – performance



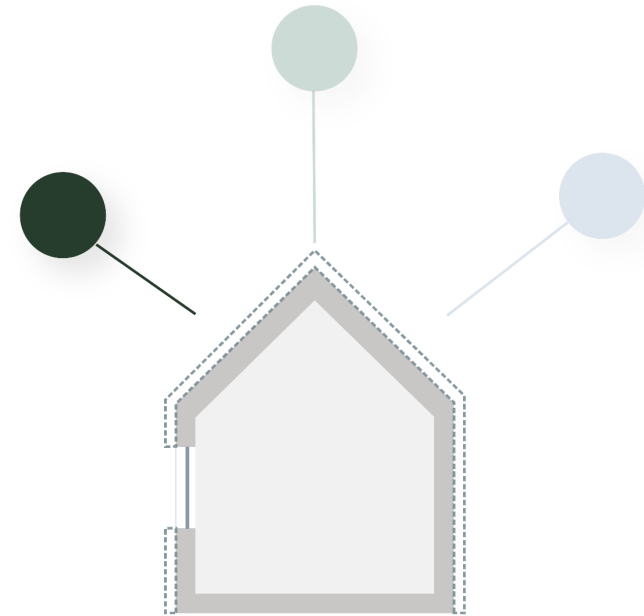
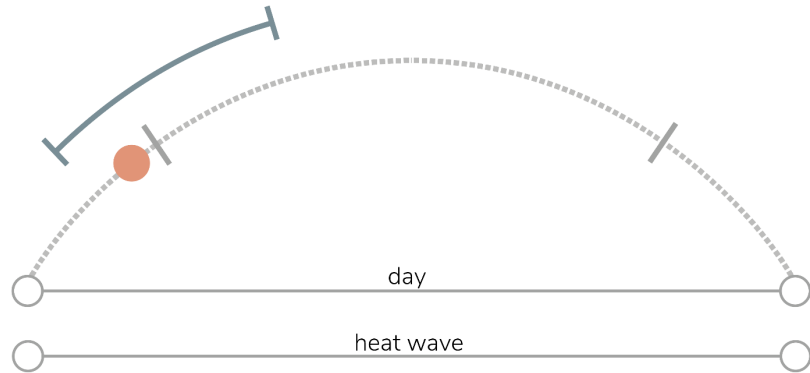
# Final evaluation

SET hourly data – performance



# Final design

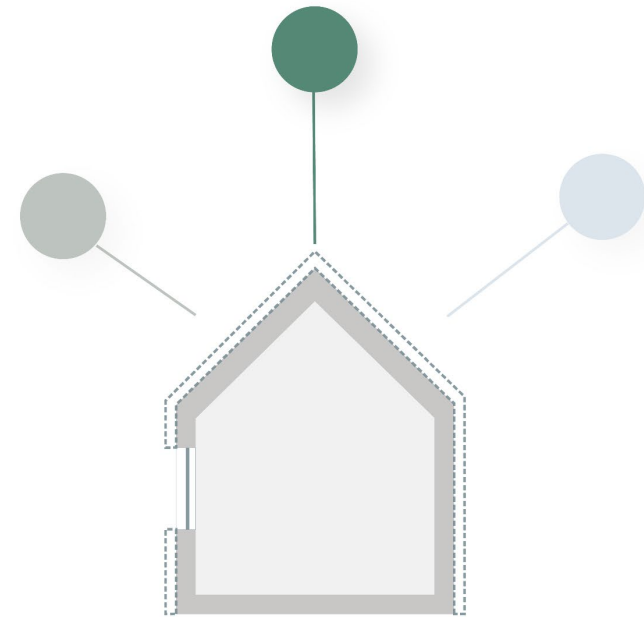
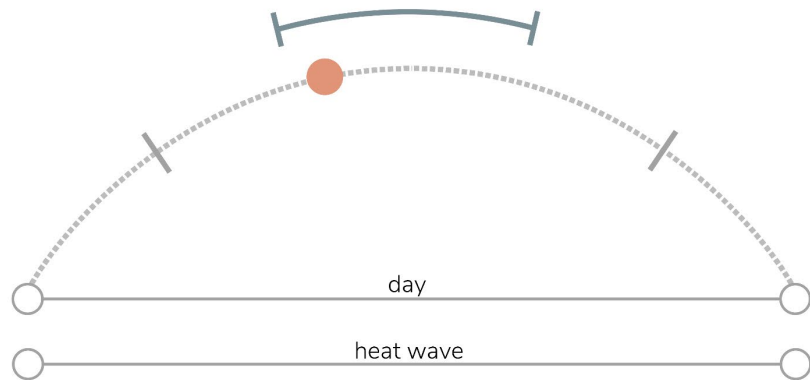
recommendations



**resistance**  
robustness  
recoverability

# Final design

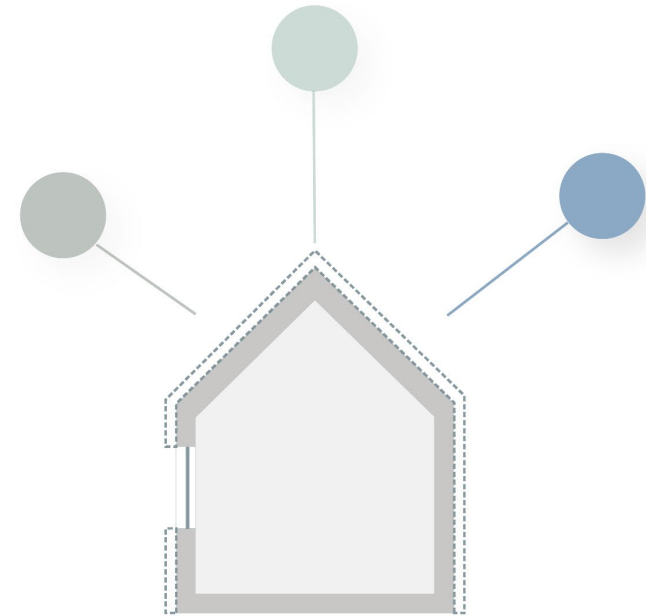
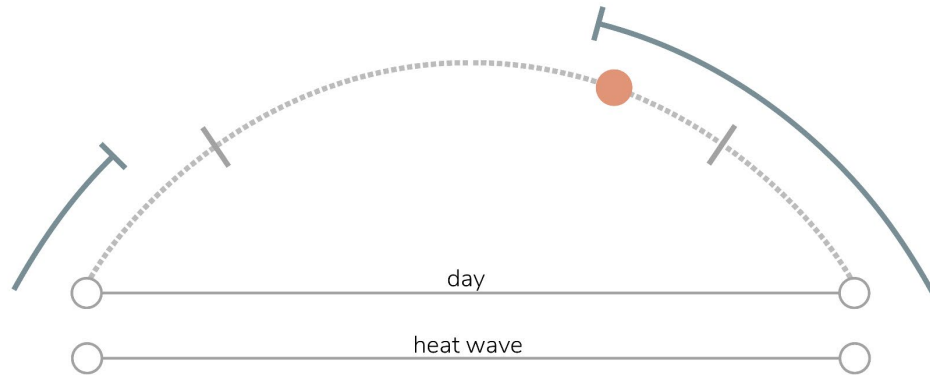
recommendations



resistance  
**robustness**  
recoverability

# Final design

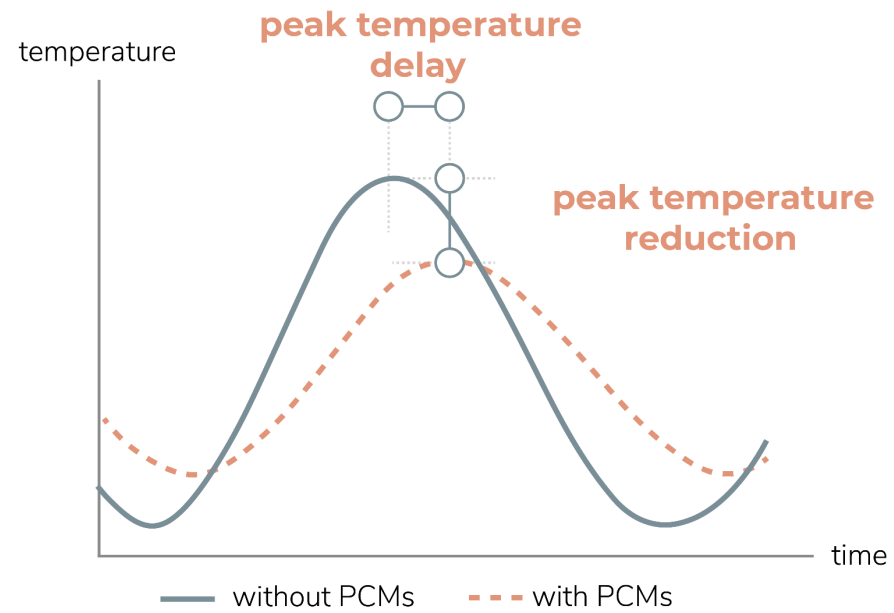
recommendations



resistance  
robustness  
recoverability

# Final design

phase change material

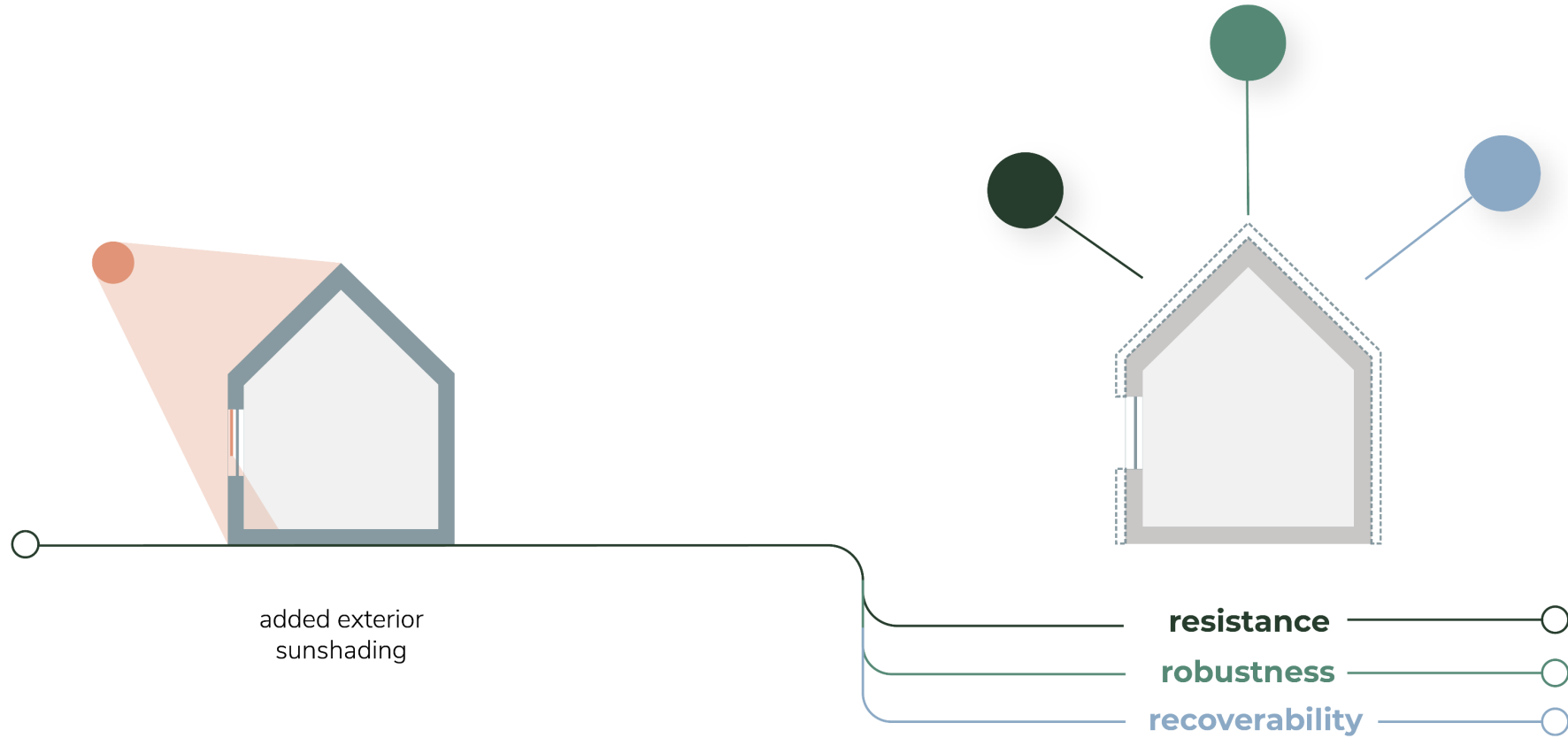


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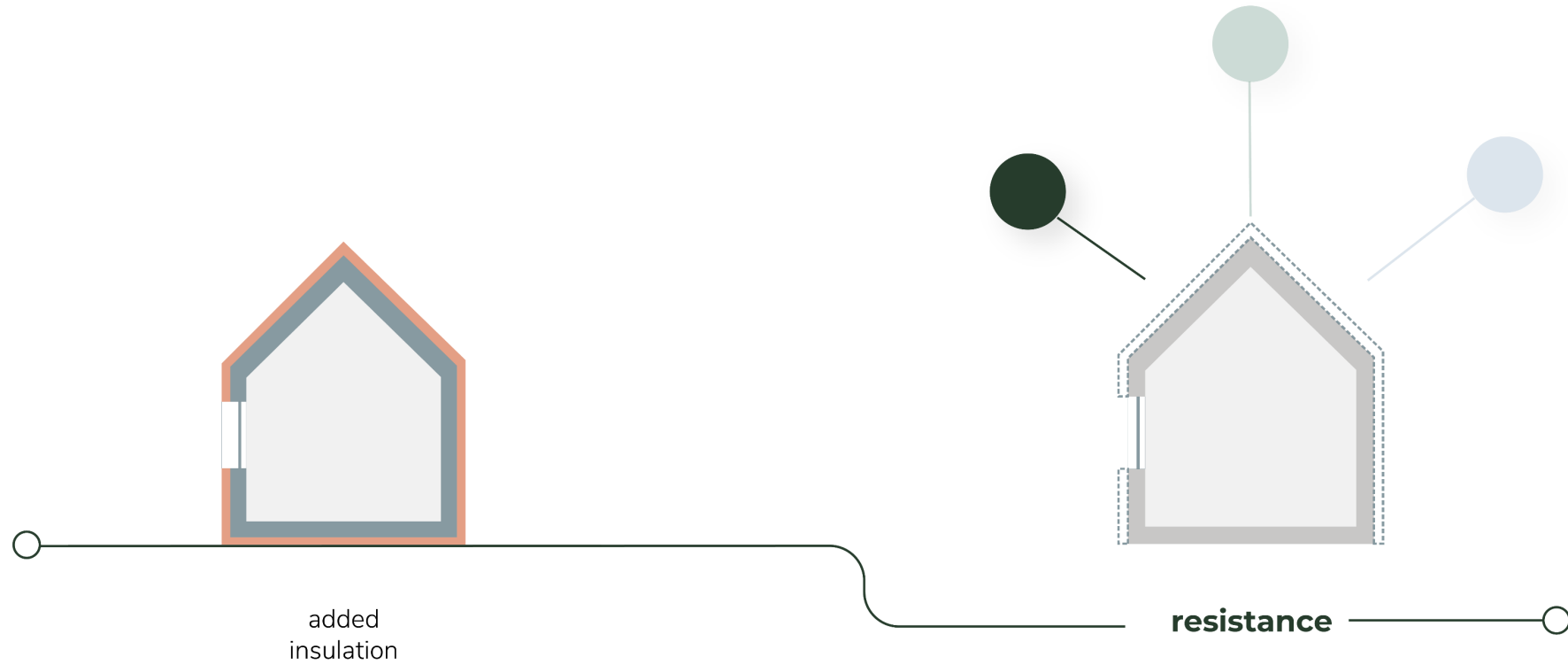
# Final design

recommendations



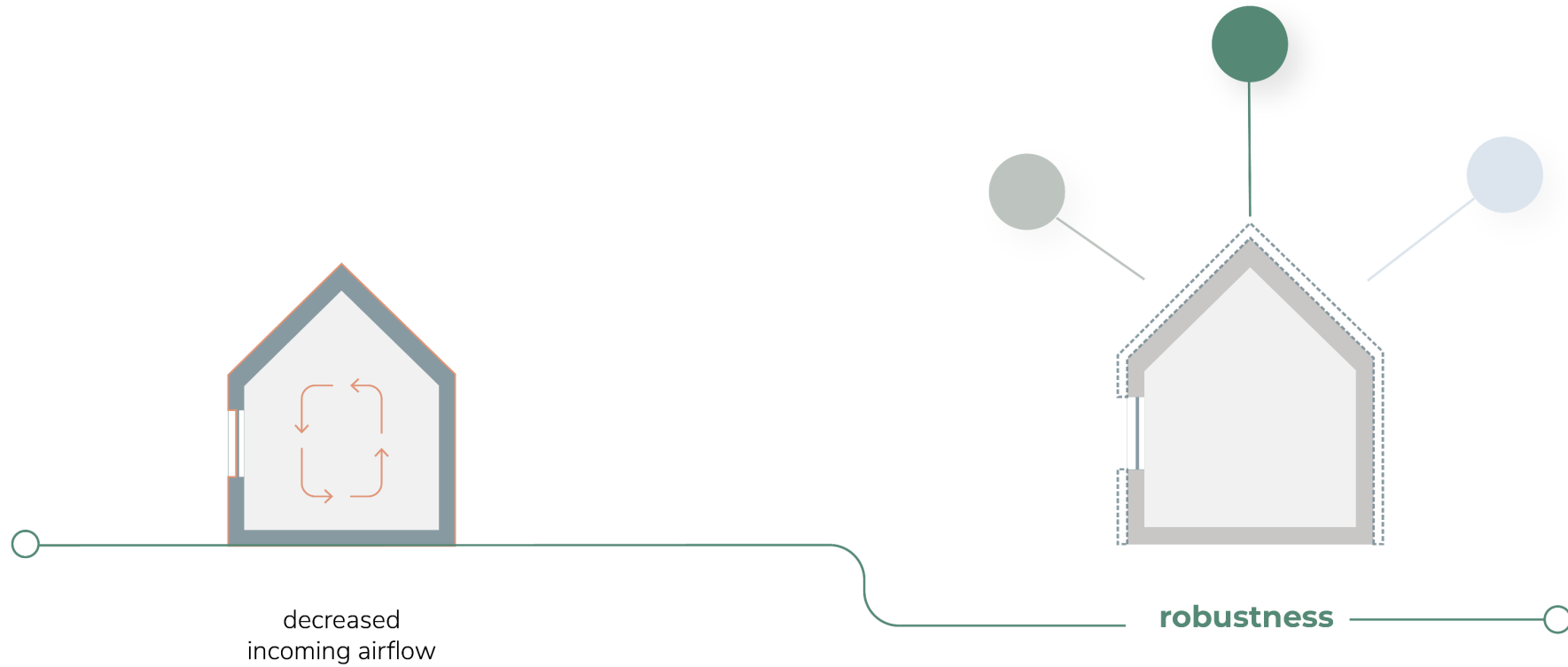
# Final design

recommendations



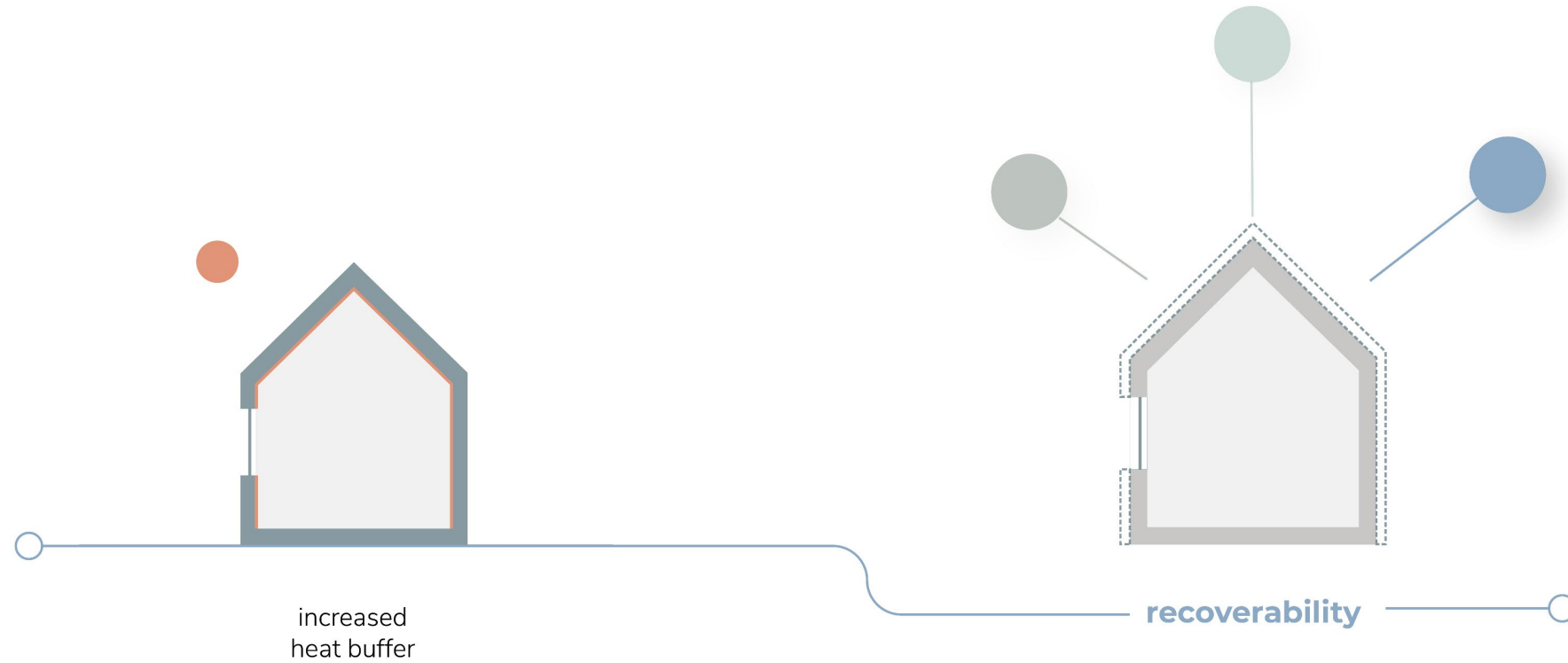
# Final design

recommendations



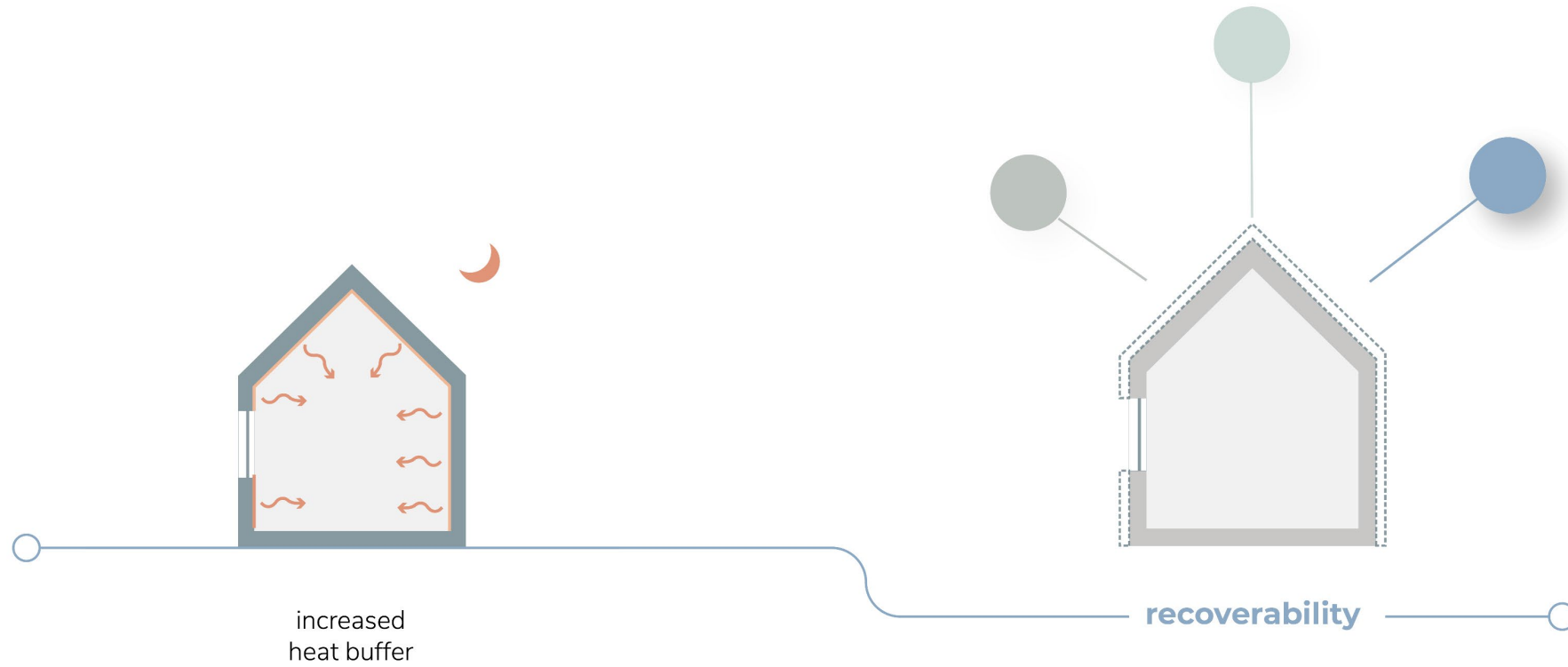
# Final design

recommendations



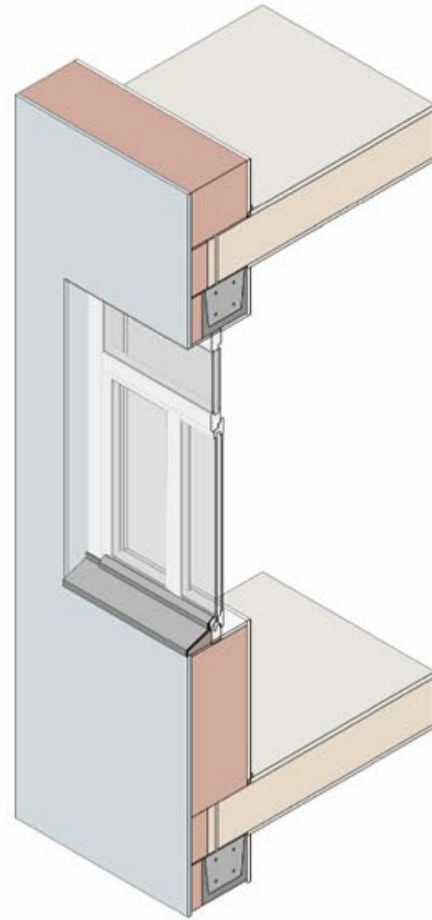
# Final design

recommendations

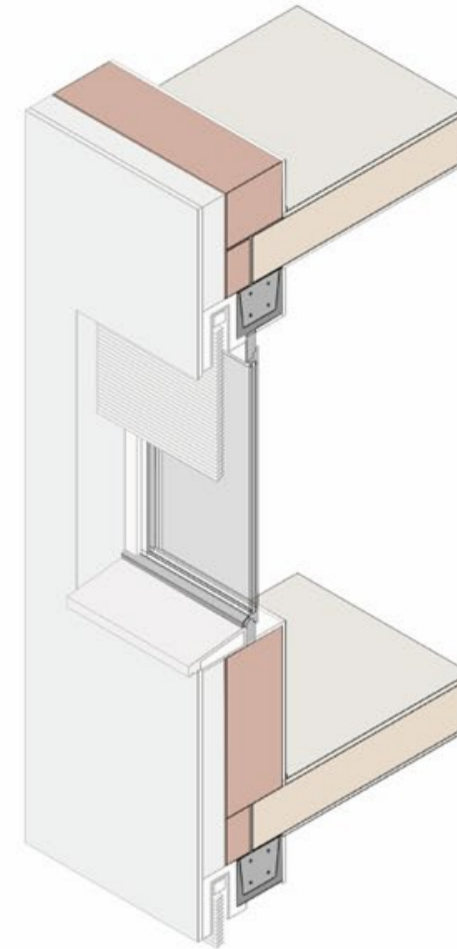


# Final design

current state vs. retrofit



**current state**

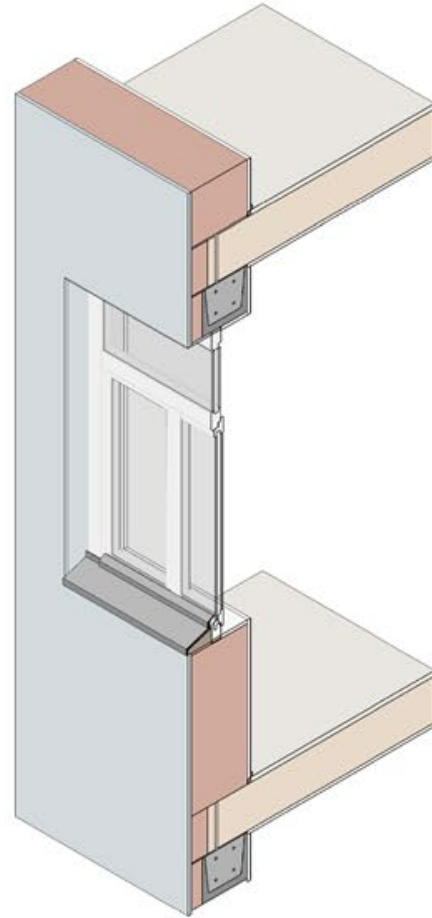


**retrofit**  
window replacement

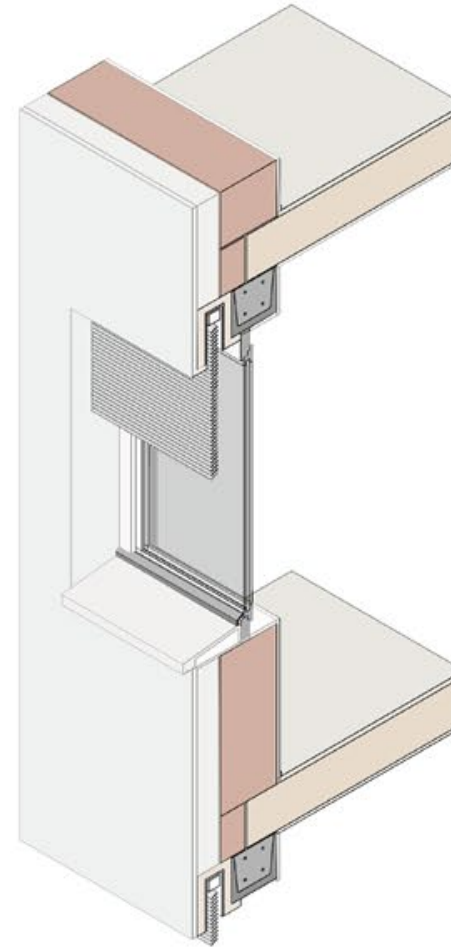
**robustness**

# Final design

current state vs. retrofit



**current state**

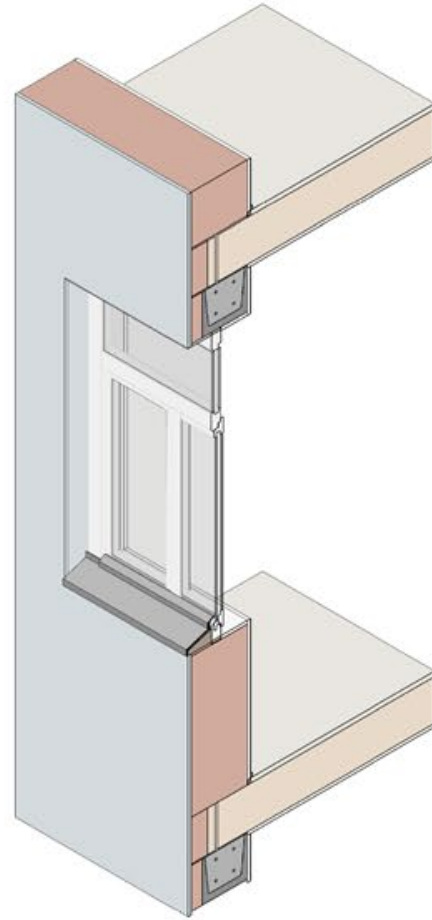


**retrofit**  
addition sunshade

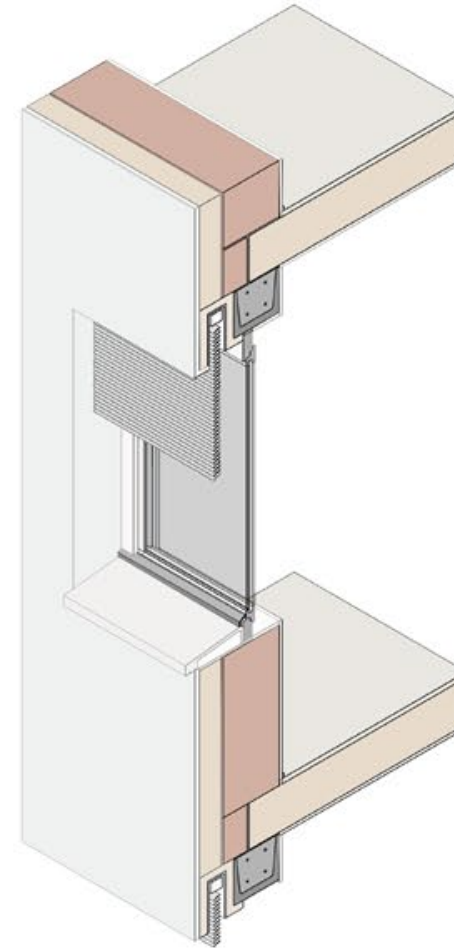
**resistance**  
**robustness**  
**recoverability**

# Final design

current state vs. retrofit



**current state**

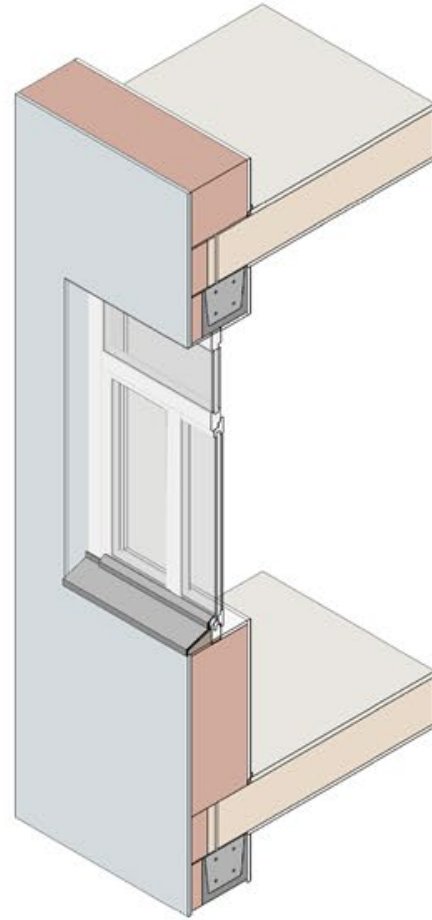


**retrofit**  
addition insulation

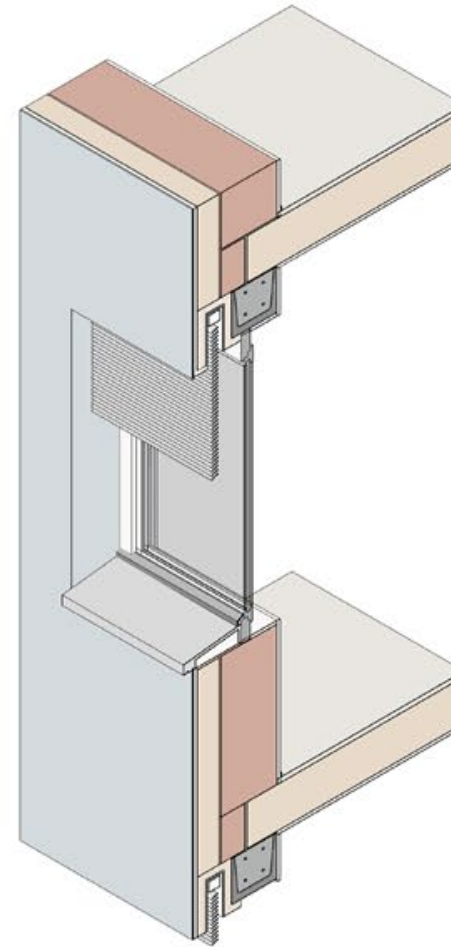
**resistance**

# Final design

current state vs. retrofit



**current state**



**retrofit**  
addition insulation

**recoverability**

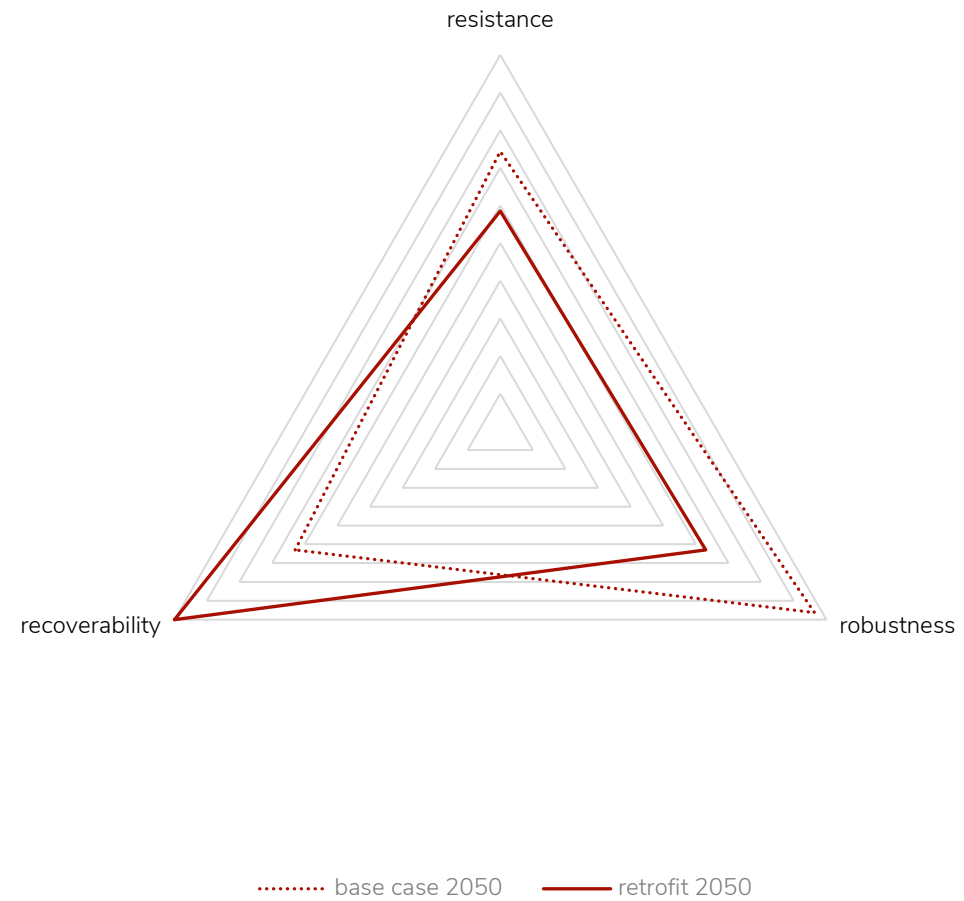
# Final design

evaluation



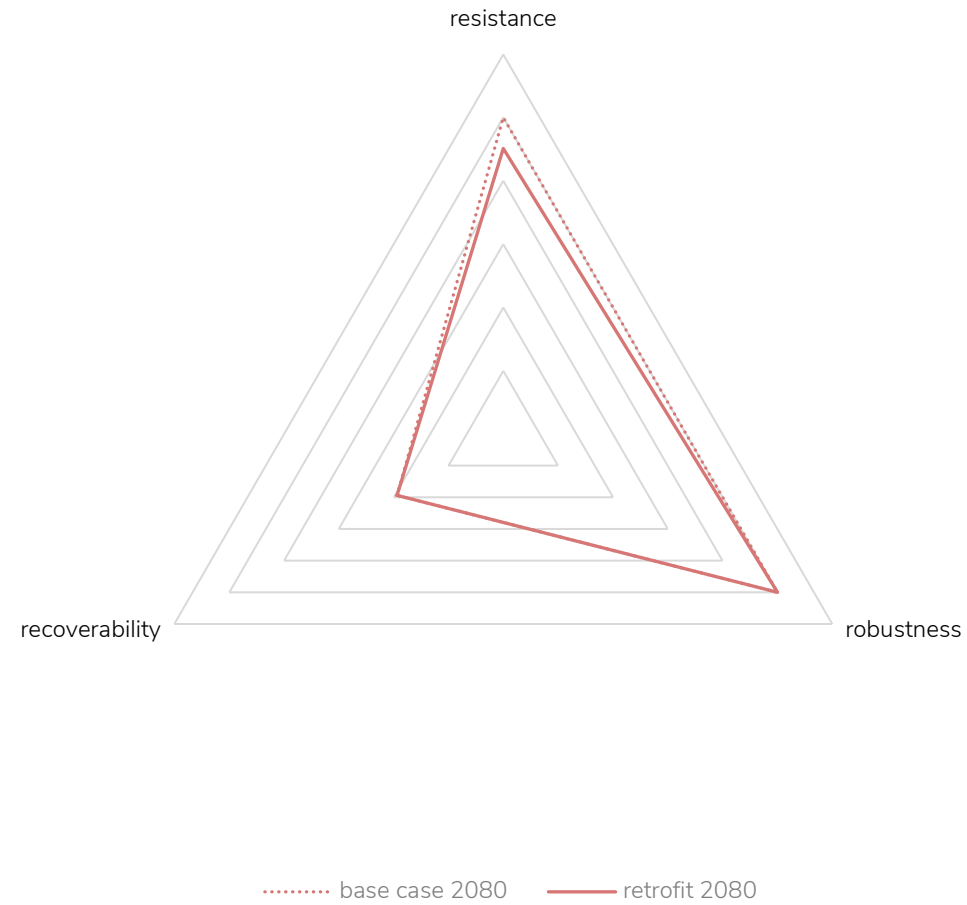
# Final design

evaluation



# Final design

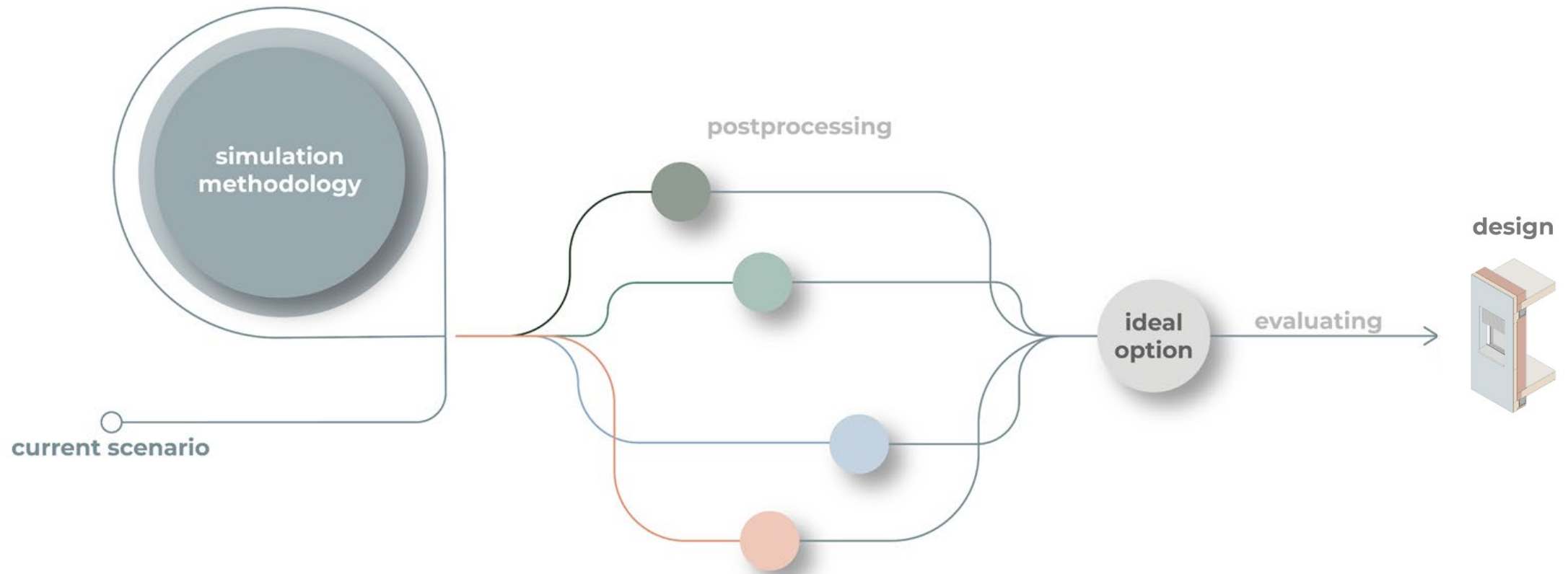
evaluation



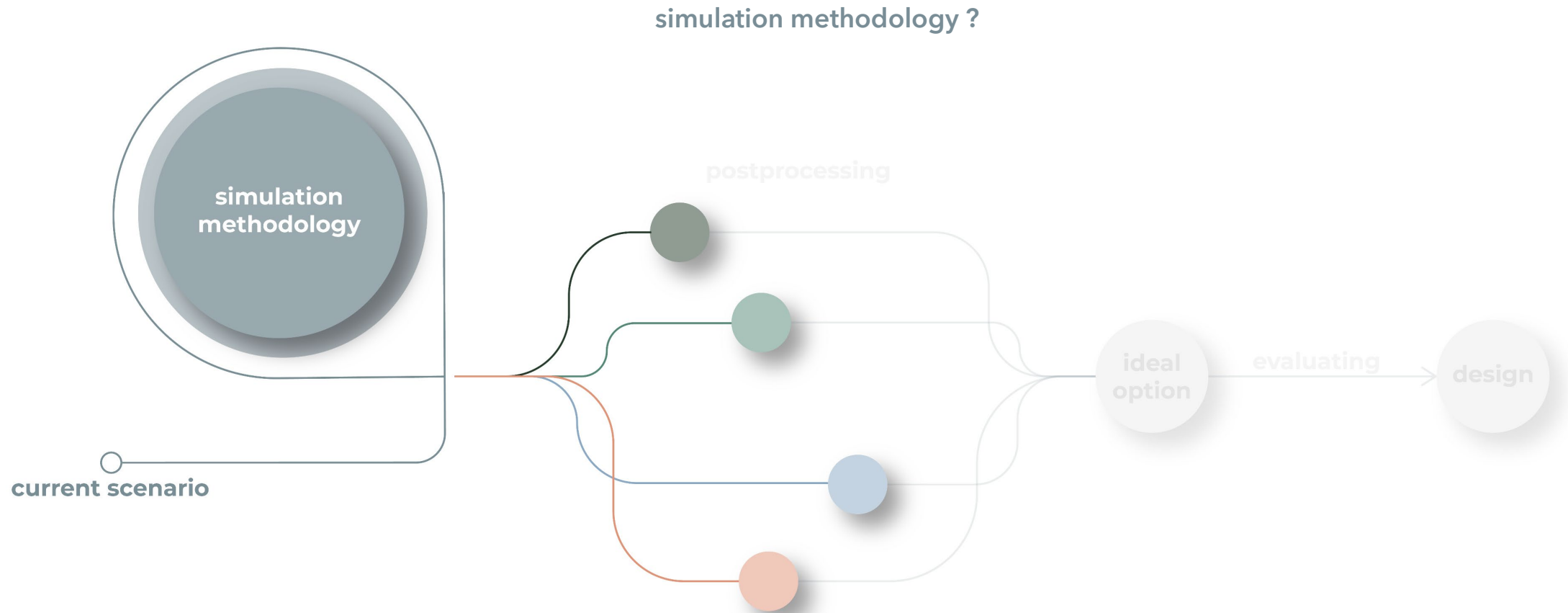
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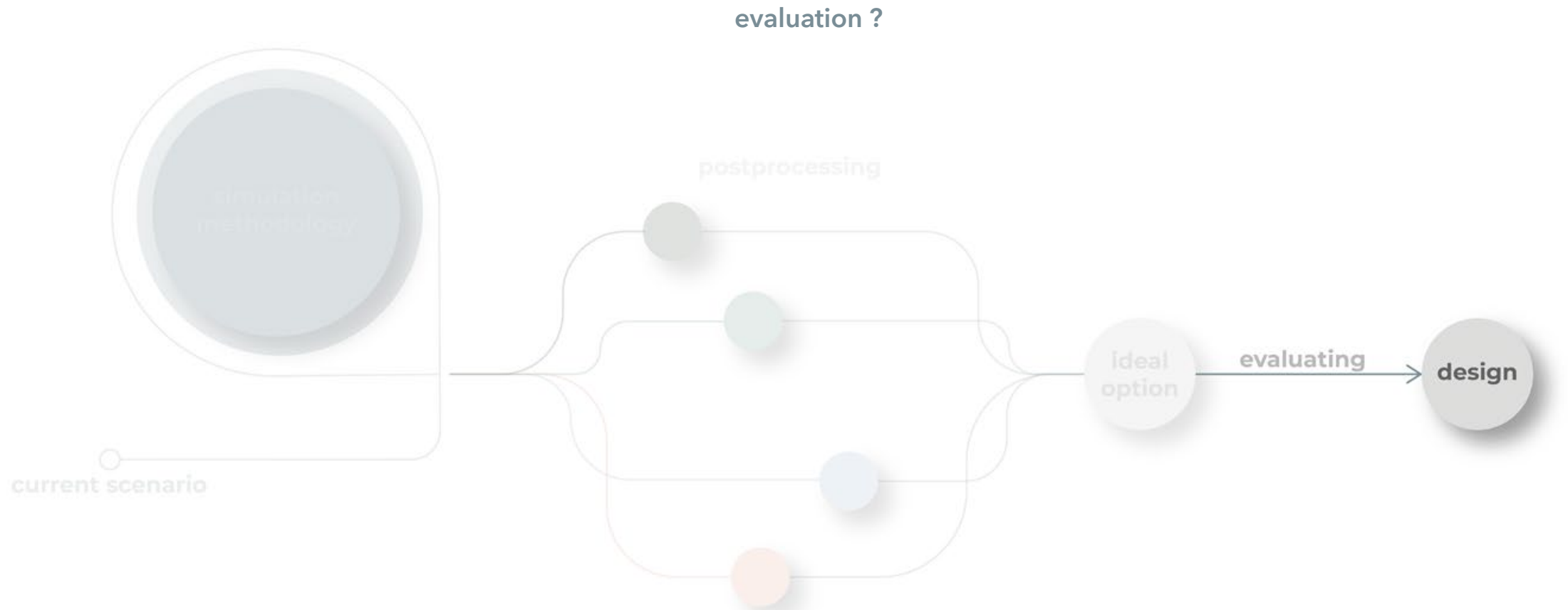
# Conclusion



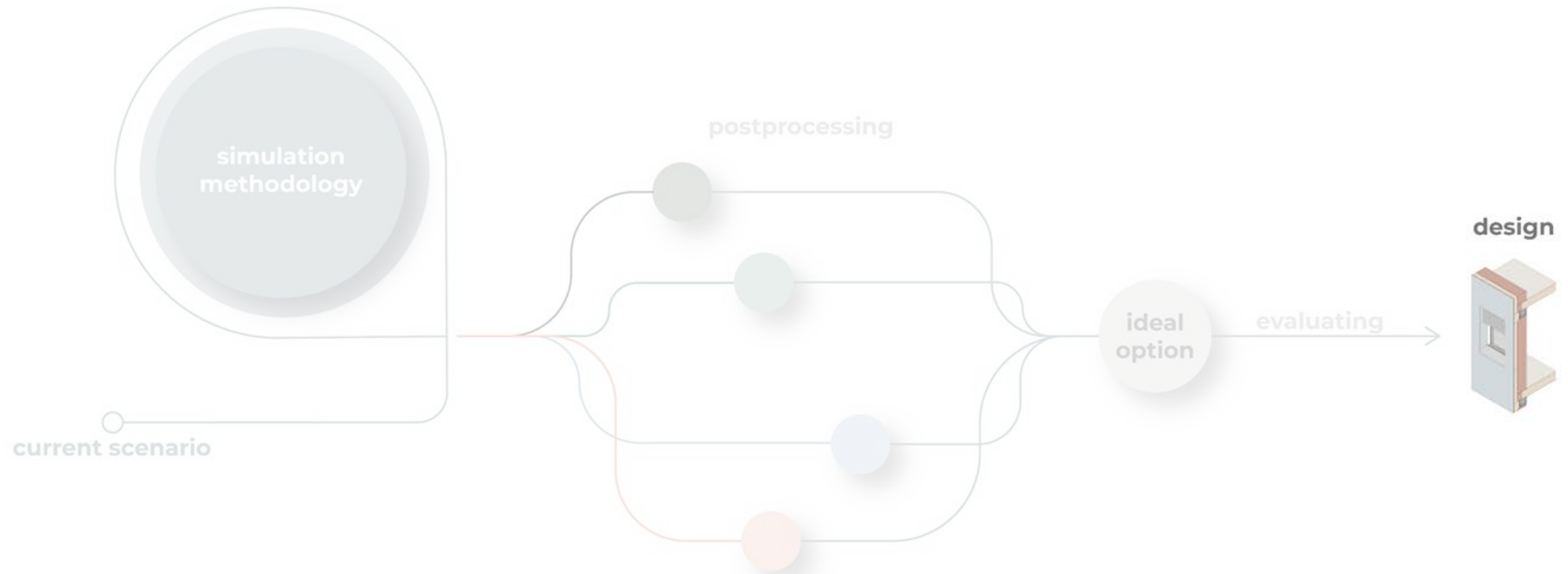
# Conclusion



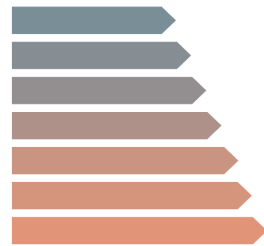
# Conclusion



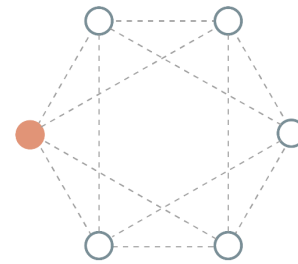
# Conclusion



# Future challenges



**thermal resilience  
classification**



**multi-criteria  
decision-making**

Thank you

## resources

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