A Digital Design Tool for Floods and Heatwaves Resilient Facade System

Quantification of Facade Resilience

Final Presentation

Date- 26-06-2024

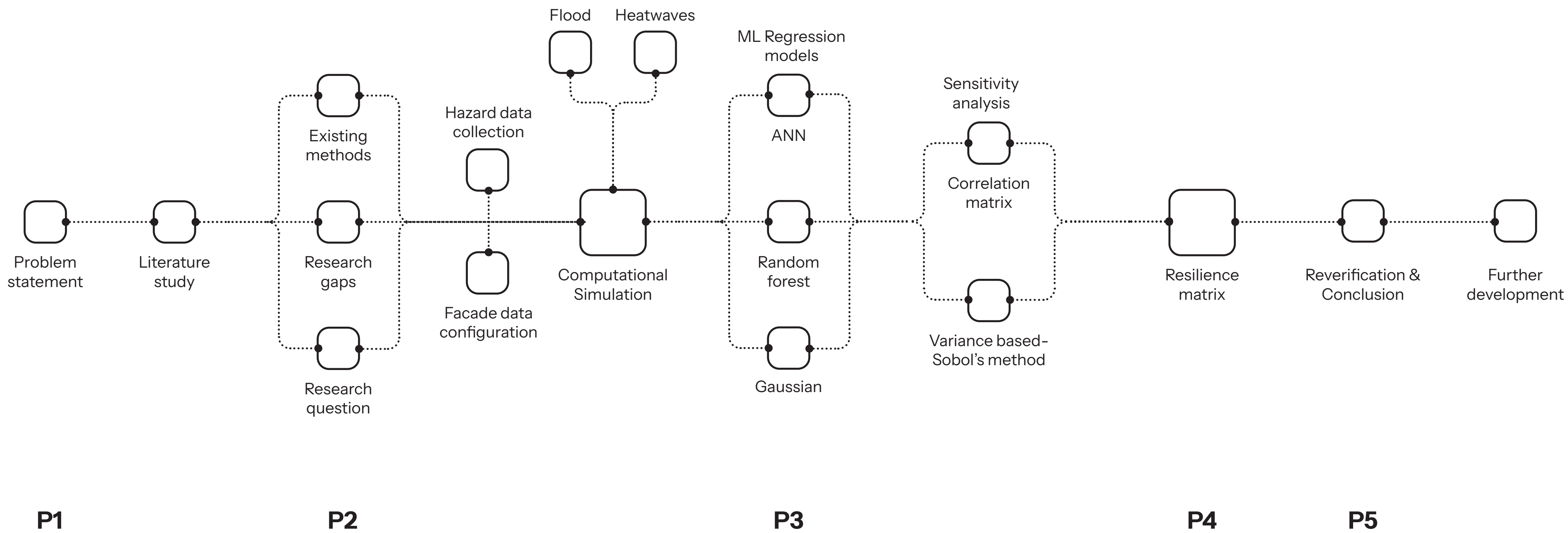
Graduation Project
Msc Building Technology track
Delft University of Technology

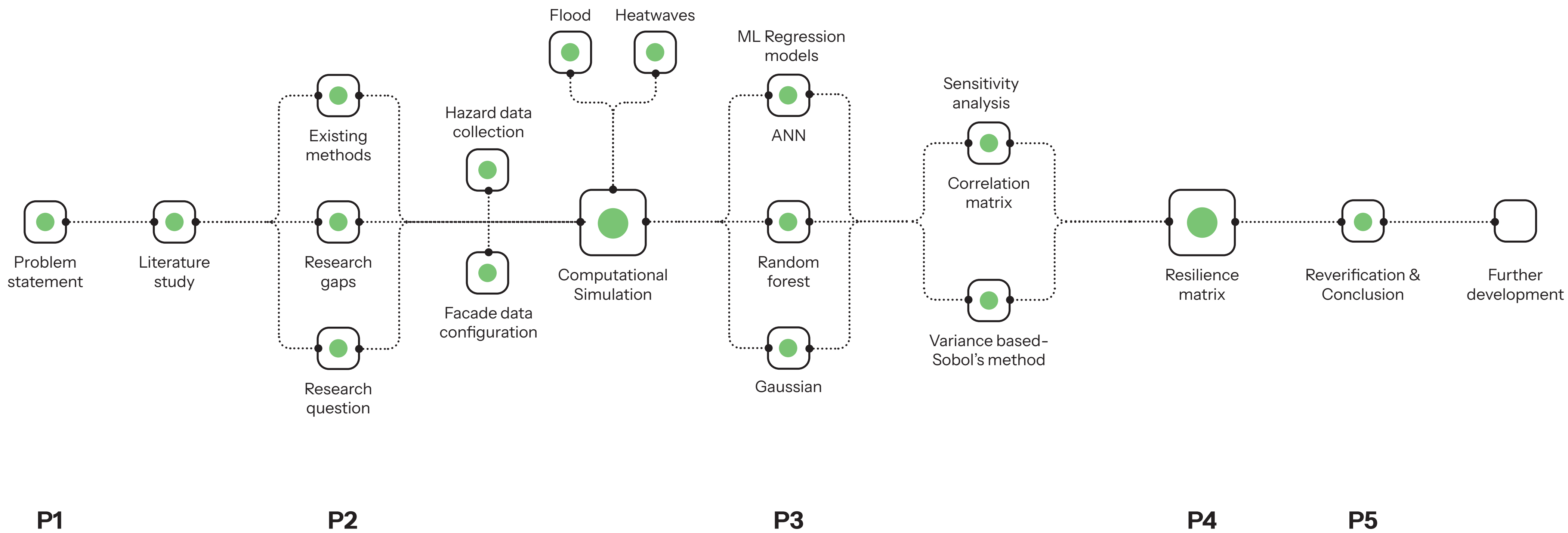
Student
Aashish Sadaphal- 5794714

Mentor
Simona Bianchi (First Mentor)
Alessandra Luna Navarro (Second Mentor)

Delegate
Henriette H. Bier

The aim of this study is to create a tool for **quantifying facade resilience** against **flood** and **heatwaves** and assist designers or engineers in identifying the resilient facade combination.


Problem statement
Literature study
Existing methods
Research gaps
Research question
Hazard data collection
Facade data configuration
Flood
Heatwaves
Computational Simulation
ML Regression models
ANN
Random forest
Gaussian
Sensitivity analysis
Correlation matrix
Variance based-Sobol's method
Resilience matrix
Reverification & Conclusion
Further development
P1
P2
P3
P4
P5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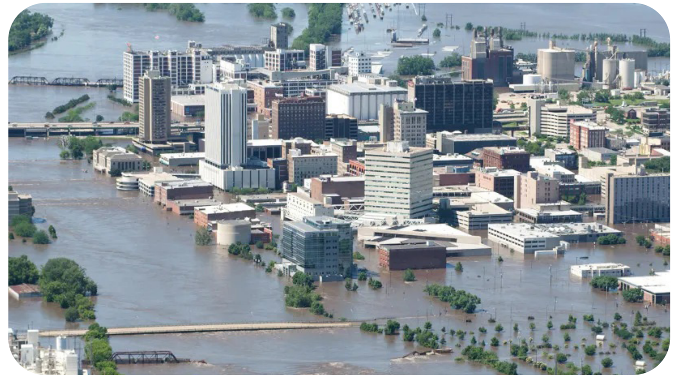
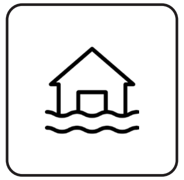
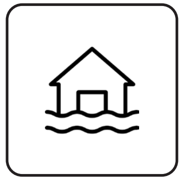
Why?

Climate change





According to the WHO,
around 45% People affected
only by flood- 1998-2017



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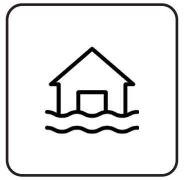
European Environment Agency reports half a trillon euros economic loss due to climate change in last four decades



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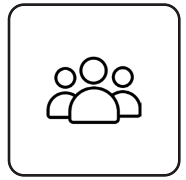

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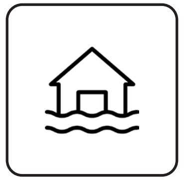
Around 10000 people lost their lives only due to extreme temperature since 2000



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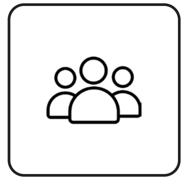

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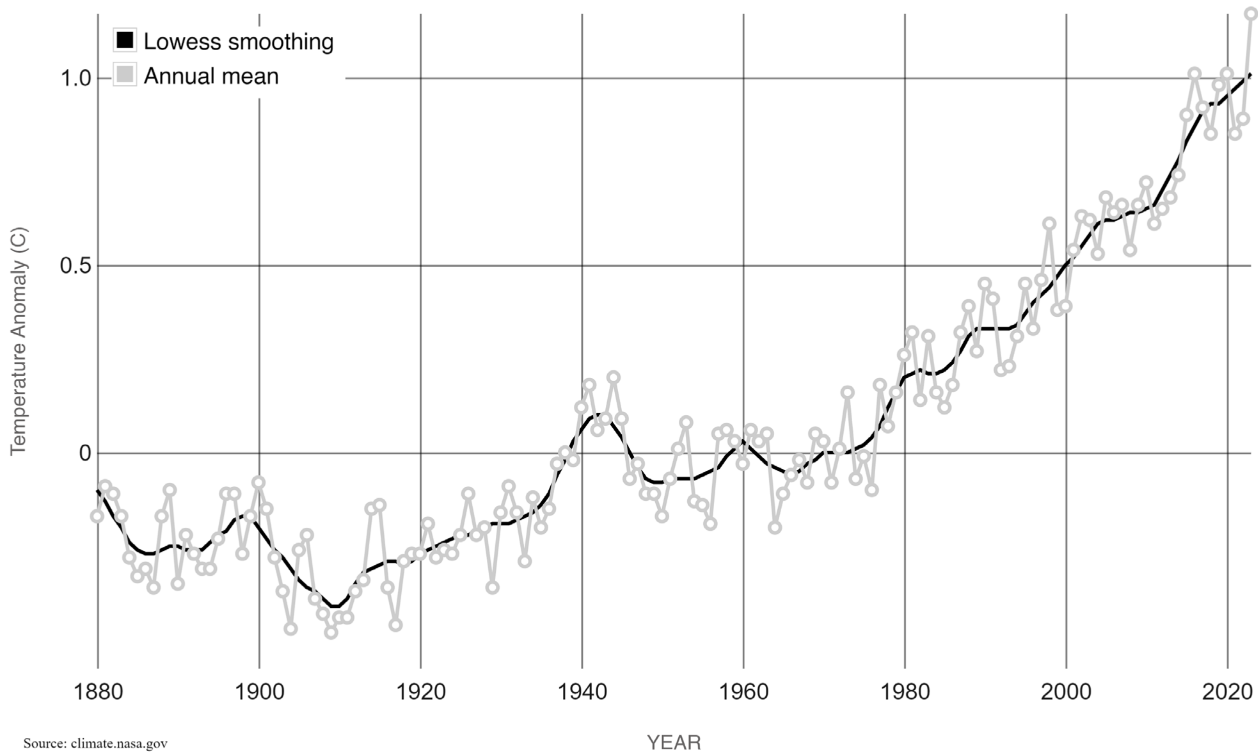
In 2023, a total of 79 disasters associated with hydrometerological hazard event were recorded in Asia, in which over 80% were related to floods and heatwaves.

more than 2000 fatalities and nine million people were directly affected by these disruptive events.

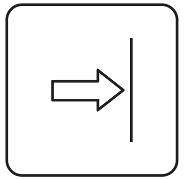
Therefore, these problems are severe, as they are getting increased day by day, and need to be solved.



Source: climate.nasa.gov

Why facade?

First line of contact



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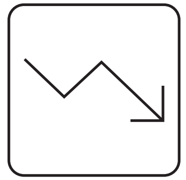

Minor intensiy of hazards can lead to significant economic losses.

First line of contact

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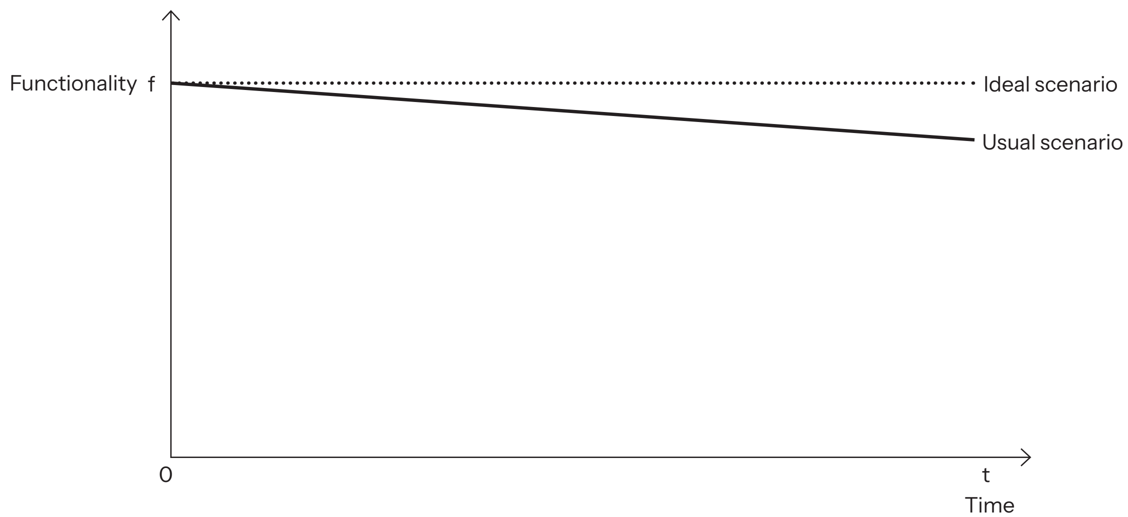
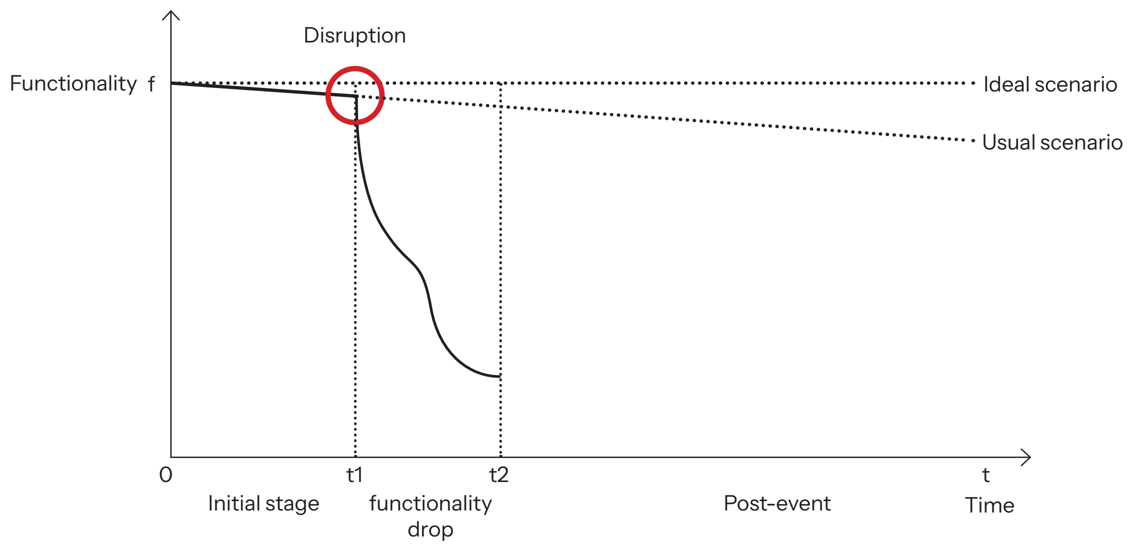
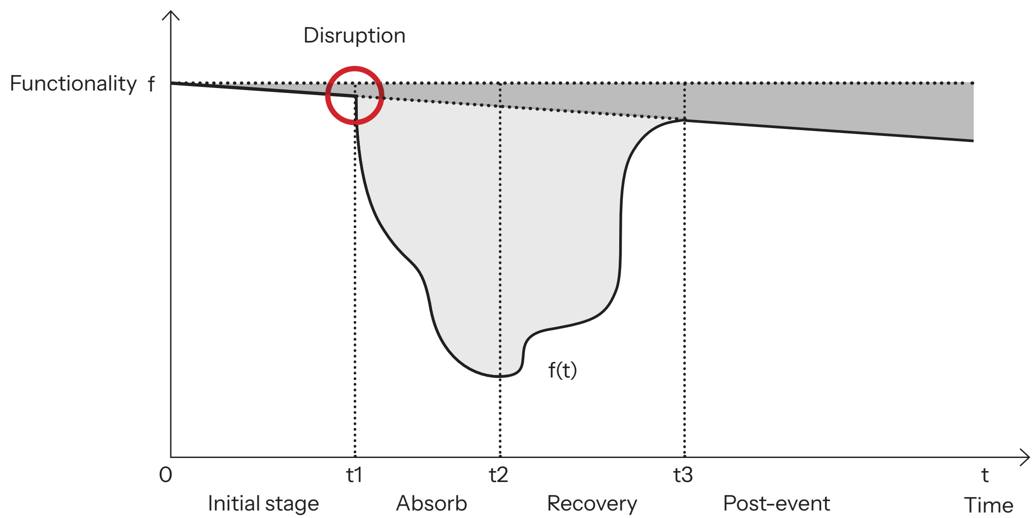
Overall building resilience

What is resilience?


Functionality f
Ideal scenario
Usual scenario
0
t
Time


Disruption
Functionality f
Ideal scenario
Usual scenario
0
t1
t2
t
Initial stage
functionality drop
Post-event
Time

Resilience is the capability of an individual, community or system to prepare, absorb, adapt and recover from disruptive events.



Research gaps

There is **no simplified practical methodology** for the designers to follow while designing flood and heatwaves resilient facade.

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Various projects are currently ongoing to assess the **resilience at district, city and region level**. However, there is still need for a tool or method which can assess the **resilience in facade**.

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There is **a lack of available tools that can solve the multi-hazard problem**. Most of the current tools provide assessment for one hazard.

Research question

How can we identify the optimal facade combination that is resilient against heatwaves and floods?

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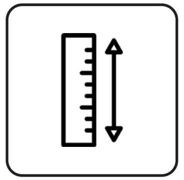

What are the **most probable stressors** associated with **heatwaves and floods** that should be considered in the research, and how do they **impact building facades** and **indoor comfort?**

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What **existing methodologies or frameworks** are available for assessing **building envelope/facade resilience,** and how do they address multi-hazard scenarios?

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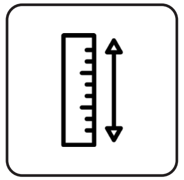

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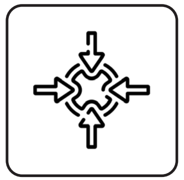

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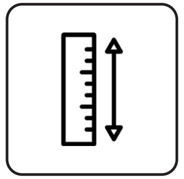

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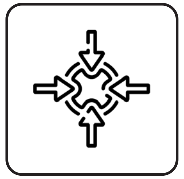

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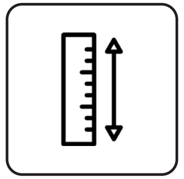

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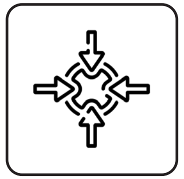

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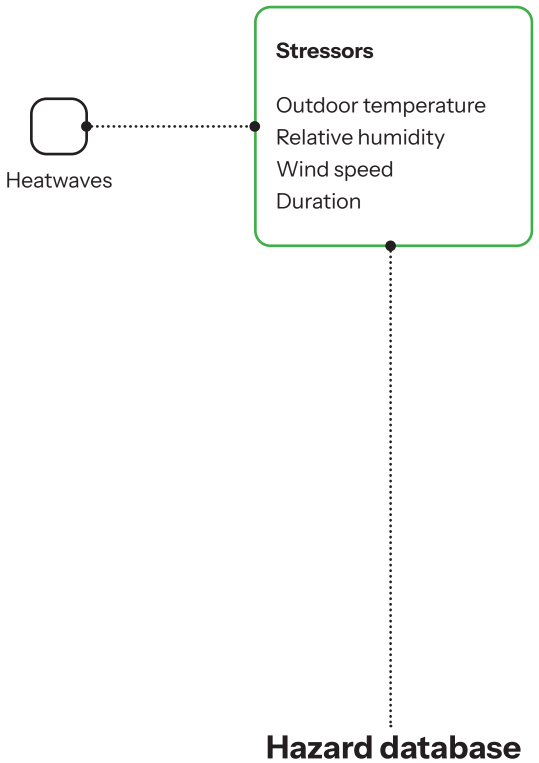
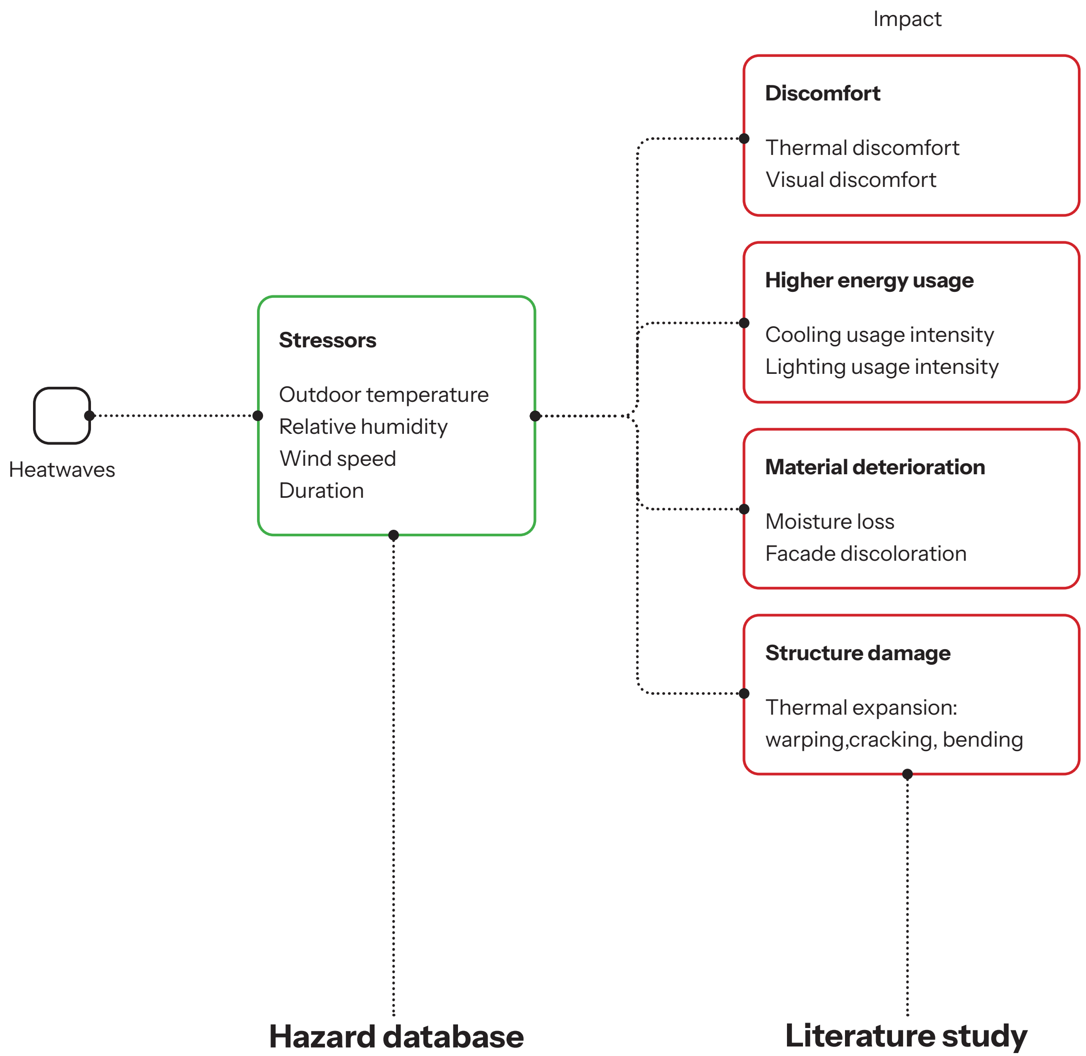
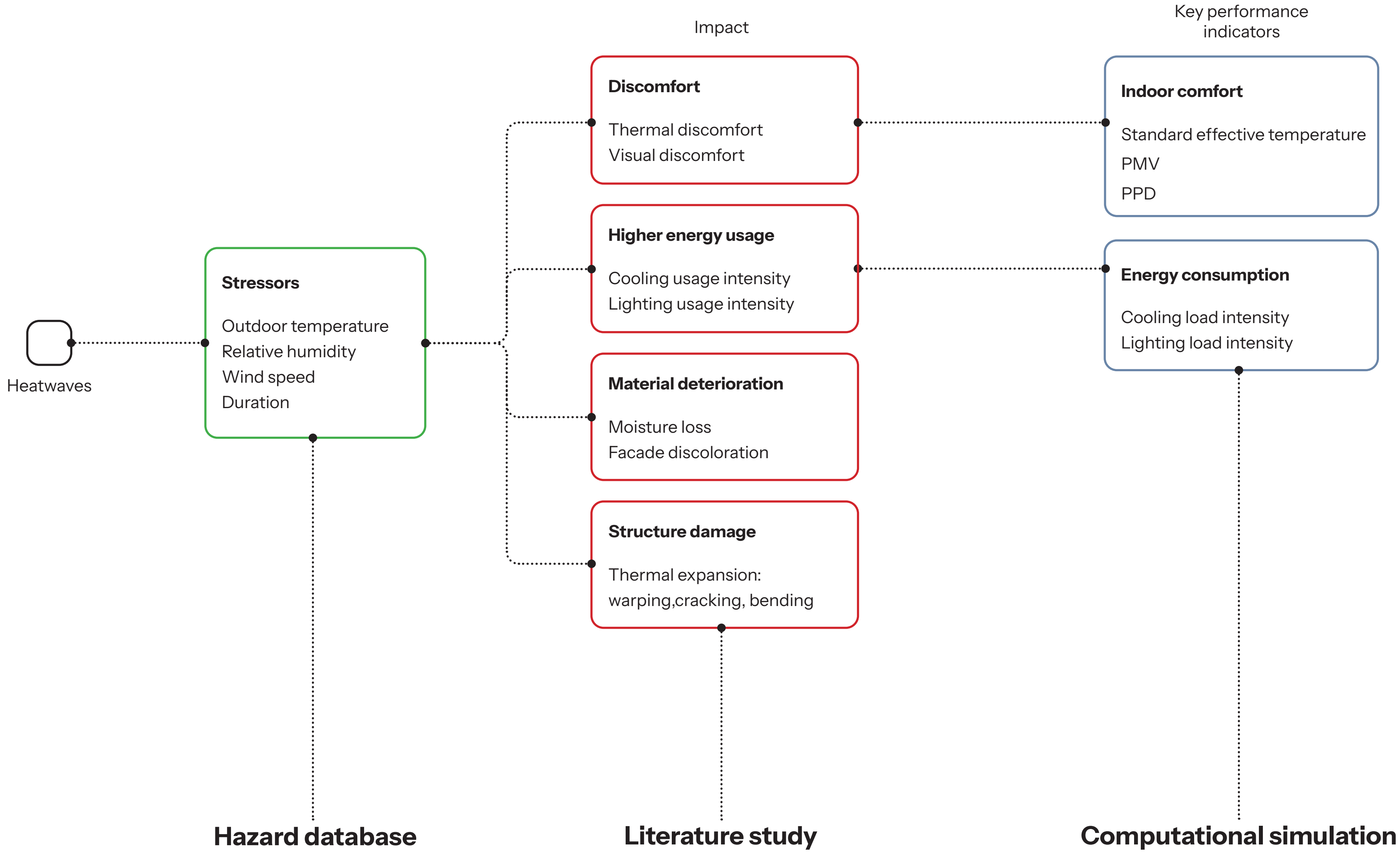
How can we define the t**otal resilience loss**, including h**eatwave and flood resilience loss**, for a facade system using a **multi-criteria decision-making process**?

Evaluation framework - Heatwaves

Heatwaves

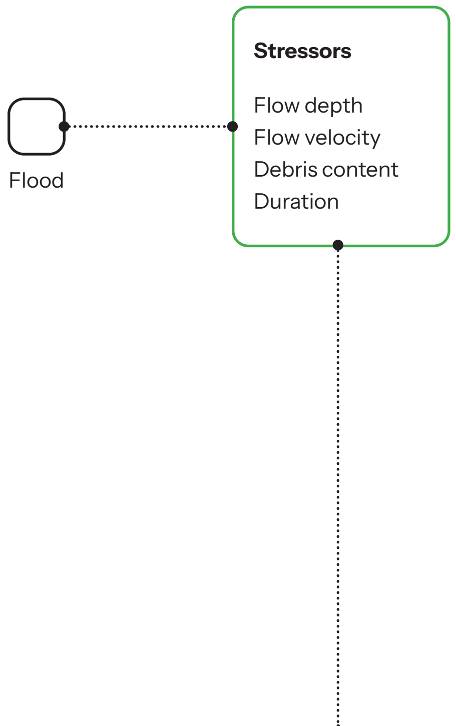

Heatwaves
Stressors
Outdoor temperature
Relative humidity
Wind speed
Duration
Hazard database


Impact
Discomfort
Thermal discomfort
Visual discomfort
Higher energy usage
Cooling usage intensity
Lighting usage intensity
Stressors
Outdoor temperature
Relative humidity
Wind speed
Duration
Heatwaves
Material deterioration
Moisture loss
Facade discoloration
Structure damage
Thermal expansion:
warping,cracking, bending
Hazard database
Literature study

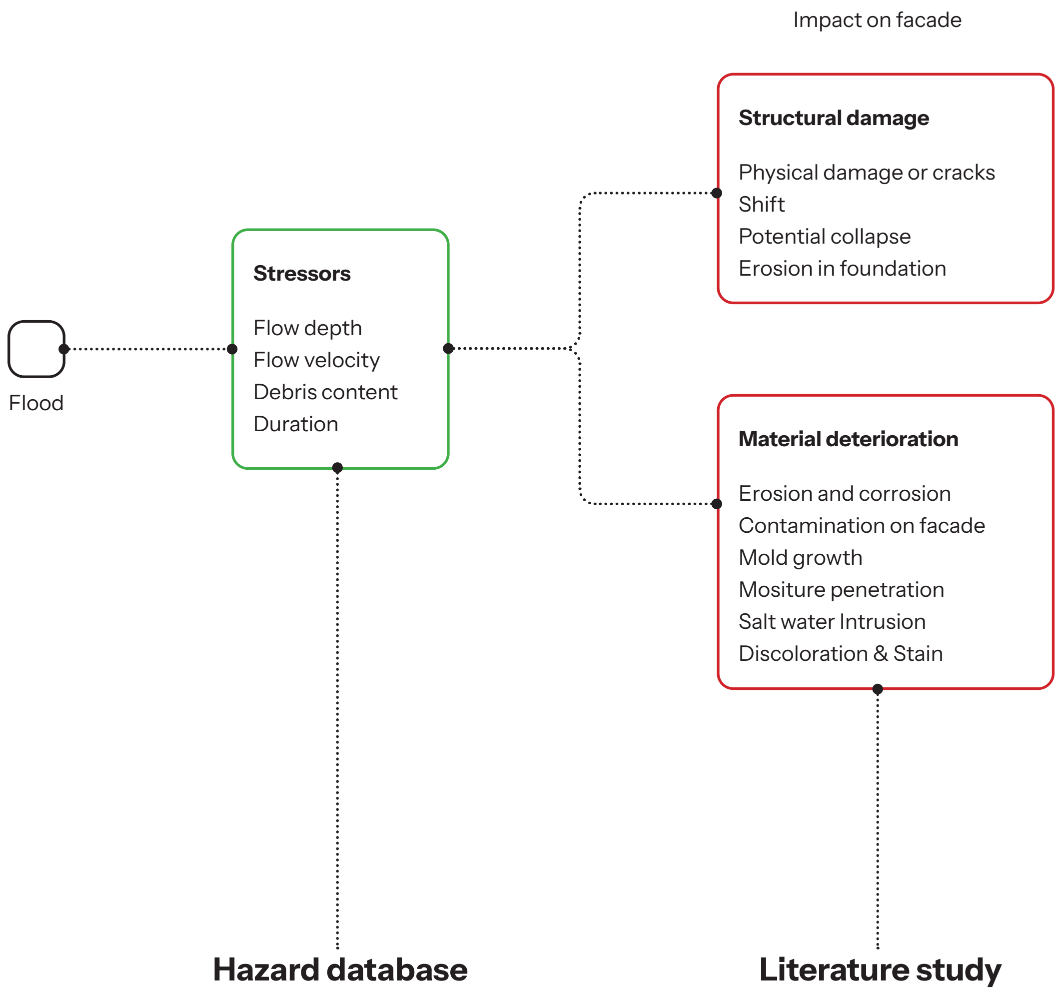

Impact
Key performance indicators
Heatwaves
Stressors
Outdoor temperature
Relative humidity
Wind speed
Duration
Discomfort
Thermal discomfort
Visual discomfort
Higher energy usage
Cooling usage intensity
Lighting usage intensity
Material deterioration
Moisture loss
Facade discoloration
Structure damage
Thermal expansion:
warping,cracking, bending
Indoor comfort
Standard effective temperature
PMV
PPD
Energy consumption
Cooling load intensity
Lighting load intensity
Hazard database
Literature study
Computational simulation

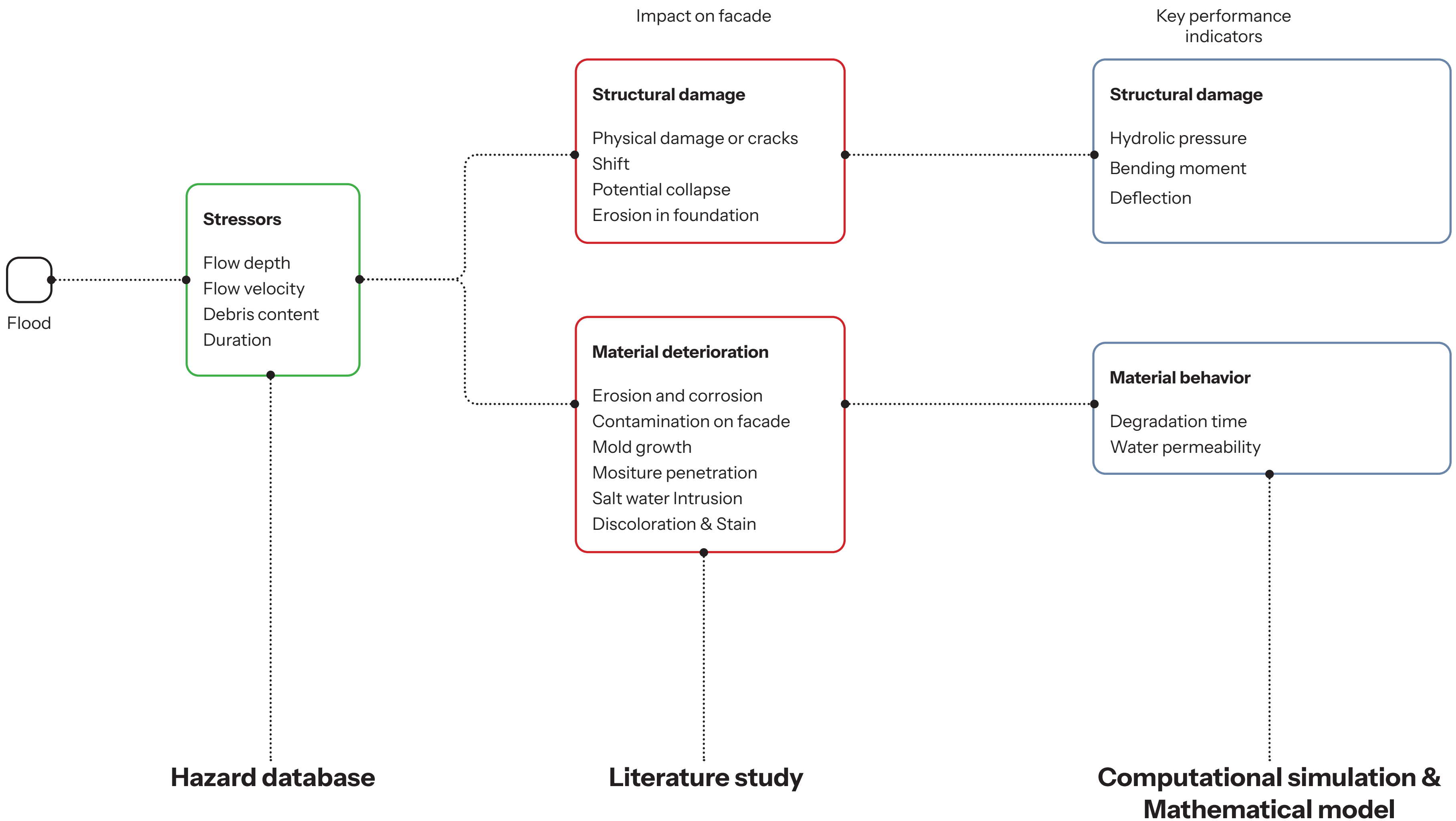
Evaluation framework – Flood

Flood



Hazard database


Impact on facade
Structural damage
Physical damage or cracks
Shift
Potential collapse
Erosion in foundation
Stressors
Flow depth
Flow velocity
Debris content
Duration
Flood
Material deterioration
Erosion and corrosion
Contamination on facade
Mold growth
Mositure penetration
Salt water Intrusion
Discoloration & Stain
Hazard database
Literature study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Potential collapse
Erosion in foundation
Material deterioration
Erosion and corrosion
Contamination on facade
Mold growth
Mositure penetration
Salt water Intrusion
Discoloration & Stain
Structural damage
Hydrolic pressure
Bending moment
Deflection
Material behavior
Degradation time
Water permeability
Hazard database
Literature study
Computational simulation & Mathematical model

Computational simulation framework- Heatwaves

Input

Building parameters

Project location
Building width
Building length
No. of floors
F/F height
Analysis floor

Facade parameters

WWR
- Aperature width
- Aperature height

Apertures
- U-value
- SHGC
- Visible transmittance

Opaque materials
- Thickness
- Conductivity
- Density
- Spec. heat
- Thermal absorption
- Solar absorption
- Visible absorption
- Surface reflectance

Building Operational parameters

Occupancy
lighting schedule
Heating & Cooling setpoints
ventilation & Infilltration
Person density
lighting load
equipment load
Efficiency of heating and cooling system

Heatwave hazard data

Dry bulb temperature
Dew point temperature
Relative humidity
Wind speed

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Facade configurations- 7168

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Input

Building parameters

Project location
Building width
Building length
No. of floors
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Analysis floor

Geometry creation

Zoning
Core development
Window generation and frame
Window labelling
Context creation

Facade parameters

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Facade configurations- 7168

Construction set

Aperature dimensions
Material specification

Building Operational parameters

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Efficiency of heating and cooling system

Program type (Office)

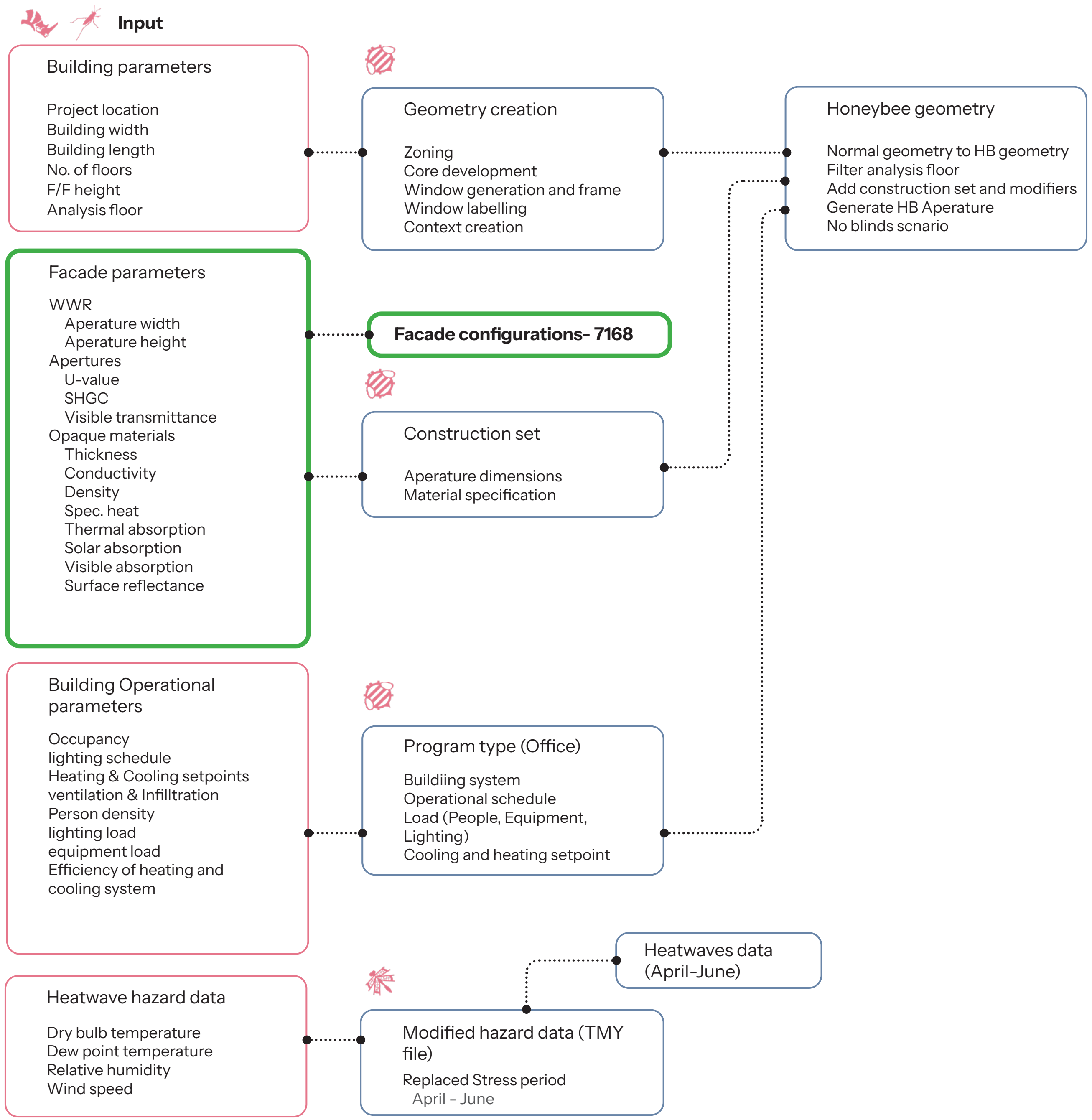
Buildiing system
Operational schedule
Load (People, Equipment, Lighting)
Cooling and heating setpoint

Heatwave hazard data

Dry bulb temperature
Dew point temperature
Relative humidity
Wind speed

Modified hazard data (TMY file)

Replaced Stress period
- April - June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Analysis floor
Geometry creation
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Core development
Window generation and frame
Window labelling
Context creation
Honeybee geometry
Normal geometry to HB geometry
Filter analysis floor
Add construction set and modifiers
Generate HB Aperature
No blinds scnario
Facade parameters
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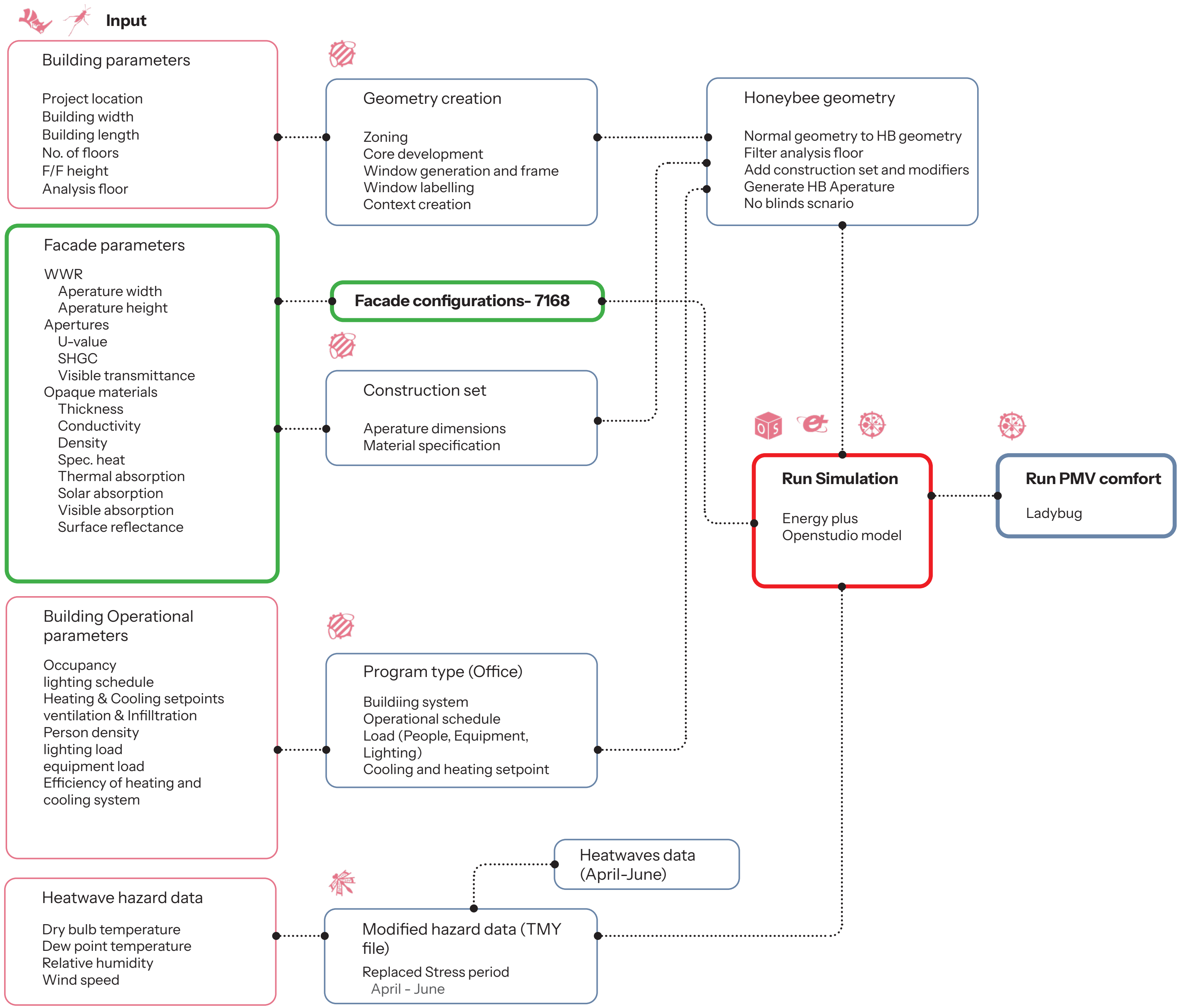
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Construction set
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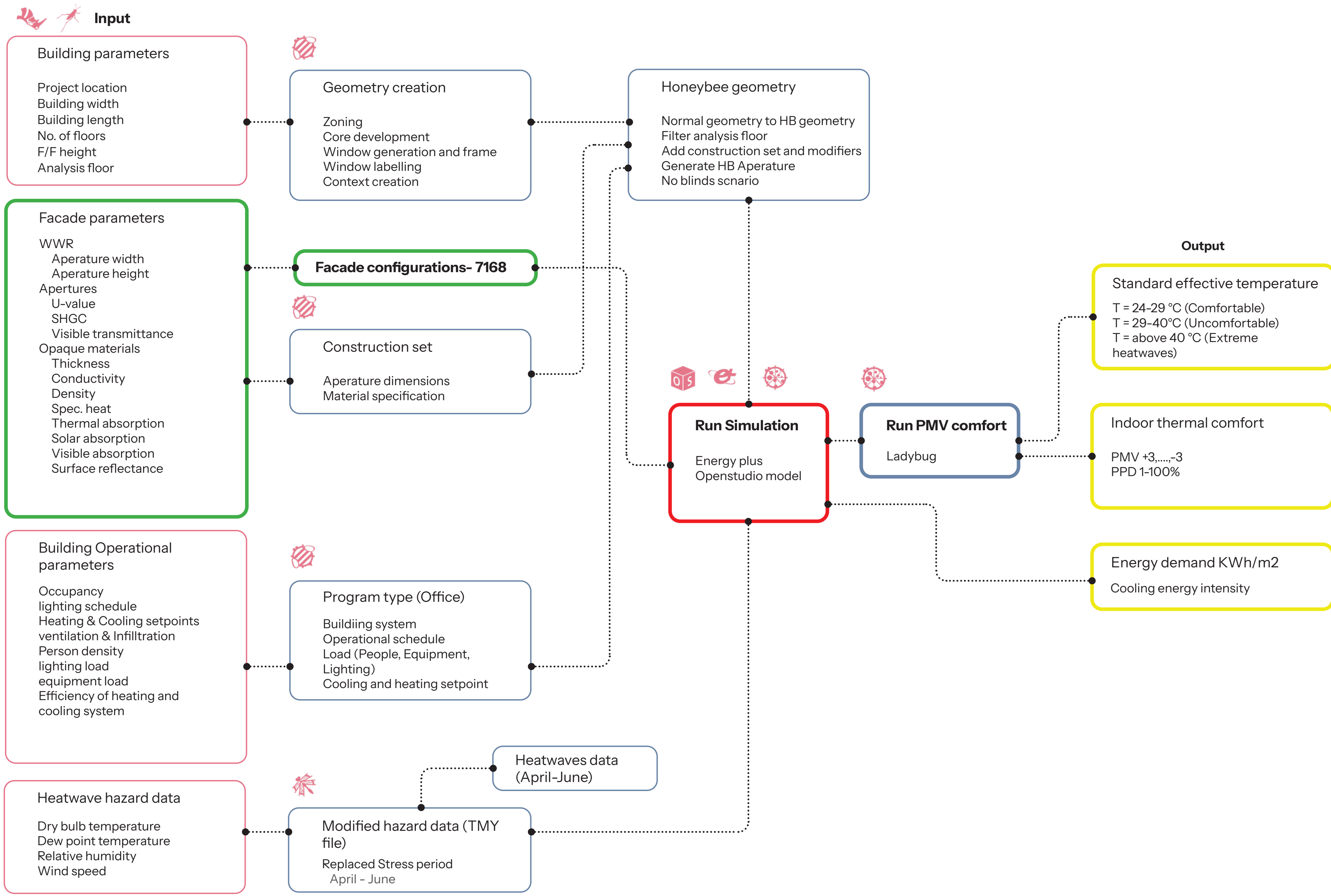
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Energy plus
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Run PMV comfort
Ladybug
Output
Standard effective temperature
T = 24-29 °C (Comfortable)
T = 29-40°C (Uncomfortable)
T = above 40 °C (Extreme heatwaves)
Indoor thermal comfort
PMV +3,....,-3
PPD 1-100%
Energy demand KWh/m2
Cooling energy intensity

Casestudy: Chennai, India
Office building- Heatwaves

Every country has different considerations for heatwaves

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As per IMD (India Meteorological Department), heatwaves is considered if the temperature reaches at least 40 °C for plain regions and 30 °C for hilly regions.

T >=40 °C

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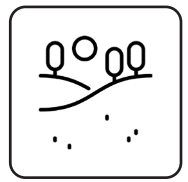
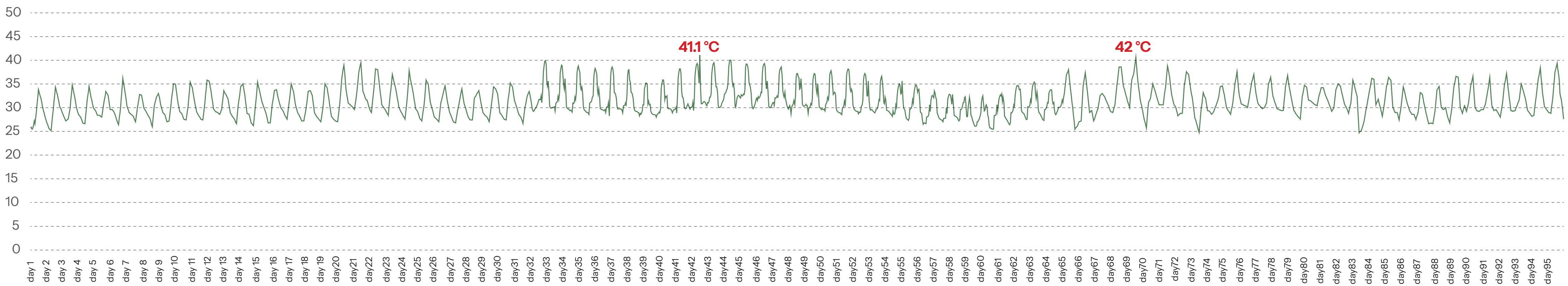


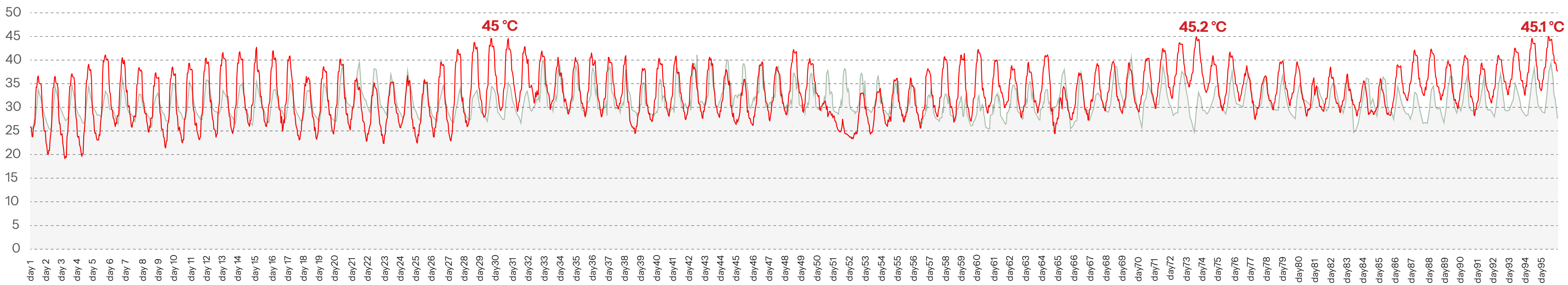
T >=30 °C

Heatwaves data modification

Typical weather data- Chennai,India (April - June)



Heatwaves 2021- Chennai,India (April - June)



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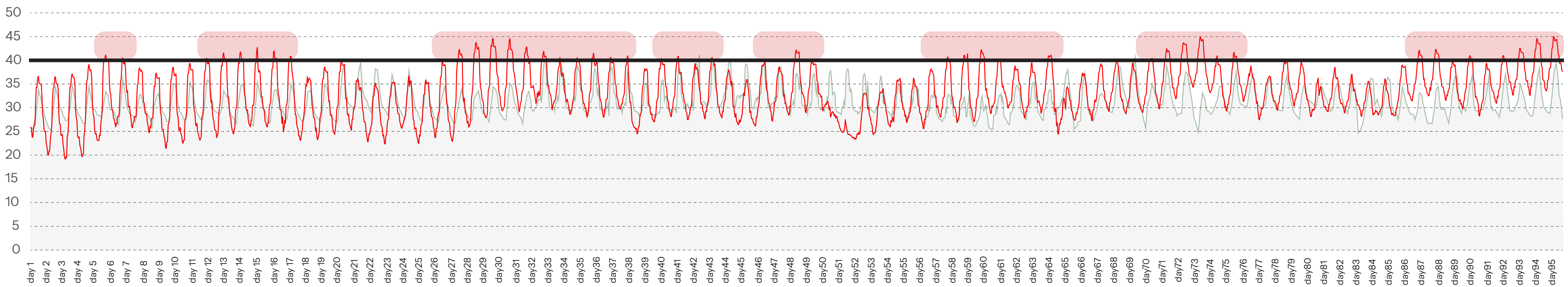
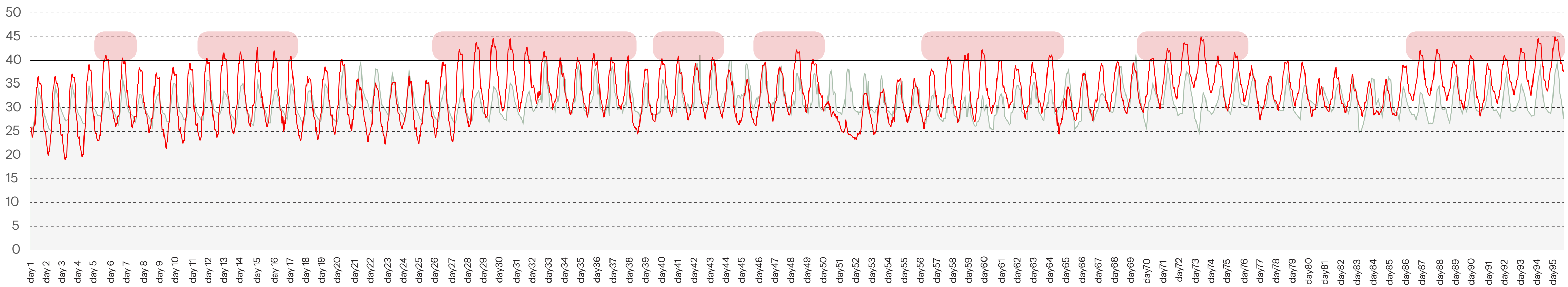


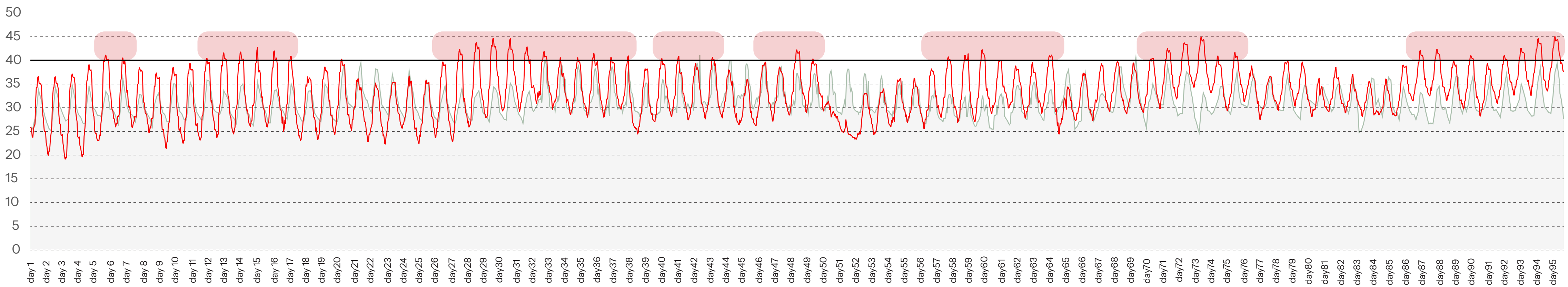
Heatwaves 2021- Chennai,India (April - June)



Heatwaves 2021 data

April
May
June

Heatwaves 2021- Chennai,India (April - June)



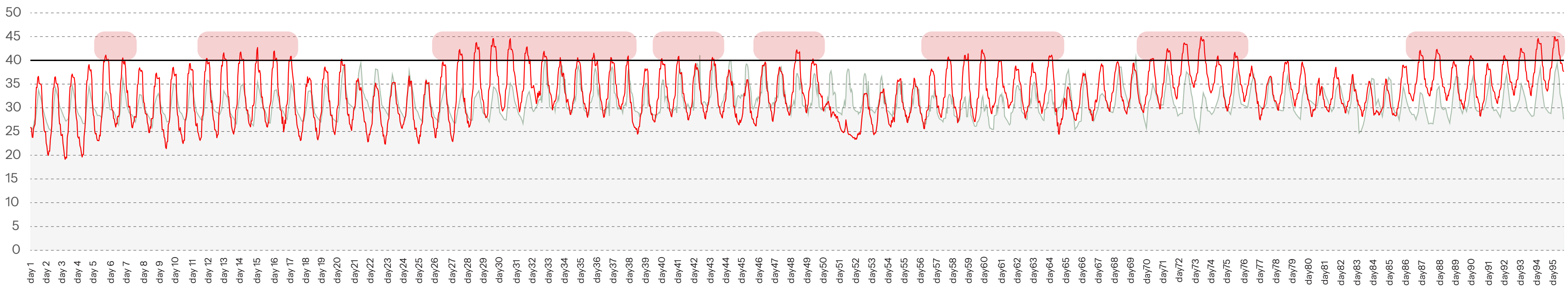
Annual weather data

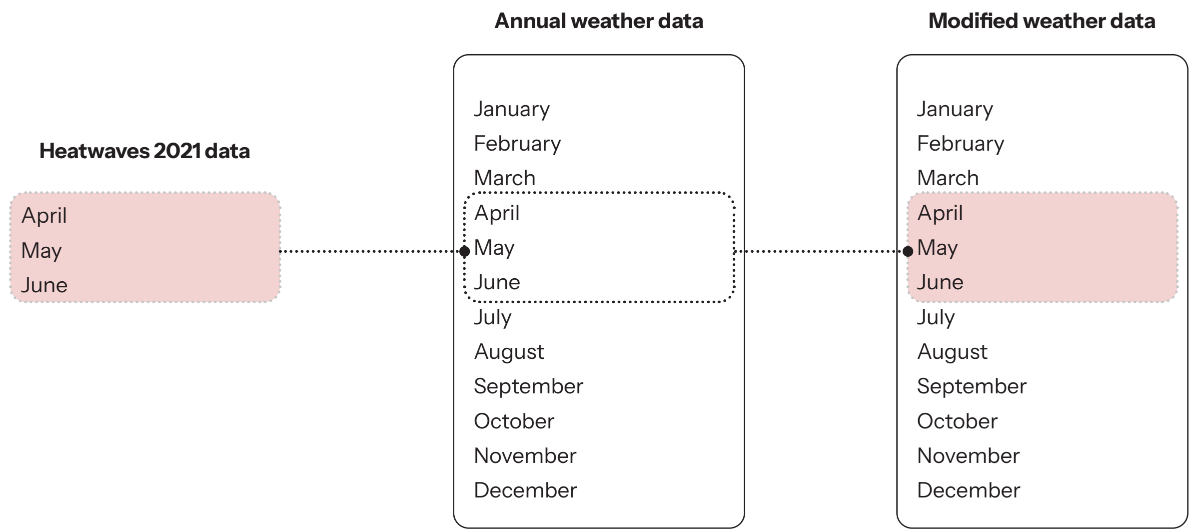
Heatwaves 2021 data

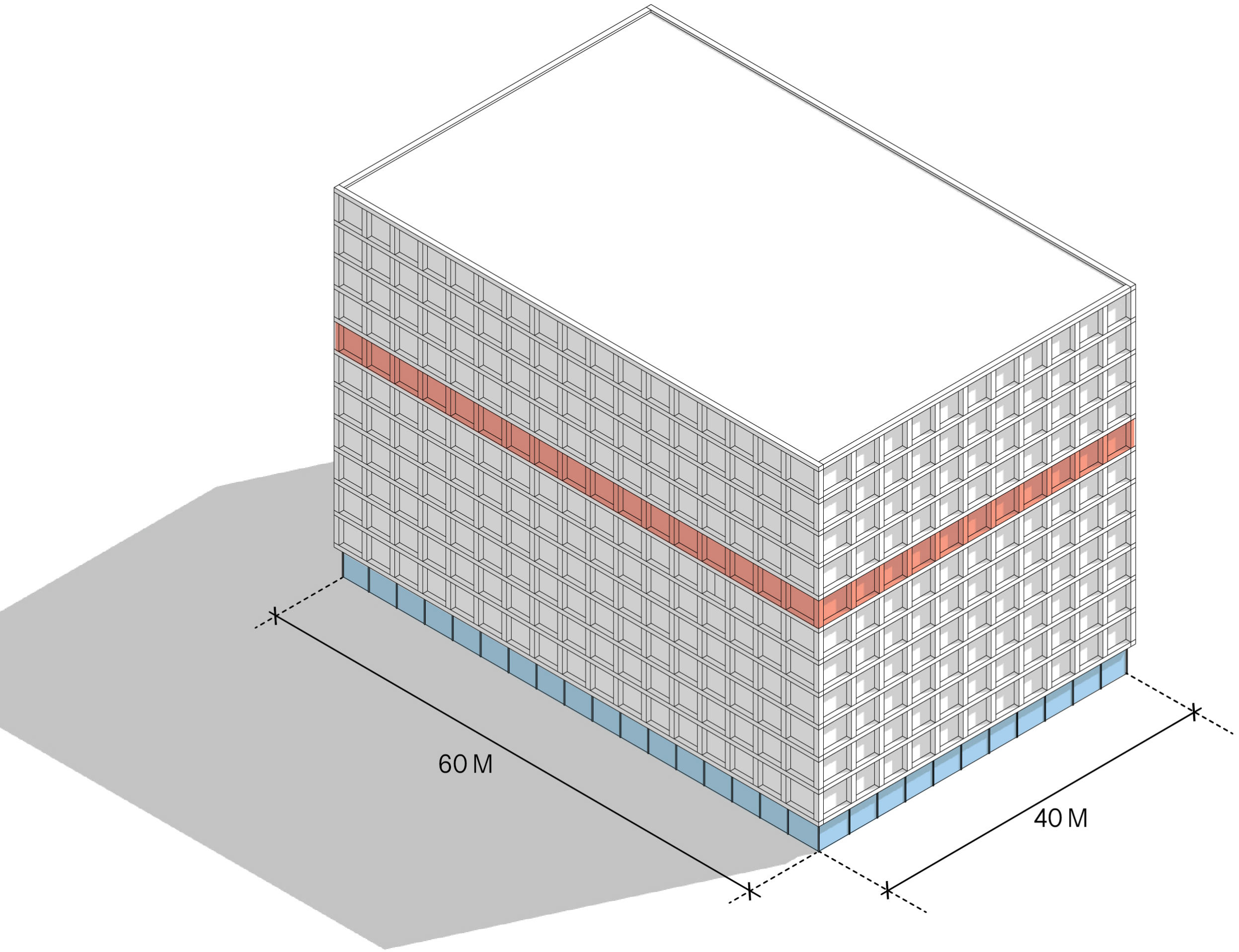
April
May
June

January
February
March
April
May
June
July
August
September
October
November
December

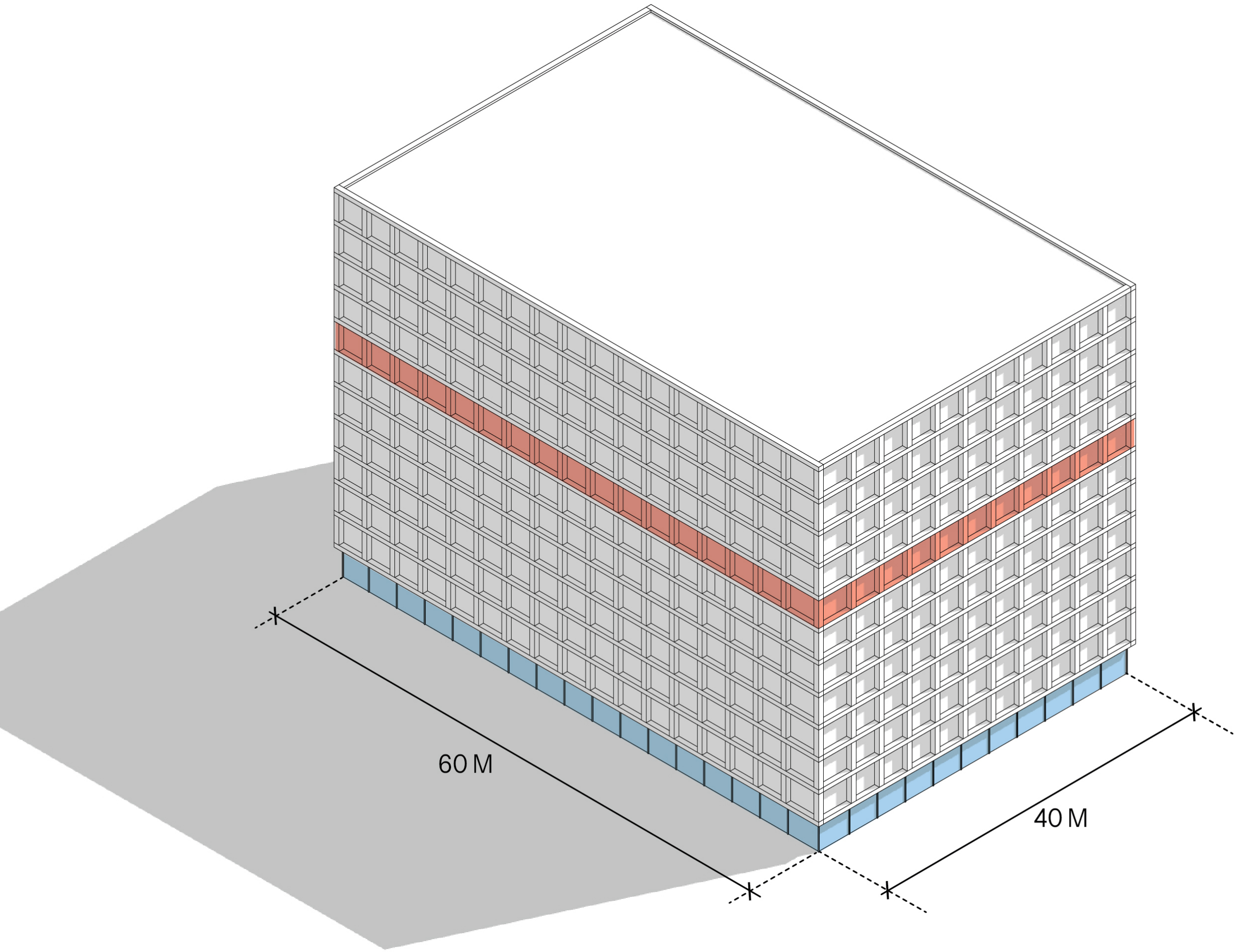
Heatwaves 2021- Chennai,India (April - June)







Office building



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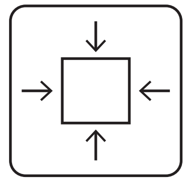
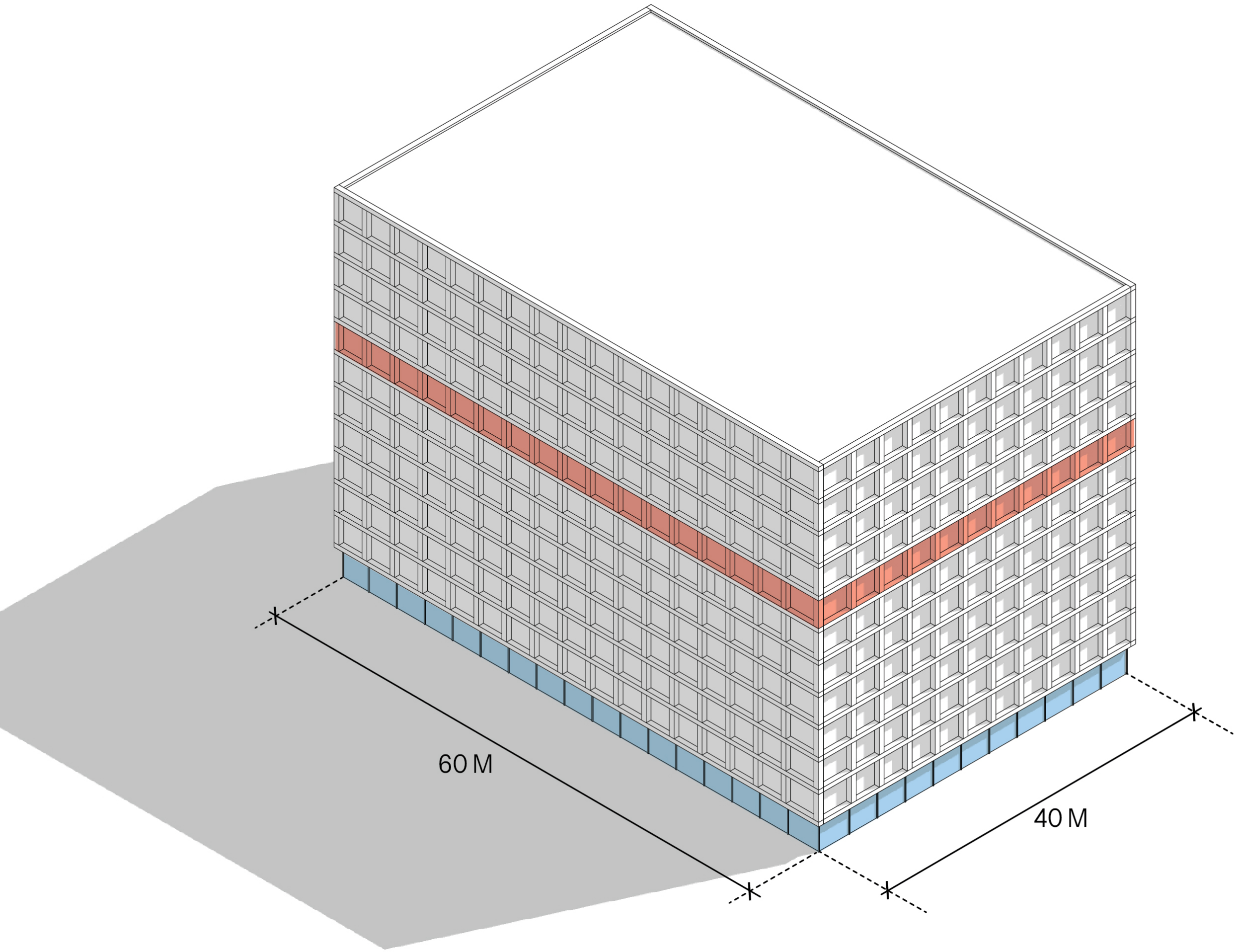


Exposed from all sides



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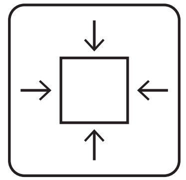
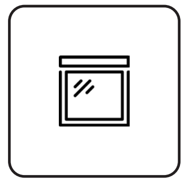
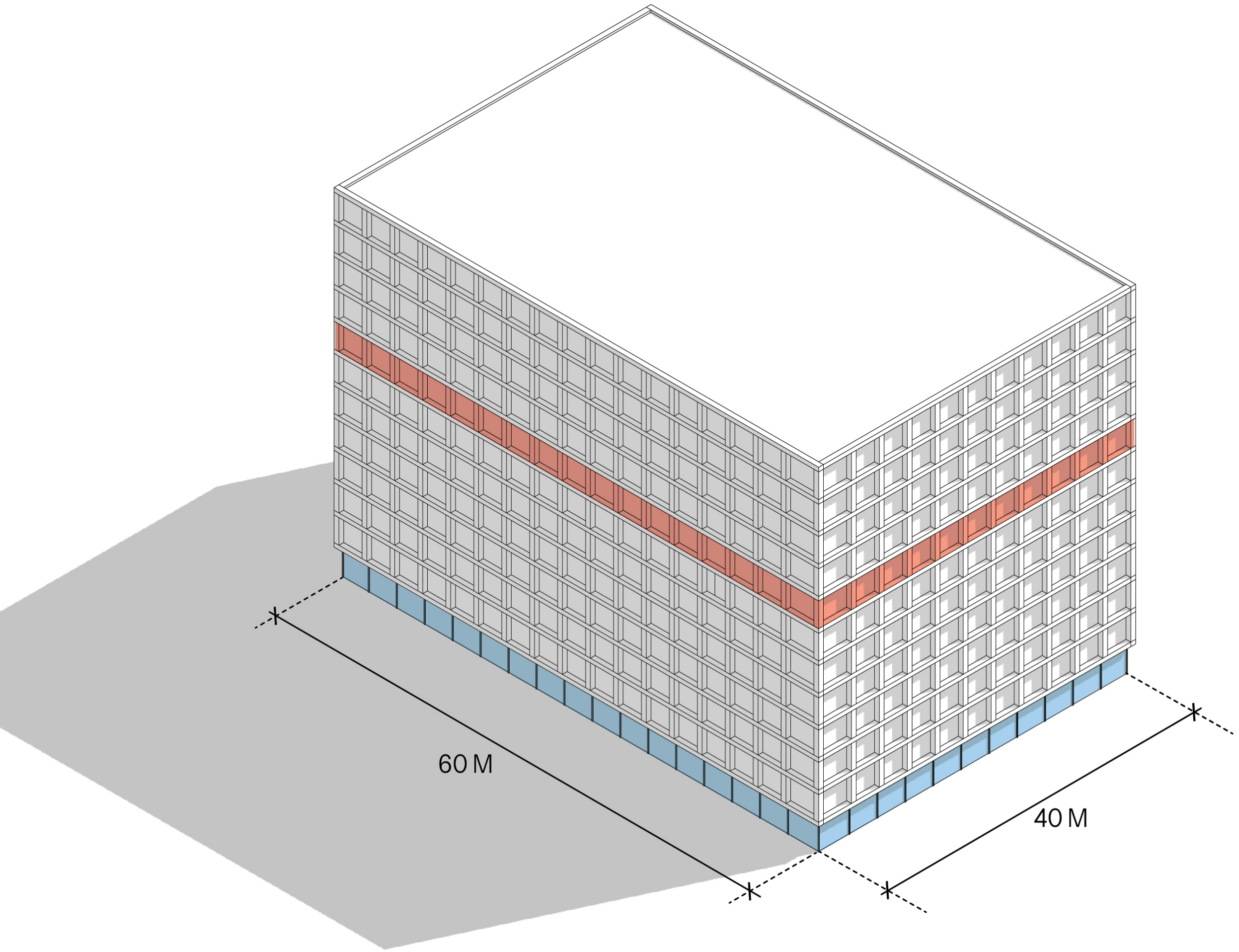


Exposed from all sides



75 % wall-window ratio

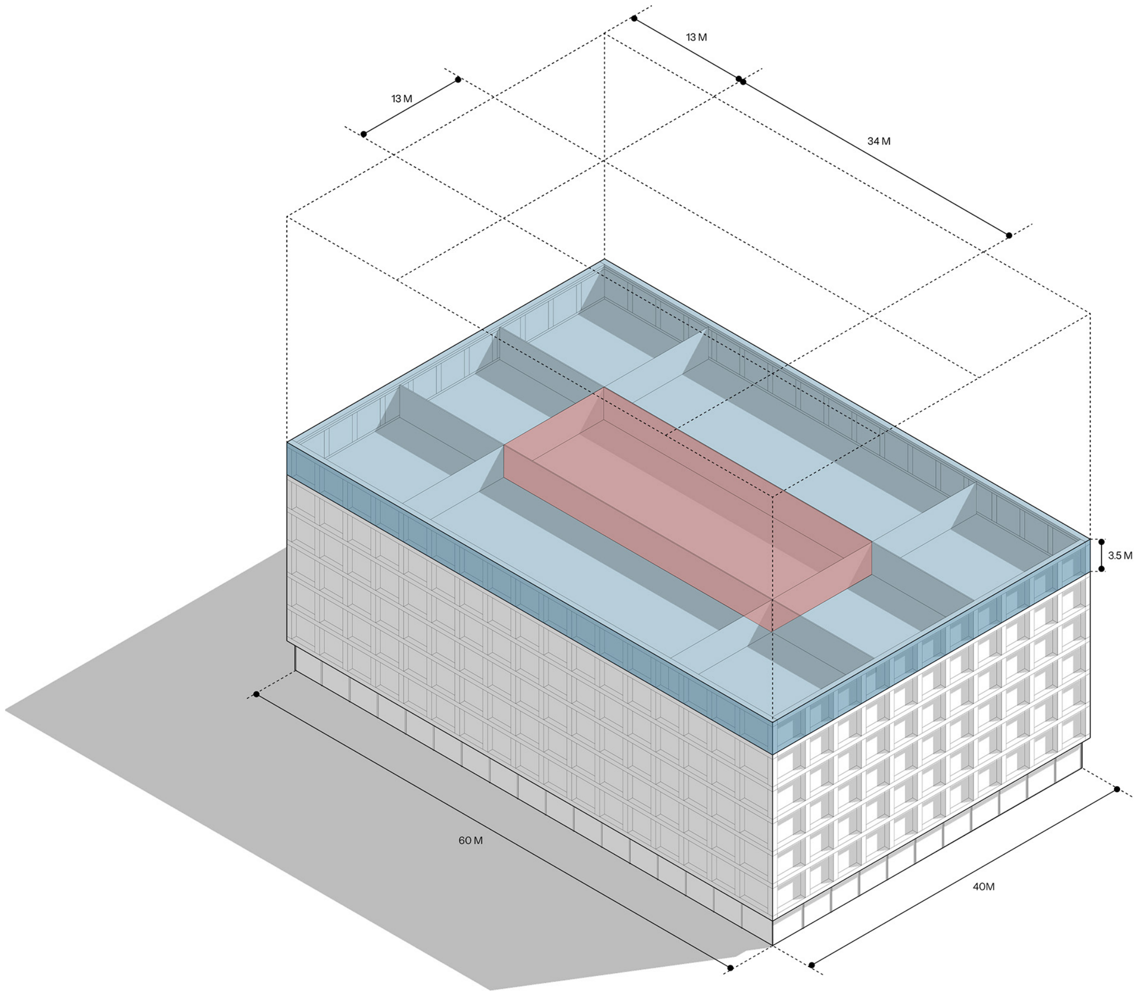


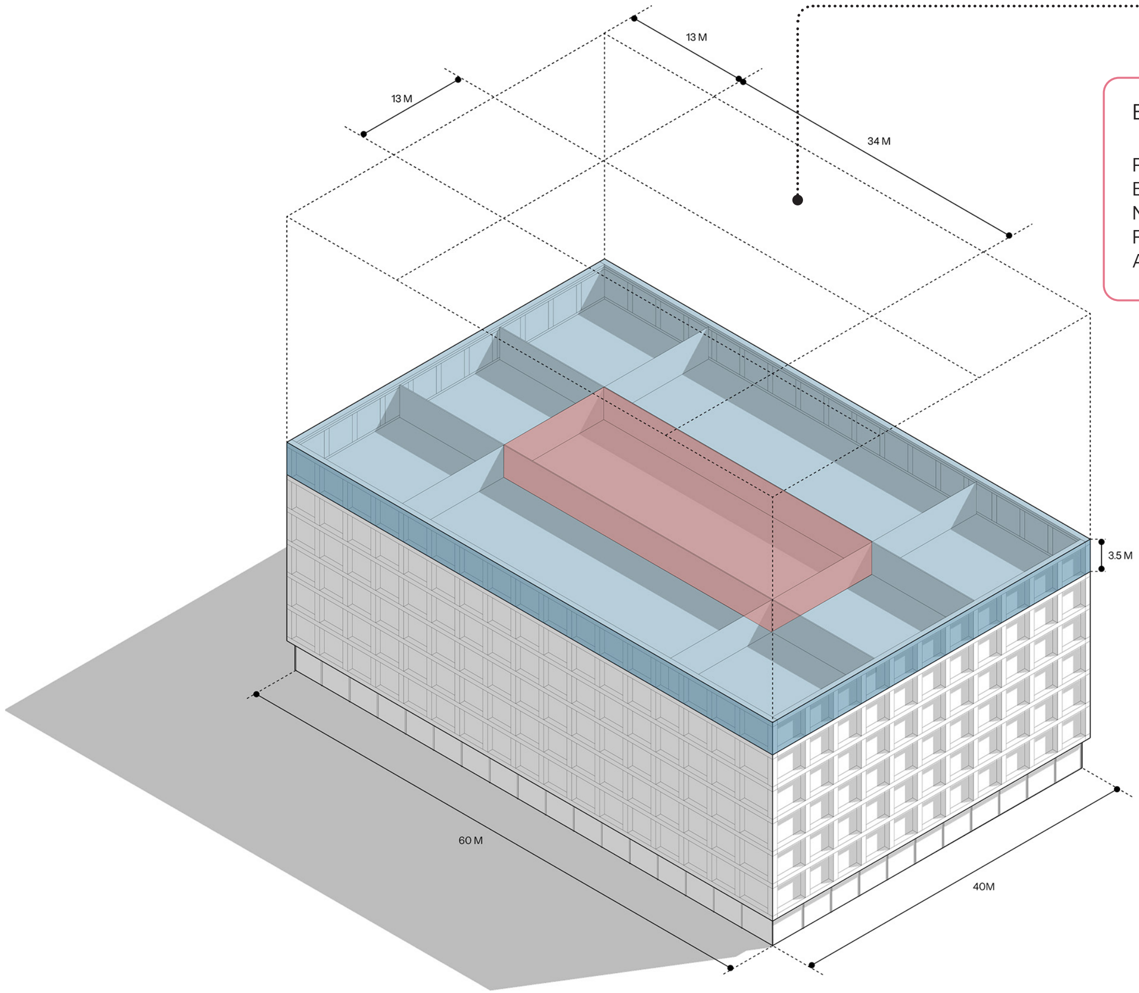
Office building

Exposed from all sides

75 % wall-window ratio

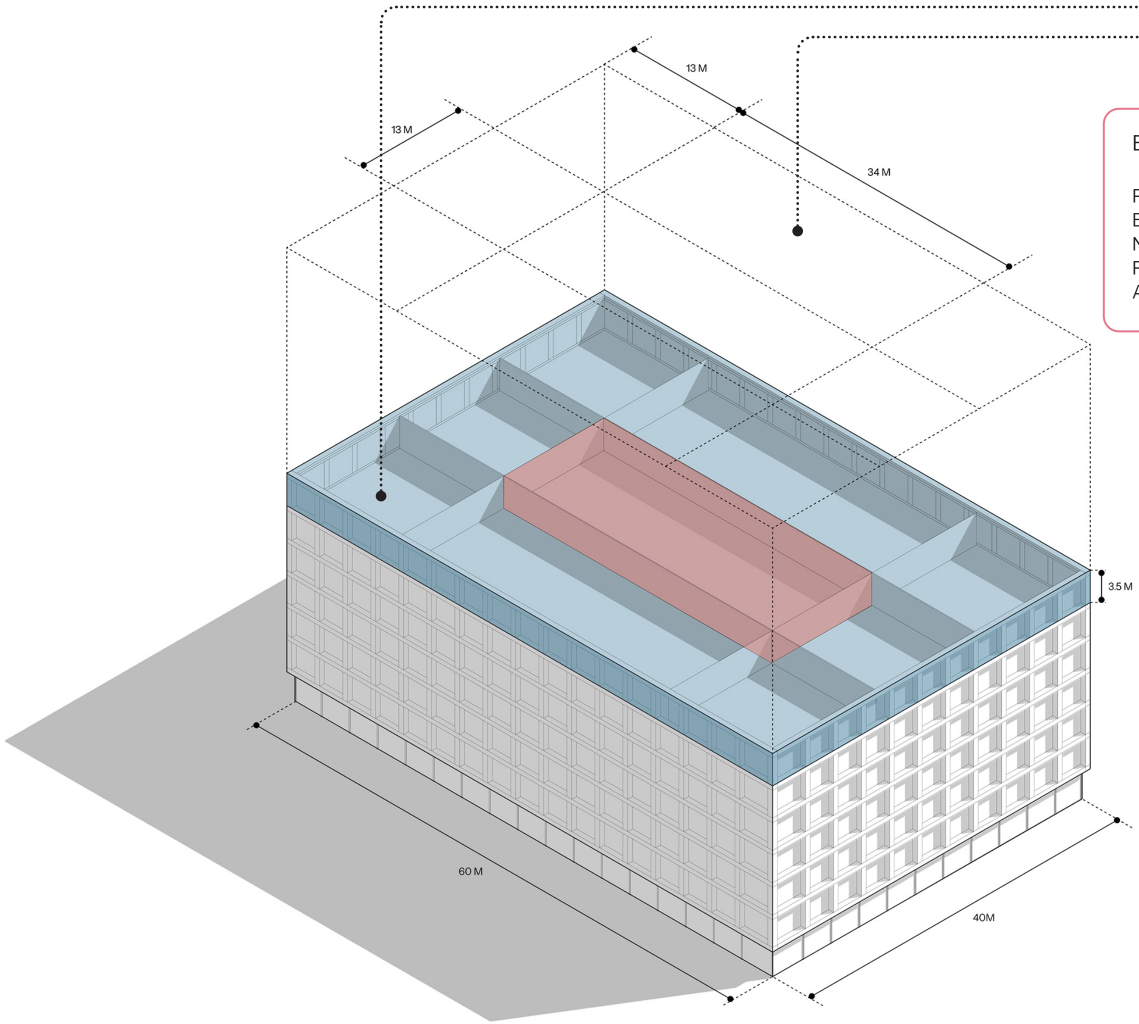
3.5 m F/F height


13 M
13 M
34 M
3.5 M
60 M
40M



Building parameters

Project location	**Chennai, India**
Building dimensions	**60 X 40 m**
No. of floors	**12**
F/F height	**3.5 m**
Analysis floor	**6th**



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Facade parameters

WWR	**75%**
Aperature width	**2.5 m**
Aperature height	**3.5 m**
Apertures	
U-value	**1.5 W/m2.K**
SHGC	**0.75**
Visible transmittance	**0.55**
Opaque materials	
Thickness	**0.1 m**
Conductivity	**0.84 W/m.K**
Density	**1800 kg/m3**
Spec. heat	**840 J/kg.K**
Thermal absorption	**0.9**
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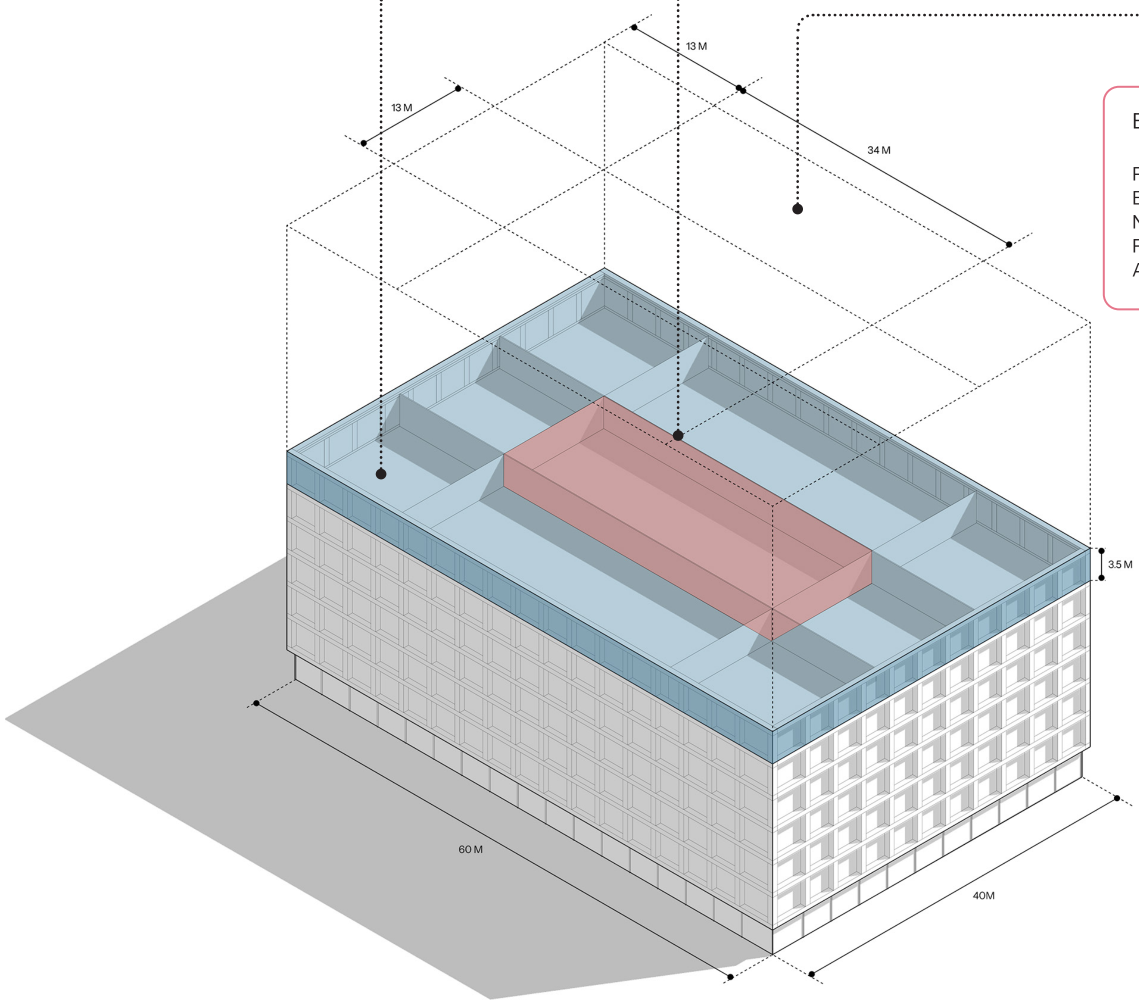

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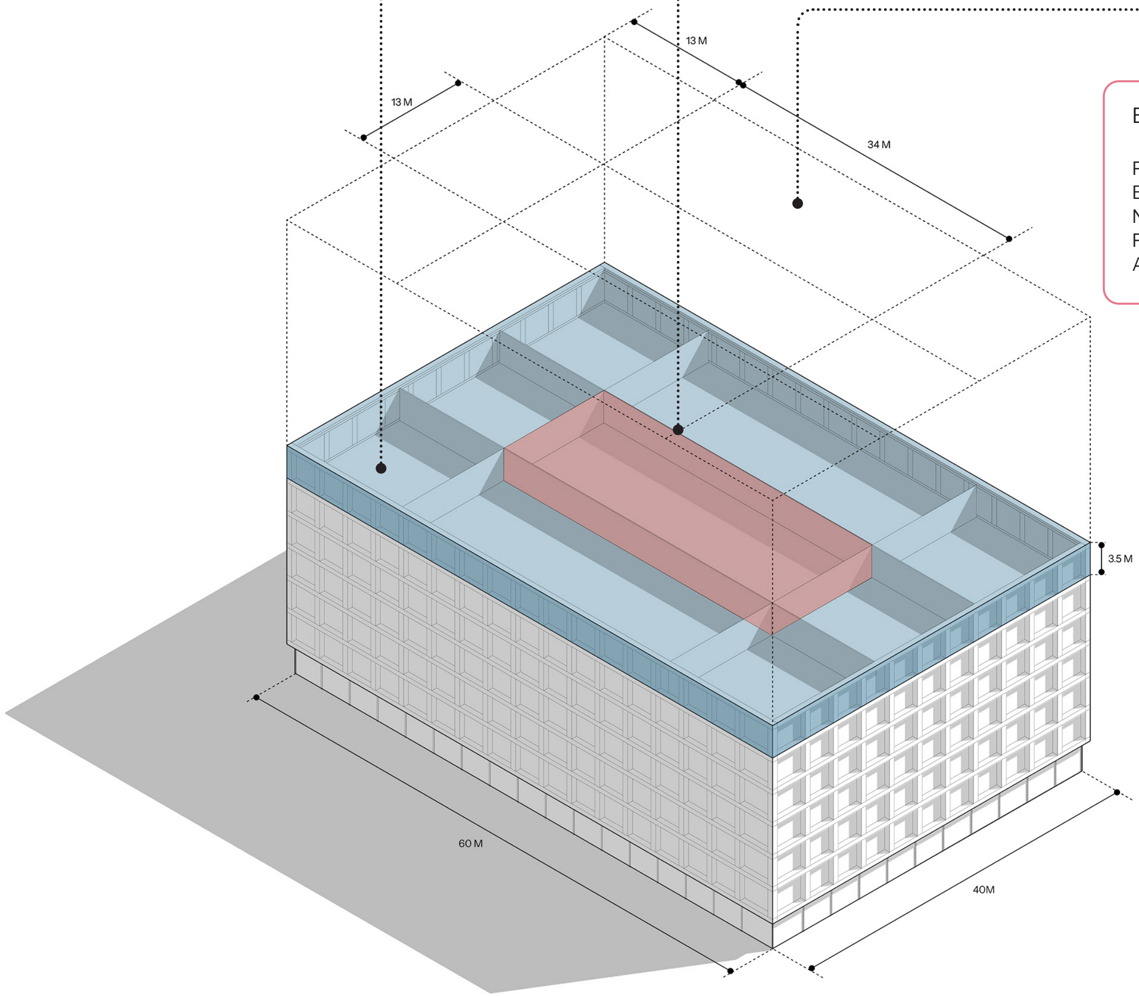
Building Operational param-eters

Occupancy	**Office schedule**
lighting schedule	**Office schedule**
Heating & Cooling set-	**24 °C & 19 °C**
points	**0.0007 m3/S**
ventilation	**0.00025 m3/S**
Infilltration	**0.07 ppl/m2**
Person density	**10 W/m2**
lighting load	**14 W/m2**
equipment load	**COP= 3 or 6**
Efficiency of heating and	
cooling system	**0.46 (as per**
Minimum clothing when	**Schiavon clothing**
Temp.>26 °C	**function)**
	0.1 m/s(by HVAC
Indoor air speed	**system guide)**



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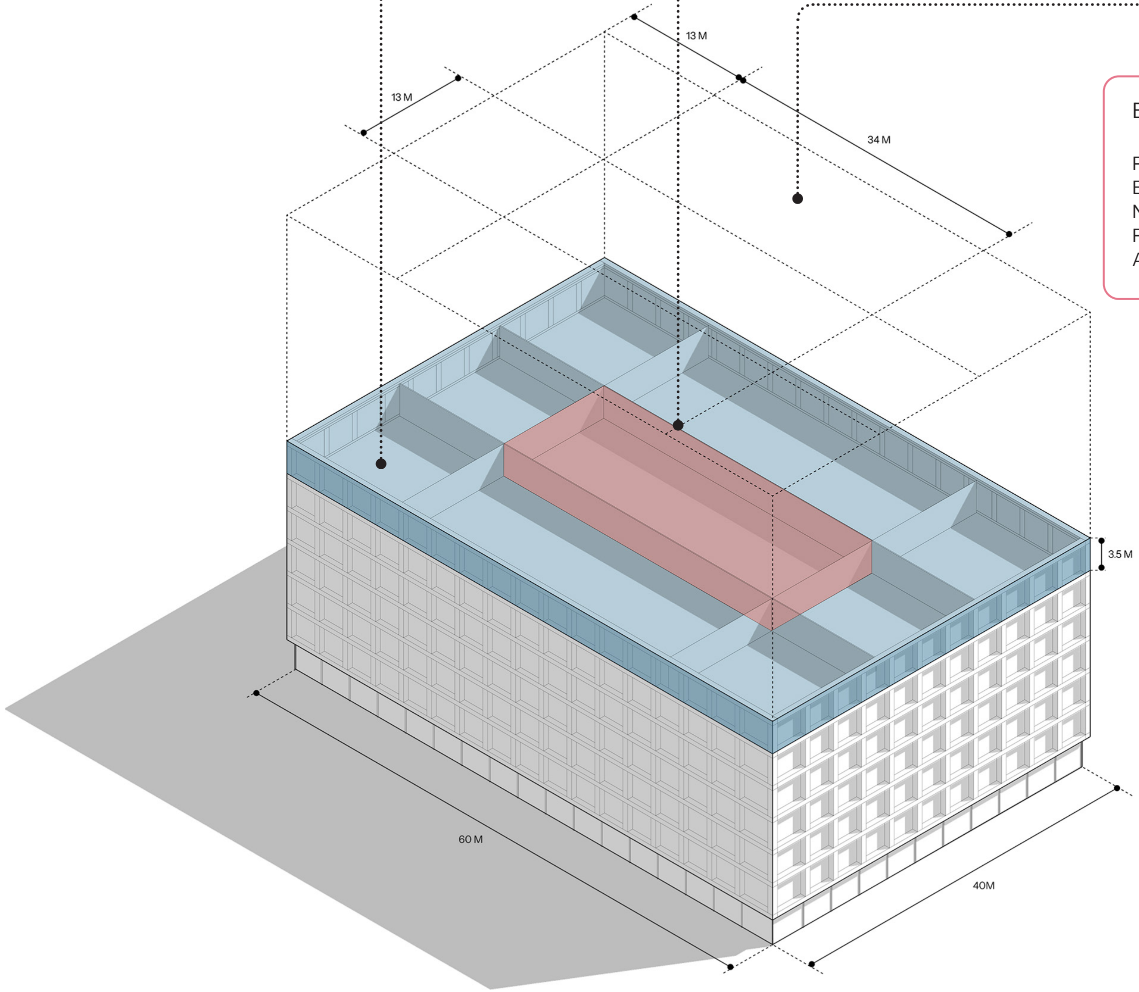
Run Simulation

Energy plus
Openstudio model

Run PMV comfort

Ladybug



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Indoor air speed	**system guide)**

Run Simulation

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Ladybug

Energy demand KWh/m2

High efficiency system	
Cooling energy intensity	**308.8 KWh/m2**
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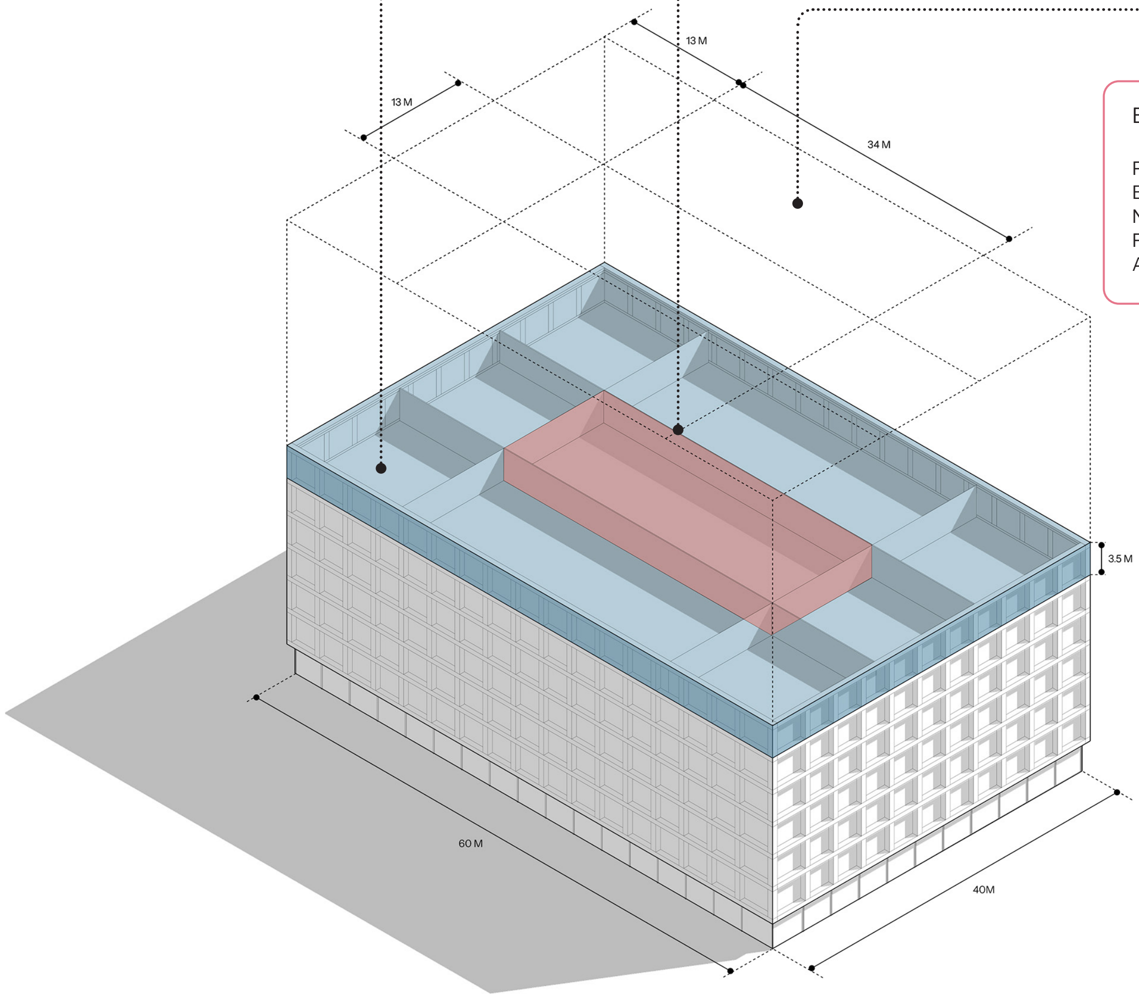

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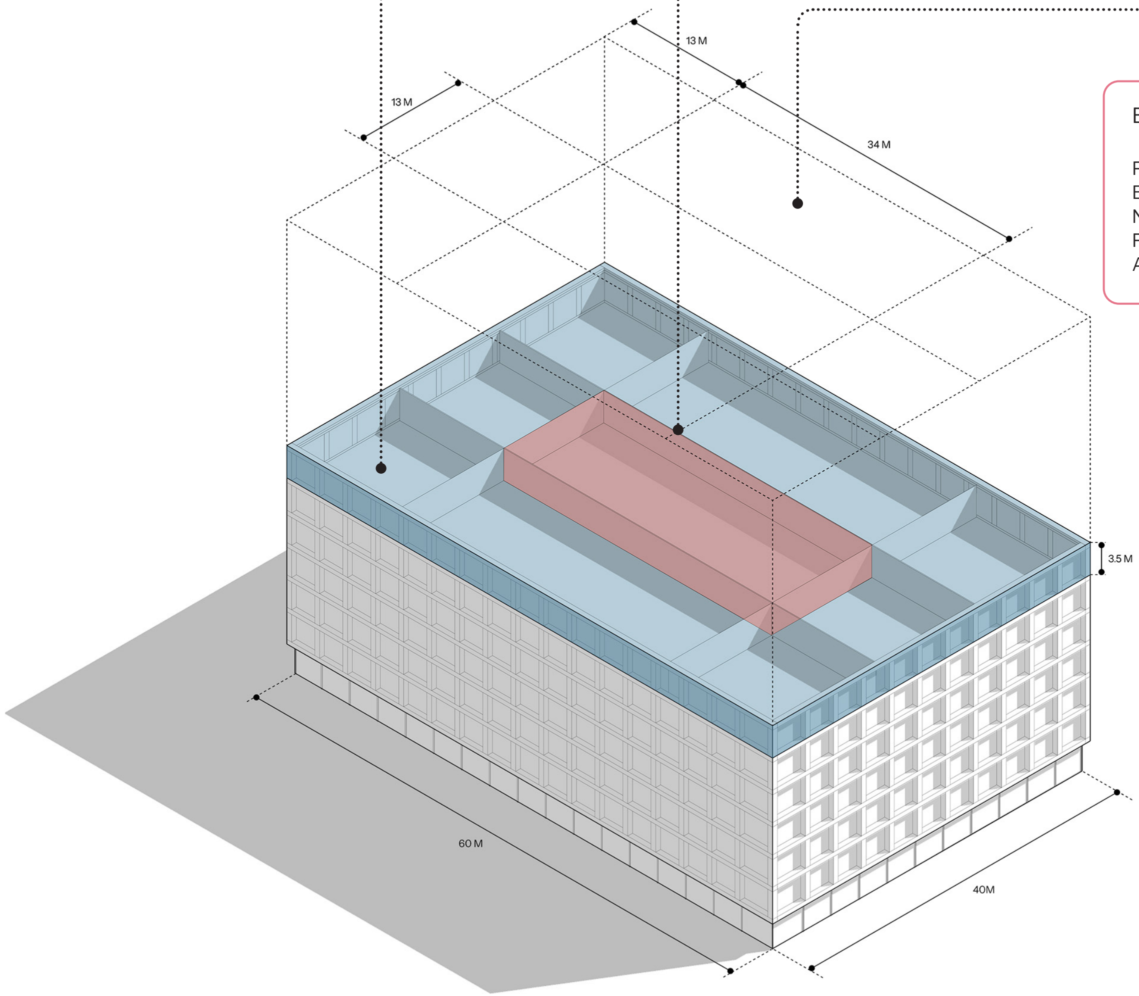
Standard effective temperture

Max. temperature **26.65 °C**



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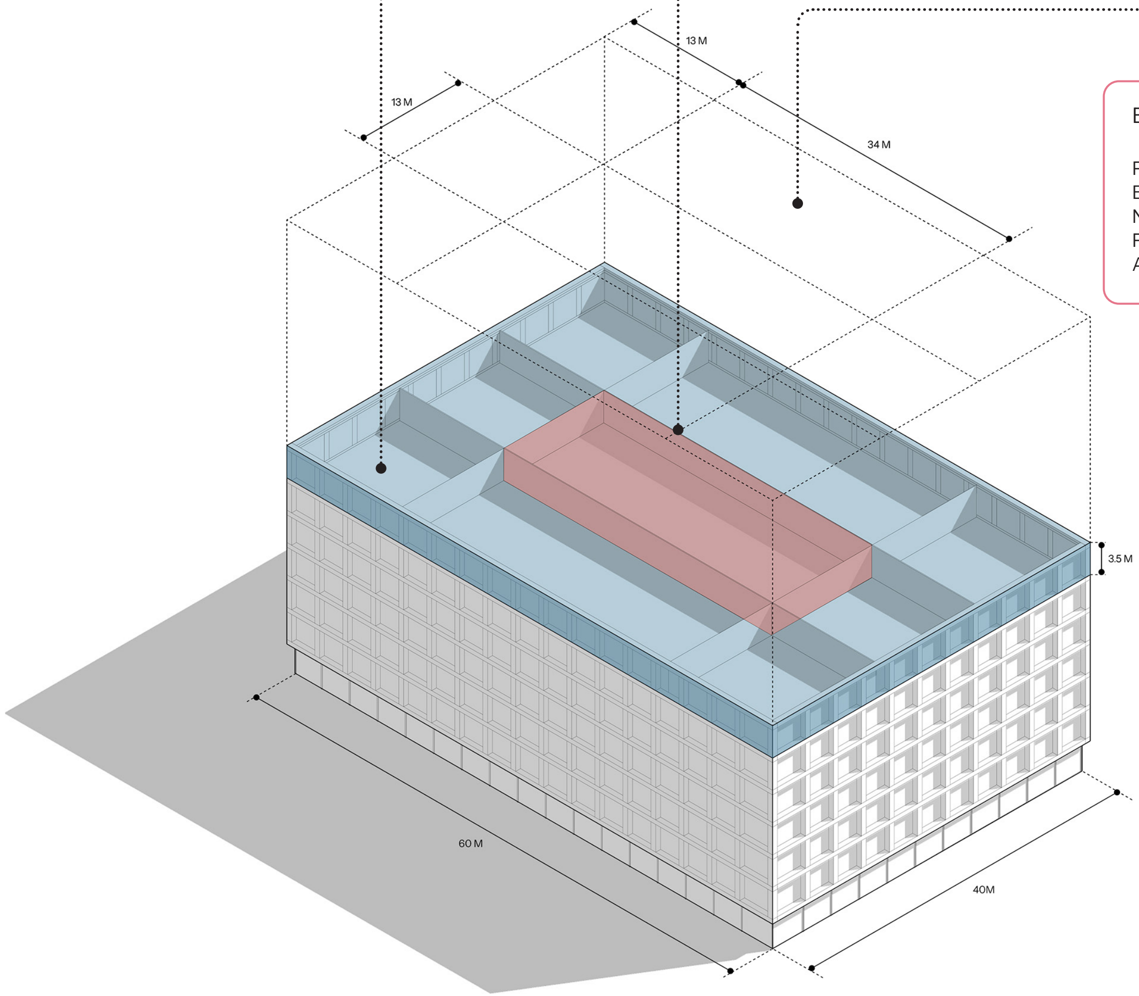
Standard effective temperture

Max. temperature **26.65 °C**

Indoor thermal comfort

PMV	**-0.71**
PPD	**16.2%**



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Cooling energy demand

Computational simulation framework – Floods

Input

Facade parameters

WWR
- Aperature width
- Aperature height

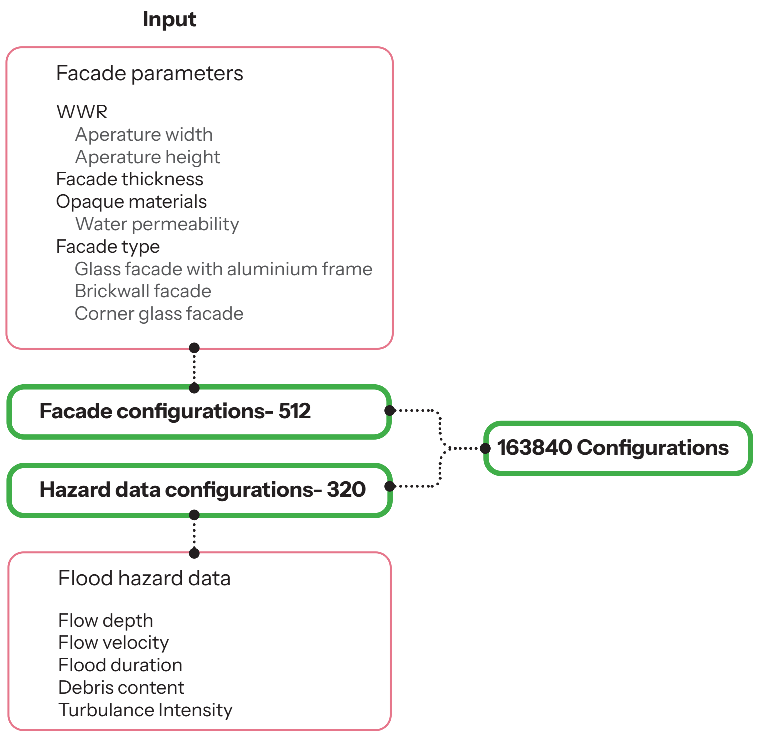
Facade thickness

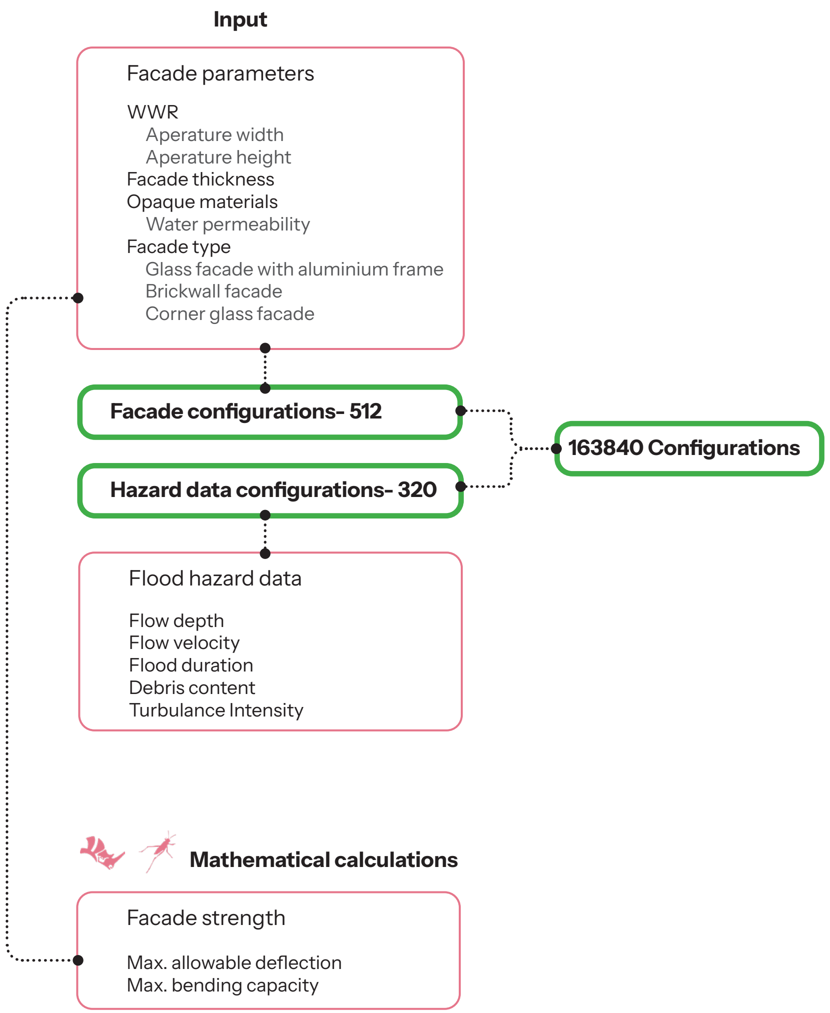
Opaque materials
- Water permeability

Facade type
- Glass facade with aluminium frame
- Brickwall facade
- Corner glass facade

Flood hazard data

Flow depth
Flow velocity
Flood duration
Debris content
Turbulance Intensity


Input
Facade parameters
WWR
Aperature width
Aperature height
Facade thickness
Opaque materials
Water permeability
Facade type
Glass facade with aluminium frame
Brickwall facade
Corner glass facade
Facade configurations- 512
Hazard data configurations- 320
163840 Configurations
Flood hazard data
Flow depth
Flow velocity
Flood duration
Debris content
Turbulance Intensity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Debris content
Turbulance Intensity
Mathematical calculations
Facade strength
Max. allowable deflection
Max. bending capacity

Input

Facade parameters

- WWR
  - Aperature width
  - Aperature height
- Facade thickness
- Opaque materials
  - Water permeability
- Facade type
  - Glass facade with aluminium frame
  - Brickwall facade
  - Corner glass facade

Ansys geometry

- Creating geometry
- Creating enclosure for flood

Facade configurations- 512

Hazard data configurations- 320

163840 Configurations

Flood hazard data

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- Flow velocity
- Flood duration
- Debris content
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Mathematical calculations

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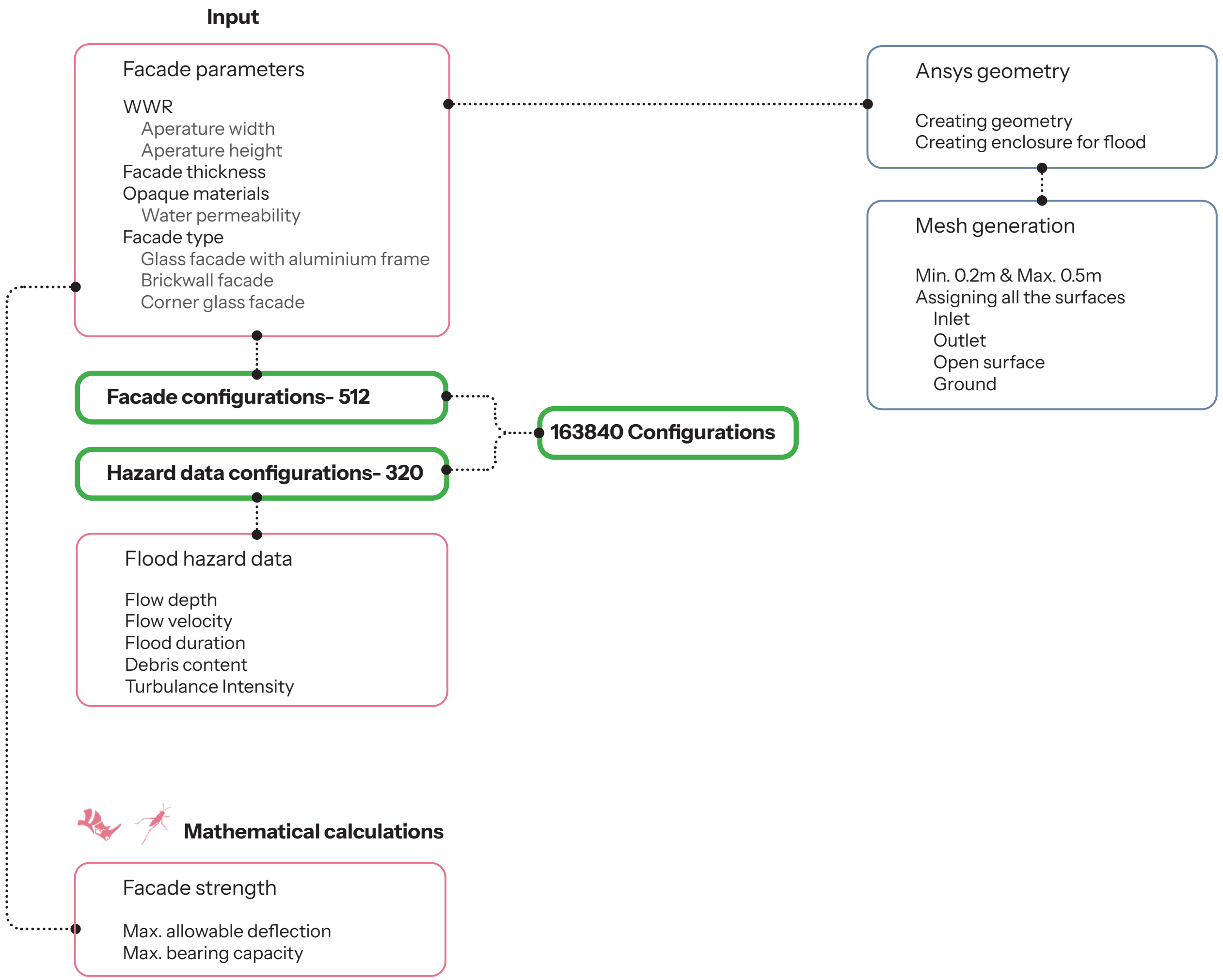
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Ansys geometry
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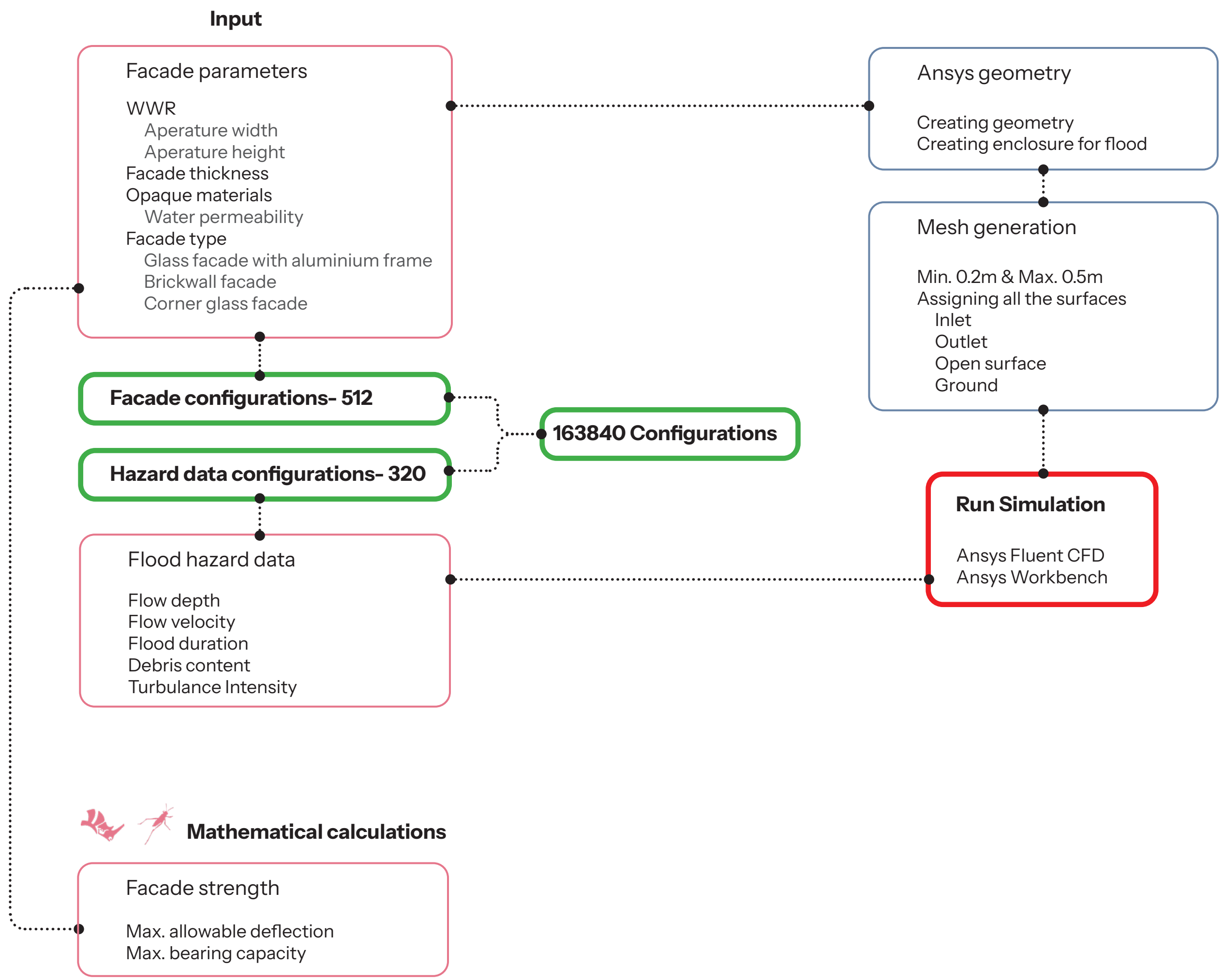
Creating enclosure for flood
Mesh generation
Min. 0.2m & Max. 0.5m
Assigning all the surfaces
Inlet
Outlet
Open surface
Ground



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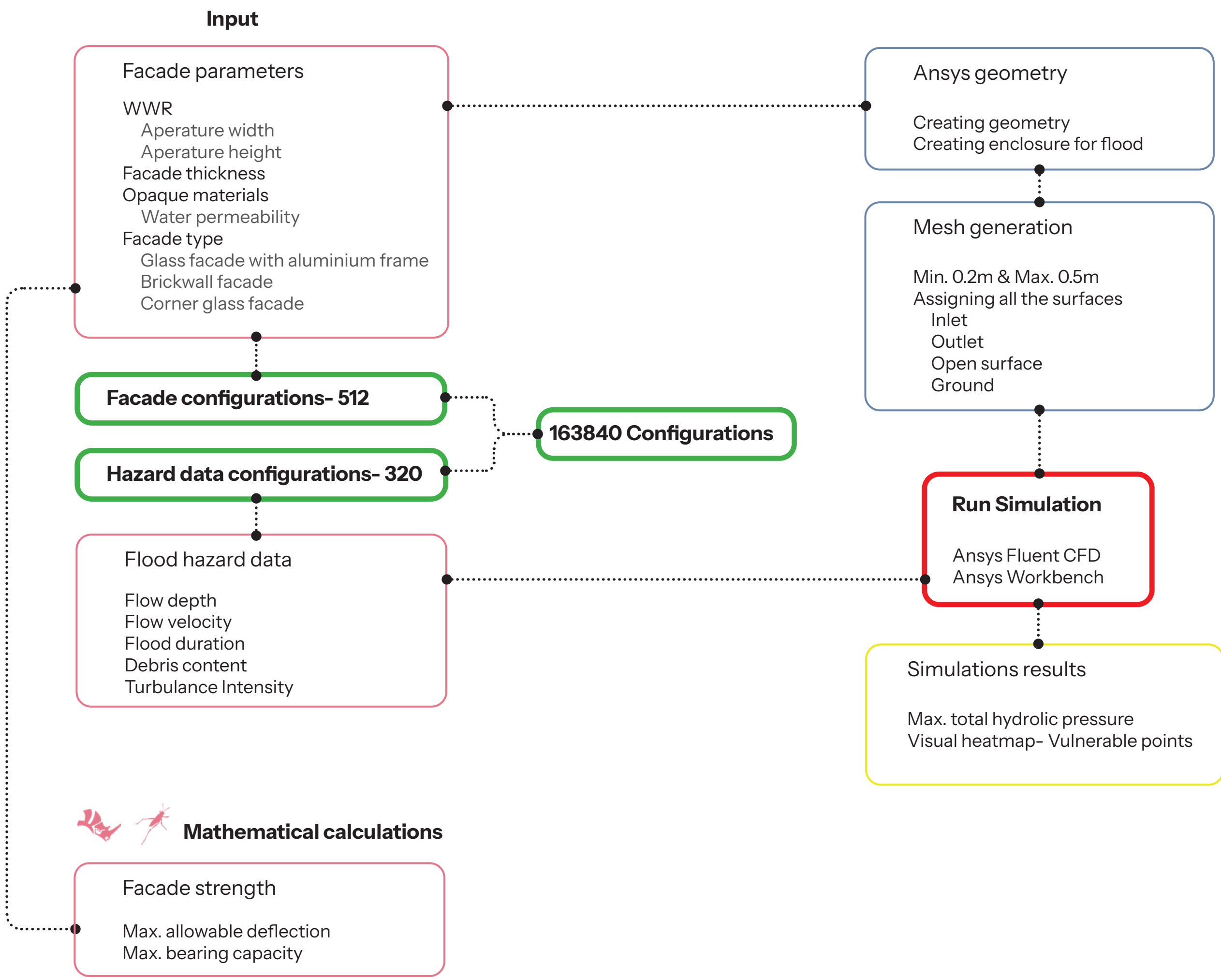
Run Simulation
Ansys Fluent CFD
Ansys Workbench



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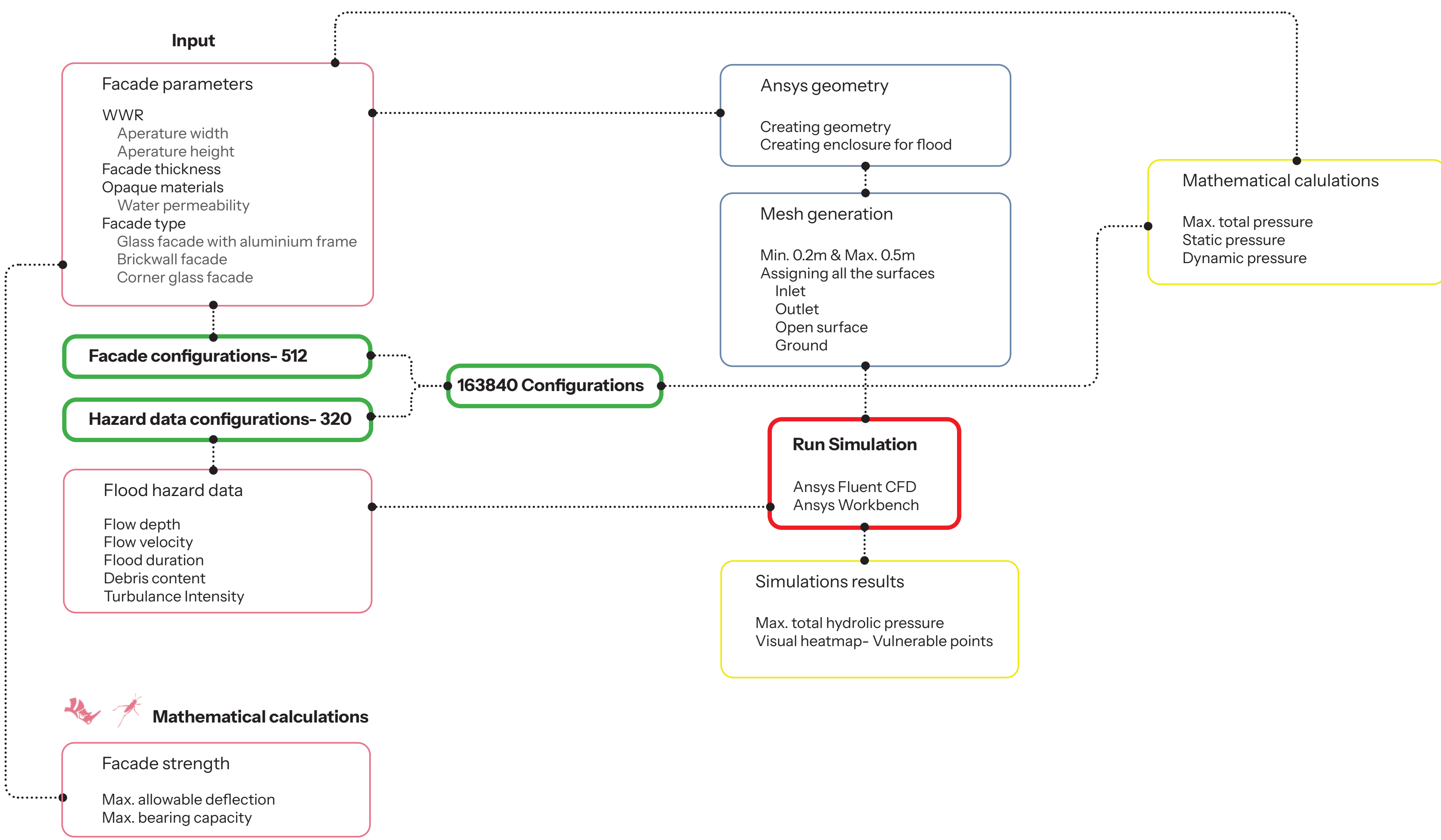
Outlet
Open surface
Ground
Run Simulation
Ansys Fluent CFD
Ansys Workbench
Simulations results
Max. total hydrolic pressure
Visual heatmap- Vulnerable points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Max. total pressure
Static pressure
Dynamic pressure
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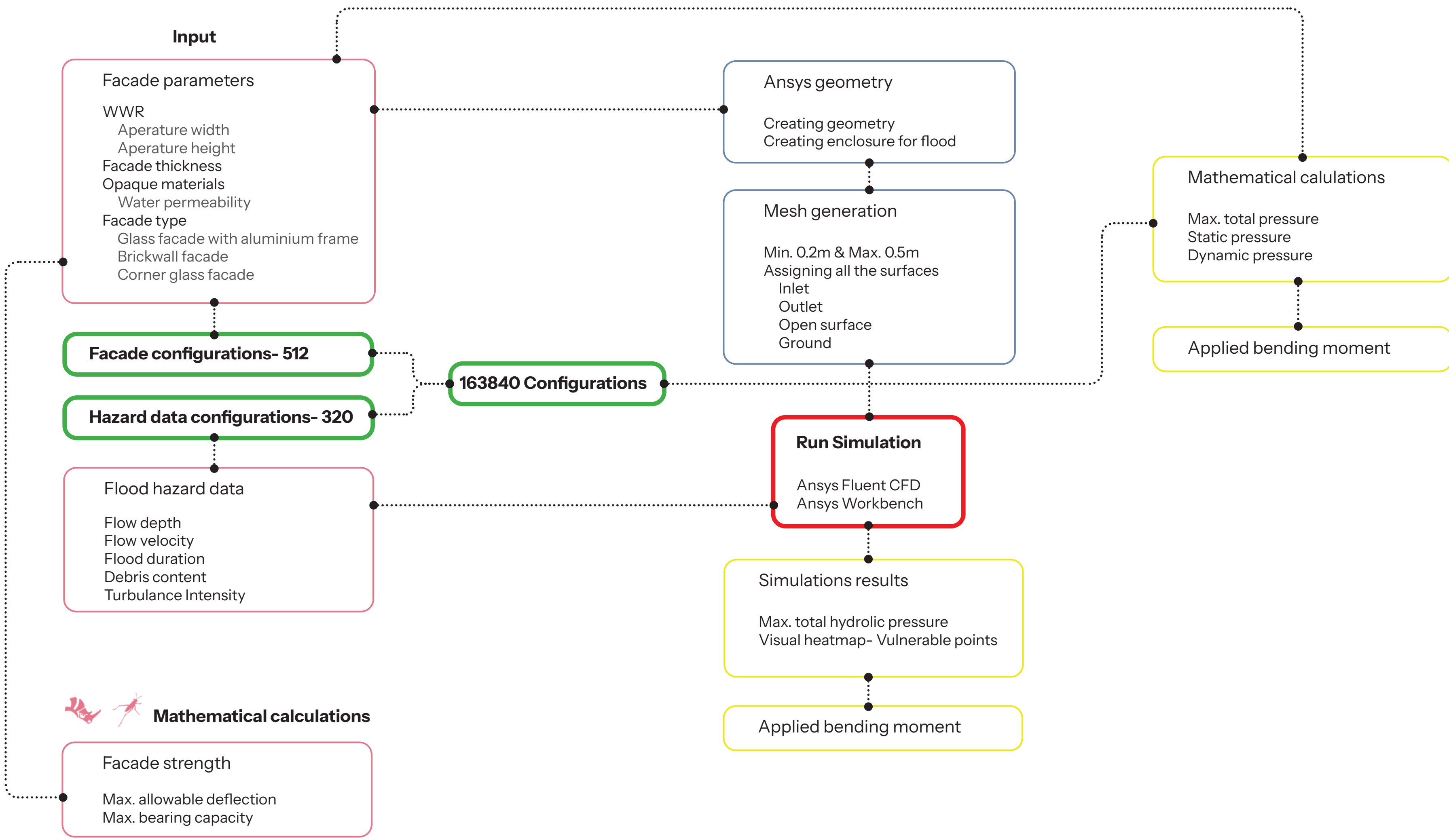

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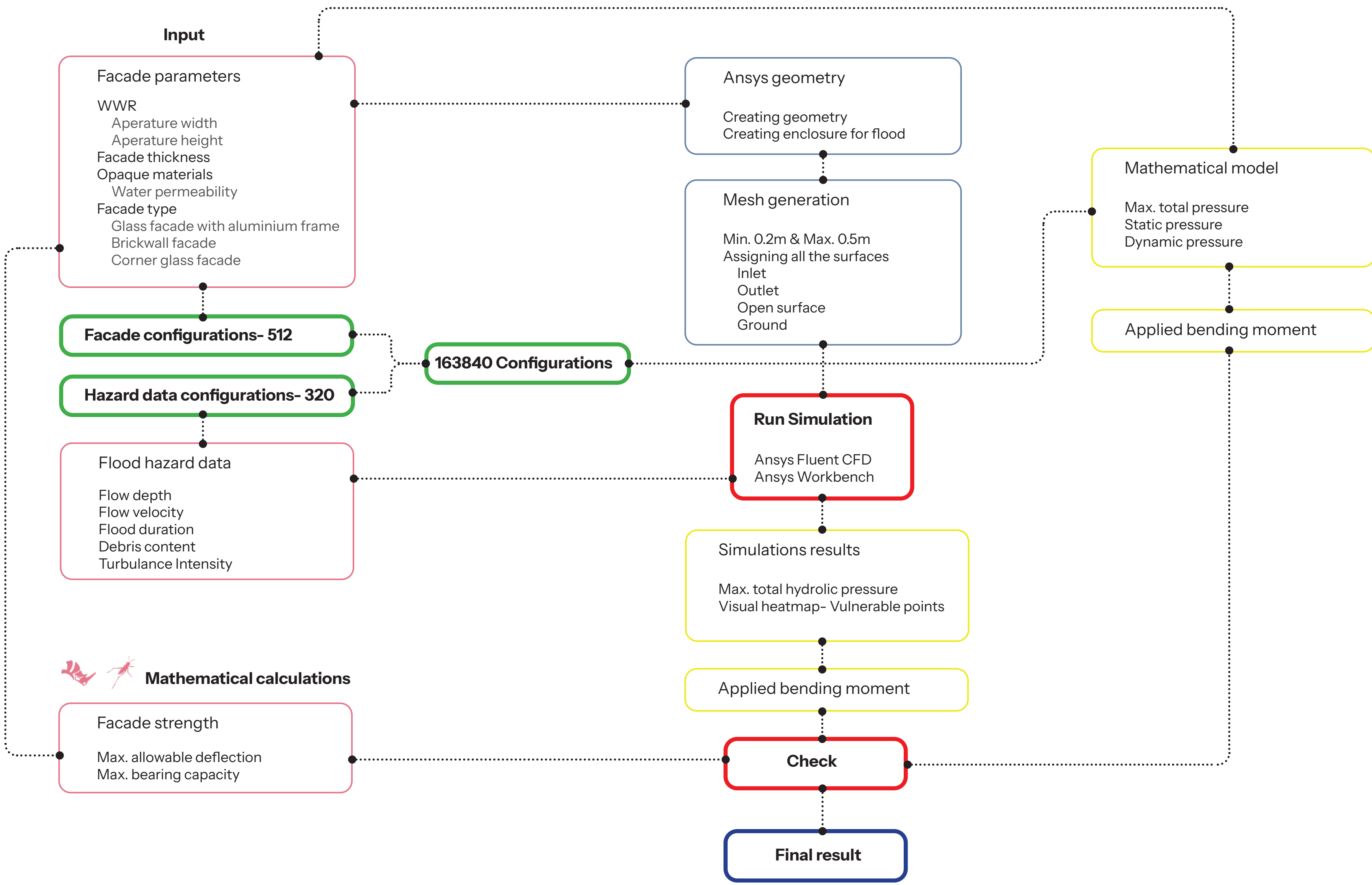
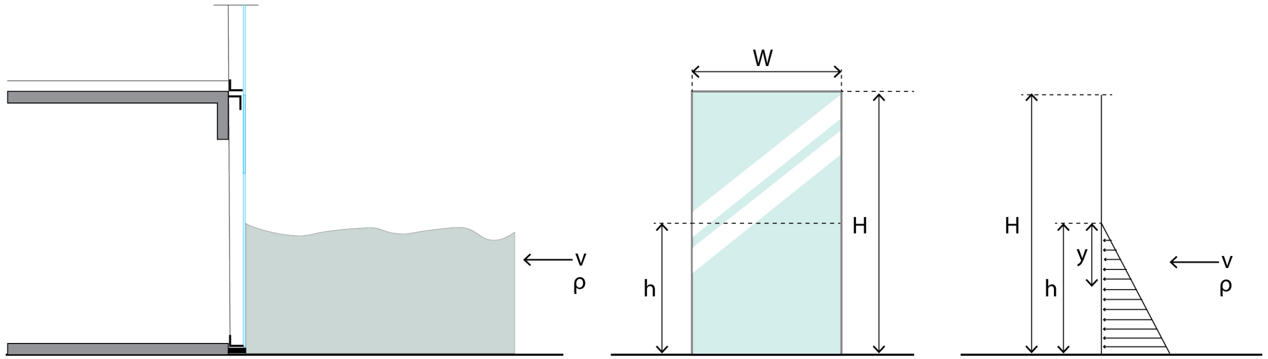
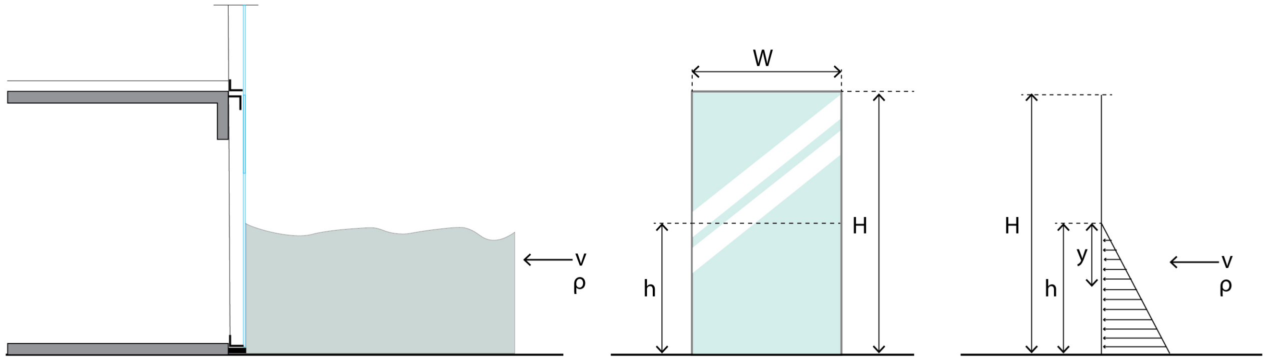
Visual heatmap- Vulnerable points
Applied bending moment
Mathematical calulations
Max. total pressure
Static pressure
Dynamic pressure
Applied bending moment


Input
Facade parameters
WWR
Aperature width
Aperature height
Facade thickness
Opaque materials
Water permeability
Facade type
Glass facade with aluminium frame
Brickwall facade
Corner glass facade
Facade configurations- 512
Hazard data configurations- 320
163840 Configurations
Flood hazard data
Flow depth
Flow velocity
Flood duration
Debris content
Turbulance Intensity
Mathematical calculations
Facade strength
Max. allowable deflection
Max. bearing capacity
Ansys geometry
Creating geometry
Creating enclosure for flood
Mesh generation
Min. 0.2m & Max. 0.5m
Assigning all the surfaces
Inlet
Outlet
Open surface
Ground
Run Simulation
Ansys Fluent CFD
Ansys Workbench
Simulations results
Max. total hydrolic pressure
Visual heatmap- Vulnerable points
Applied bending moment
Check
Final result
Mathematical model
Max. total pressure
Static pressure
Dynamic pressure
Applied bending moment

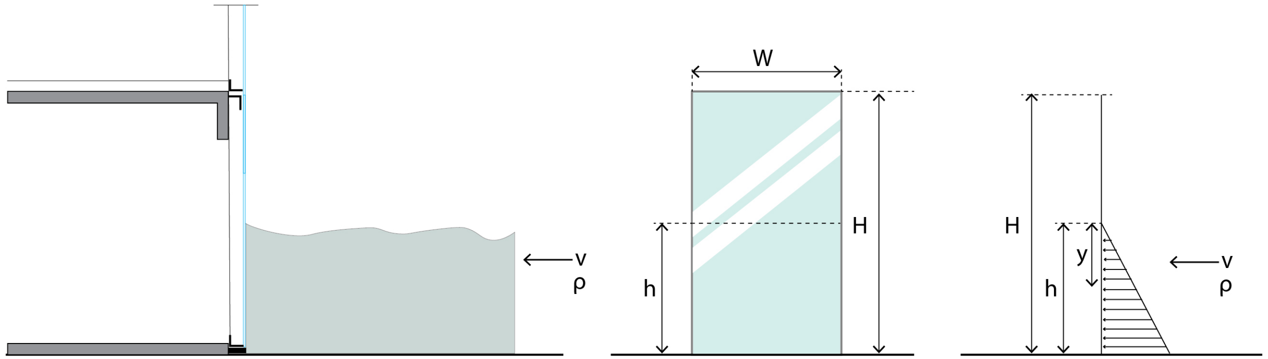
Mathematical model - Floods


v
ρ
W
H
h
H
y
h
v
ρ



To find the total force, integrate the static and dynmaic pressure from y = 0 (the base) to y = h (the top of the water level) and W is the span of the facade

$$F = \int_0^h \left(\rho g y + \frac{1}{2} \rho v^2 \right) W \, dy$$



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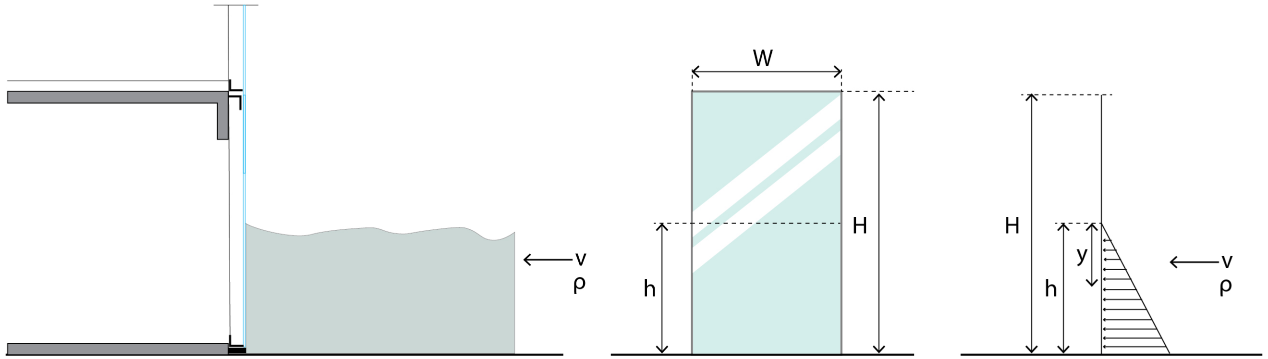
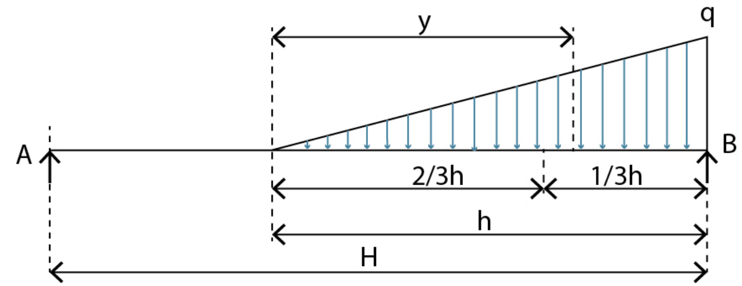
So, the total force including both the hydrostatic and dynamic pressures is

$$F_{\text{total}} = \frac{1}{2} \rho W h \left(g h + v^2 \right)$$





Max. applied bending moment

$$M = \frac{qy^3}{6h} - \frac{qh^3}{6H}(y + H - h)$$

To find the total force, integrate the static and dynmaic pressure from y = 0 (the base) to y = h (the top of the water level) and W is the span of the facade

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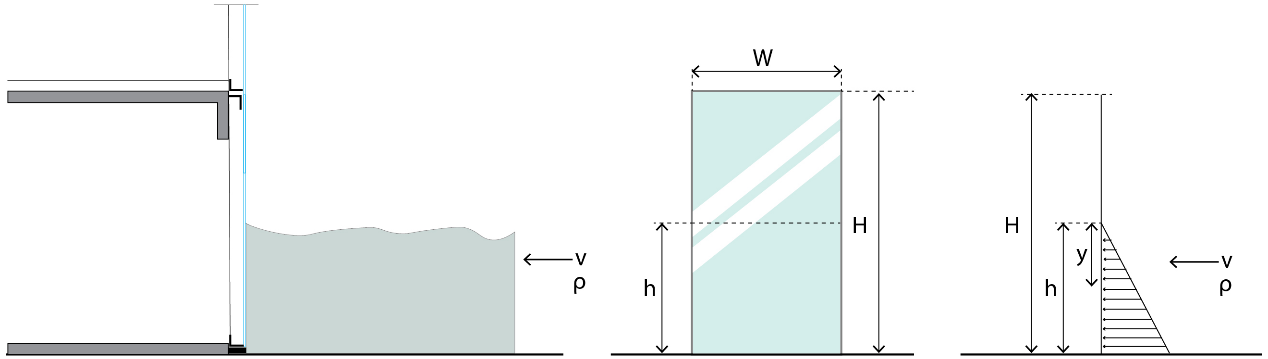

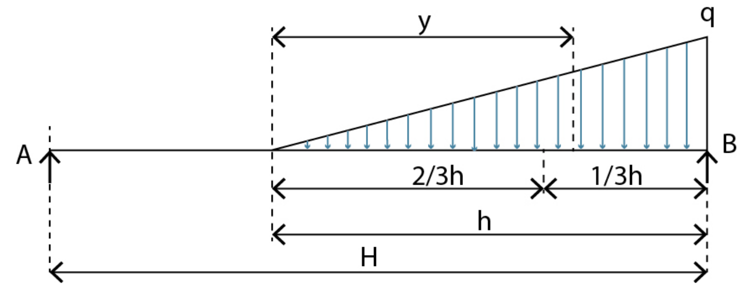

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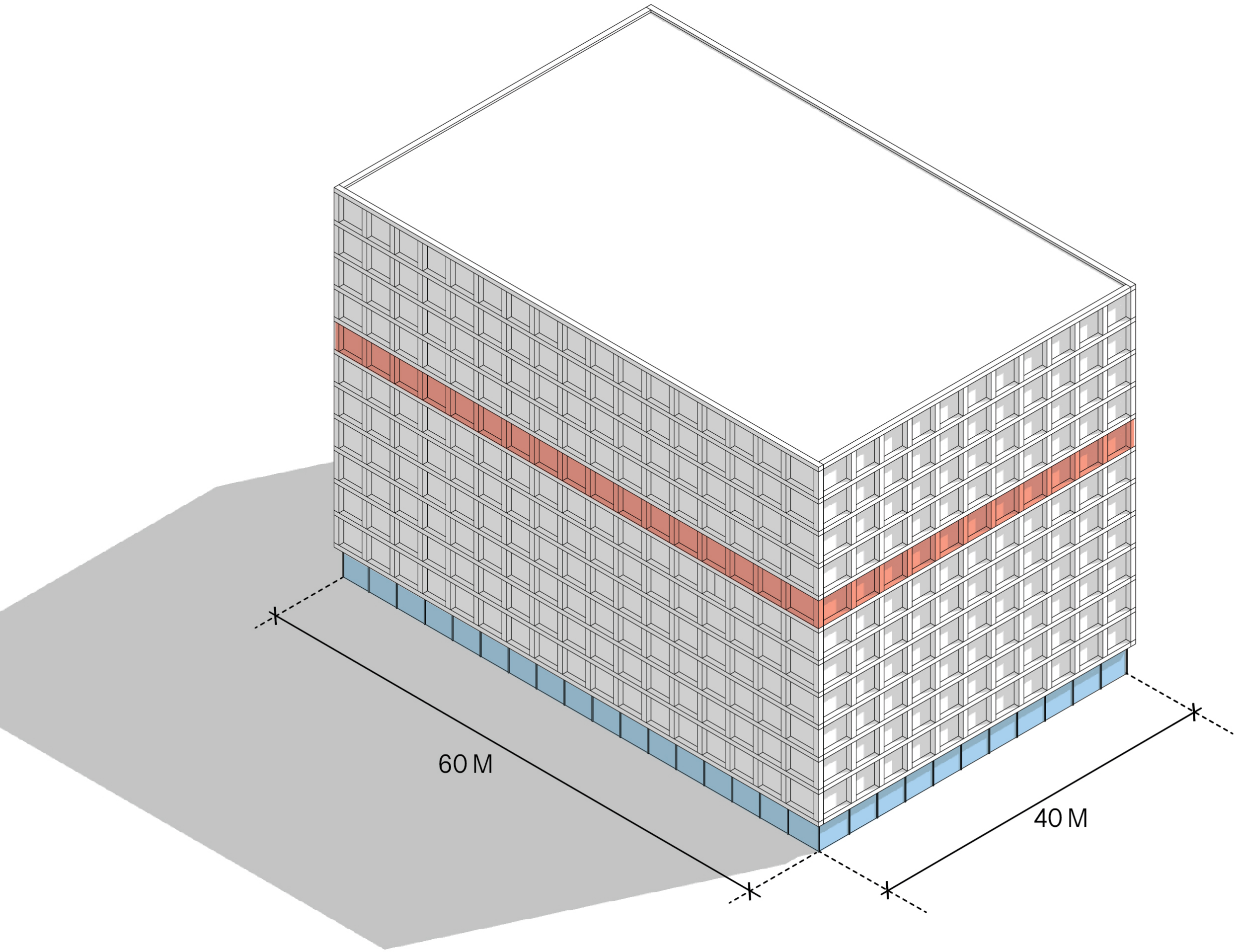
Max. applied bending moment

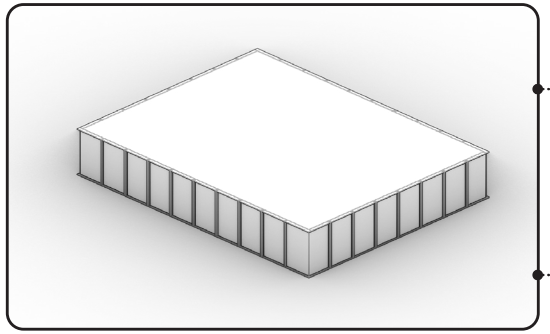
$$M = \frac{q y^3}{6h} - \frac{q h^3}{6H} (y + H - h)$$

Allowable bending moment of the facade

$$\sigma = \frac{M_{\text{allowable}} \times y}{I}$$

Casestudy: Chennai, India
Office building


60 M
40 M

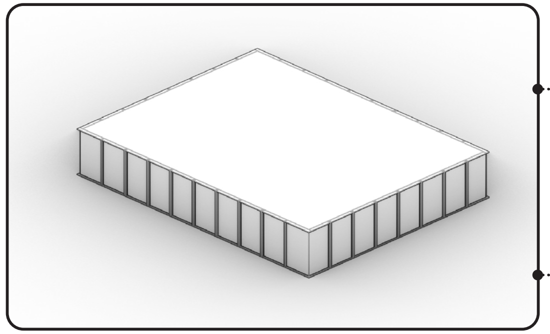


Facade parameters

Project location	**Chennai, India**
Facade type	**Glass facade**
Span b/w panels	**1.5m**
facade height	**3.5 m**

Flood intensity

Flood velocity	**1.5 m/s**
Flood height	**2m**
Turbulent intensity	**5%**
Flood water density	**1000 kg/m3**



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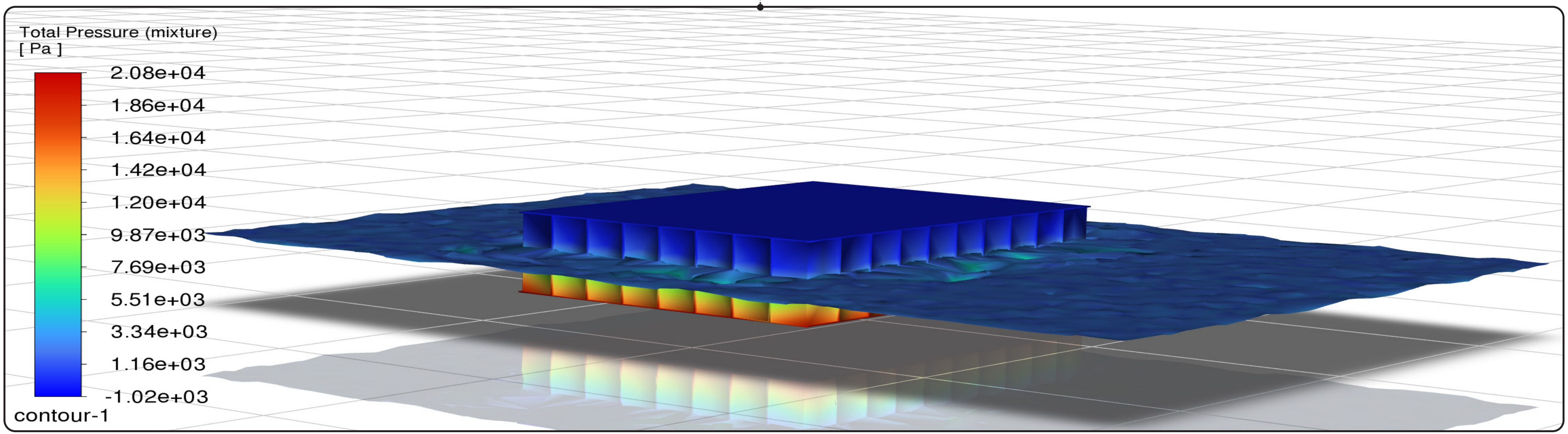
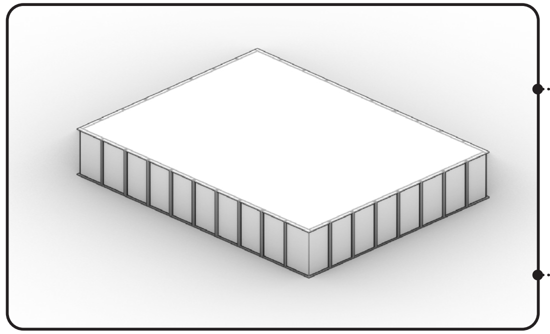
Run Simulation

Ansys fluent
Ansys Workbench





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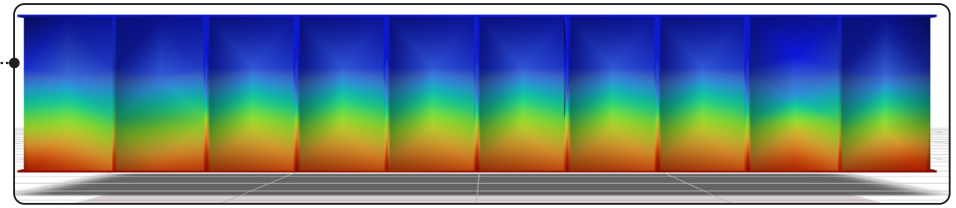

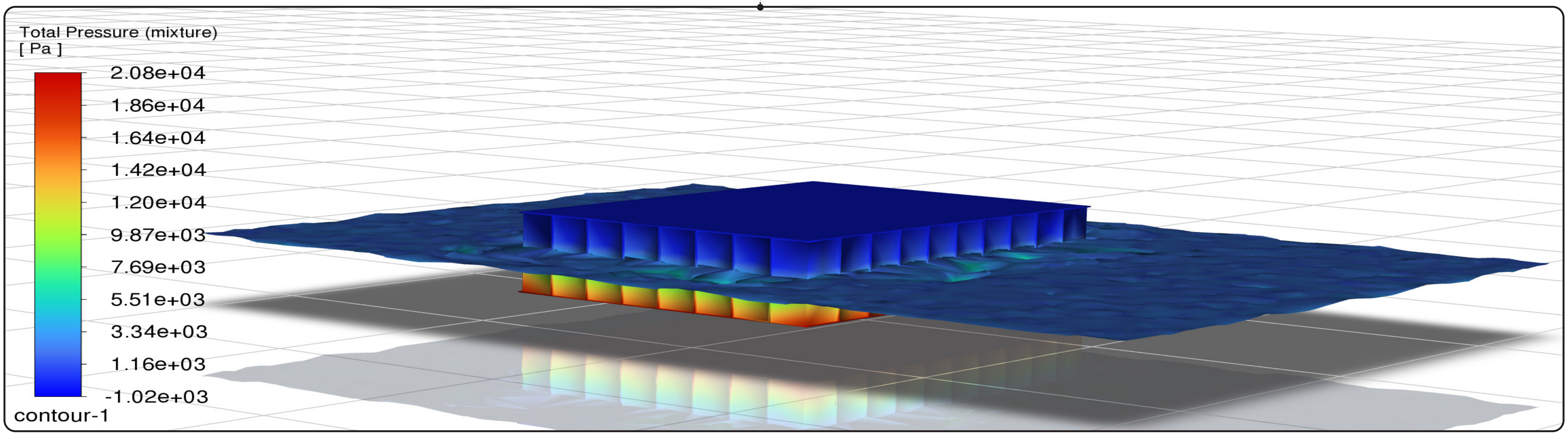

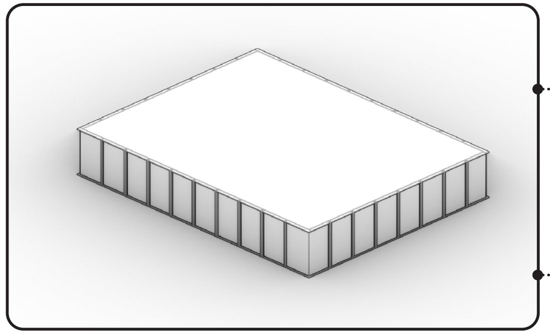

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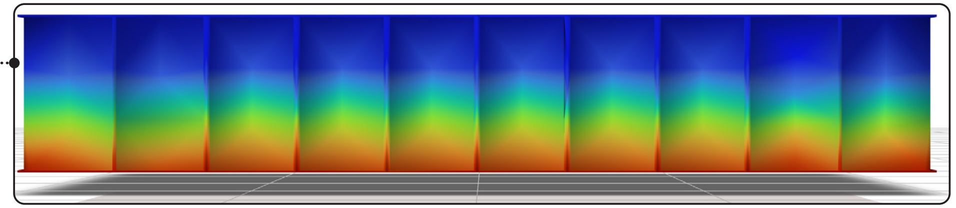
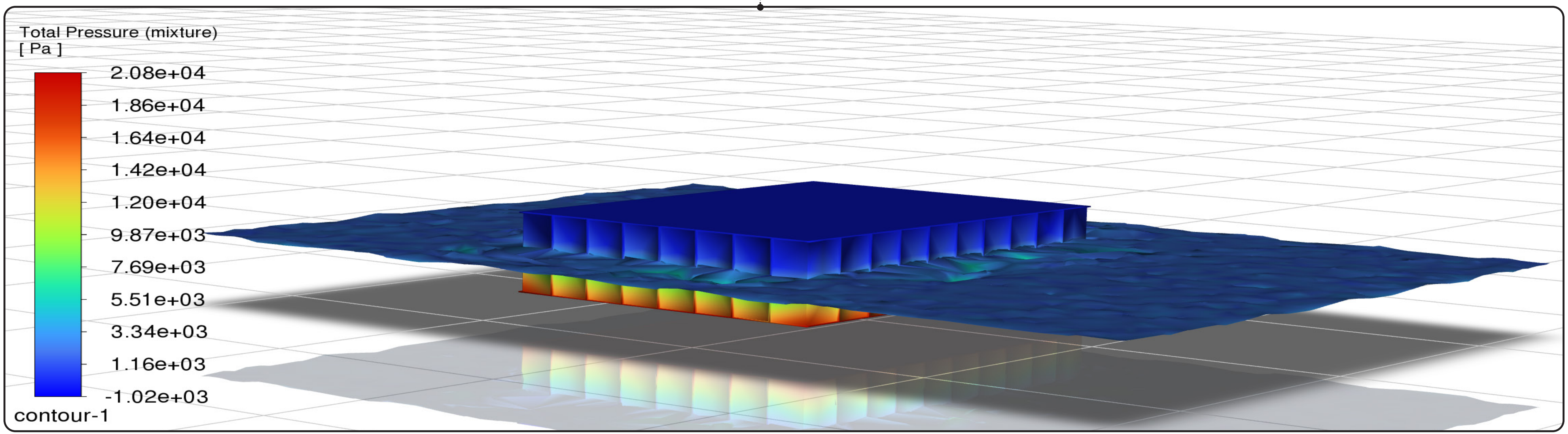
Computational simulation

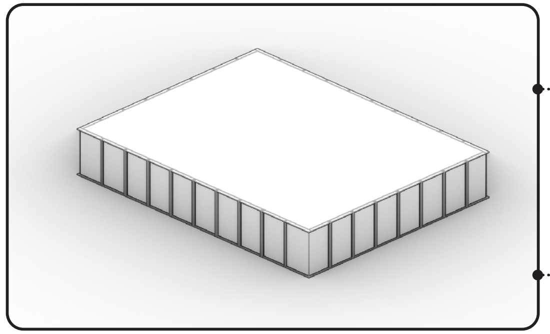
Total maximum pressure on facade = **20.8 KN/m2**

Run Simulation

Ansys fluent
Ansys Workbench







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Computational simulation

Total maximum pressure on facade = **20.8 KN/m2**

Mathematical calculation

Static pressure p = ρ g h
Dynamic pressure p = ρv2/2

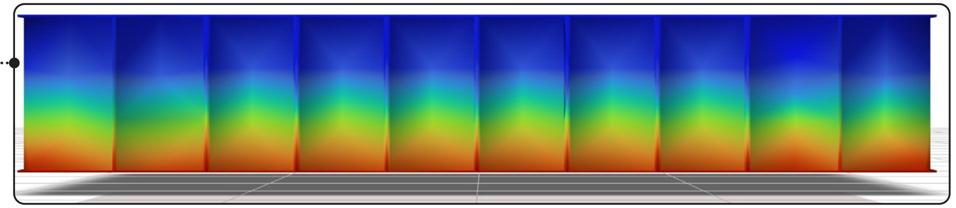
Stagnent pressure = Static pressure + Dynamic pressure

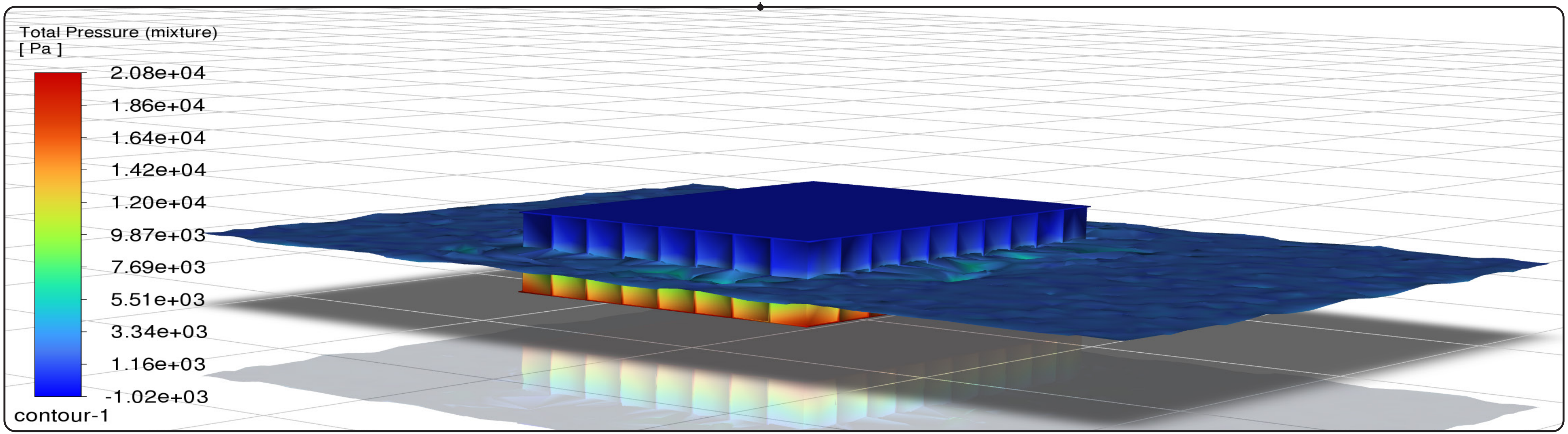
Static pressure = **19.6 KN/m2**
Dynamic pressure = **1.125 KN/m2**

Total pressure **= 20.725 KN/m2**

Run Simulation

Ansys fluent
Ansys Workbench





Inputs

Heatwaves

Facade parameters

- WWR
  - Aperature width
  - Aperature height
- Apertures
  - U-value
  - SHGC
  - Visible transmittance
- Opaque materials
  - Thickness
  - Conductivity
  - Density
  - Spec. heat
  - Thermal absorption
  - Solar absorption
  - Visible absorption
  - Surface reflectance

Floods

Facade parameters

- WWR
  - Aperature width
  - Aperature height
- Facade thickness
- Opaque materials
  - Water permeability
- Facade type
  - Glass facade with aluminium frame
  - Brickwall facade
  - Corner glass facade

Flood hazard data

- Flow depth
- Flow velocity
- Flood duration
- Debris content
- Turbulence Intensity

Inputs

Heatwaves

Facade parameters

- WWR
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Floods

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- Flow depth
- Flow velocity
- Flood duration
- Debris content
- Turbulance Intensity

Outputs

Heatwaves

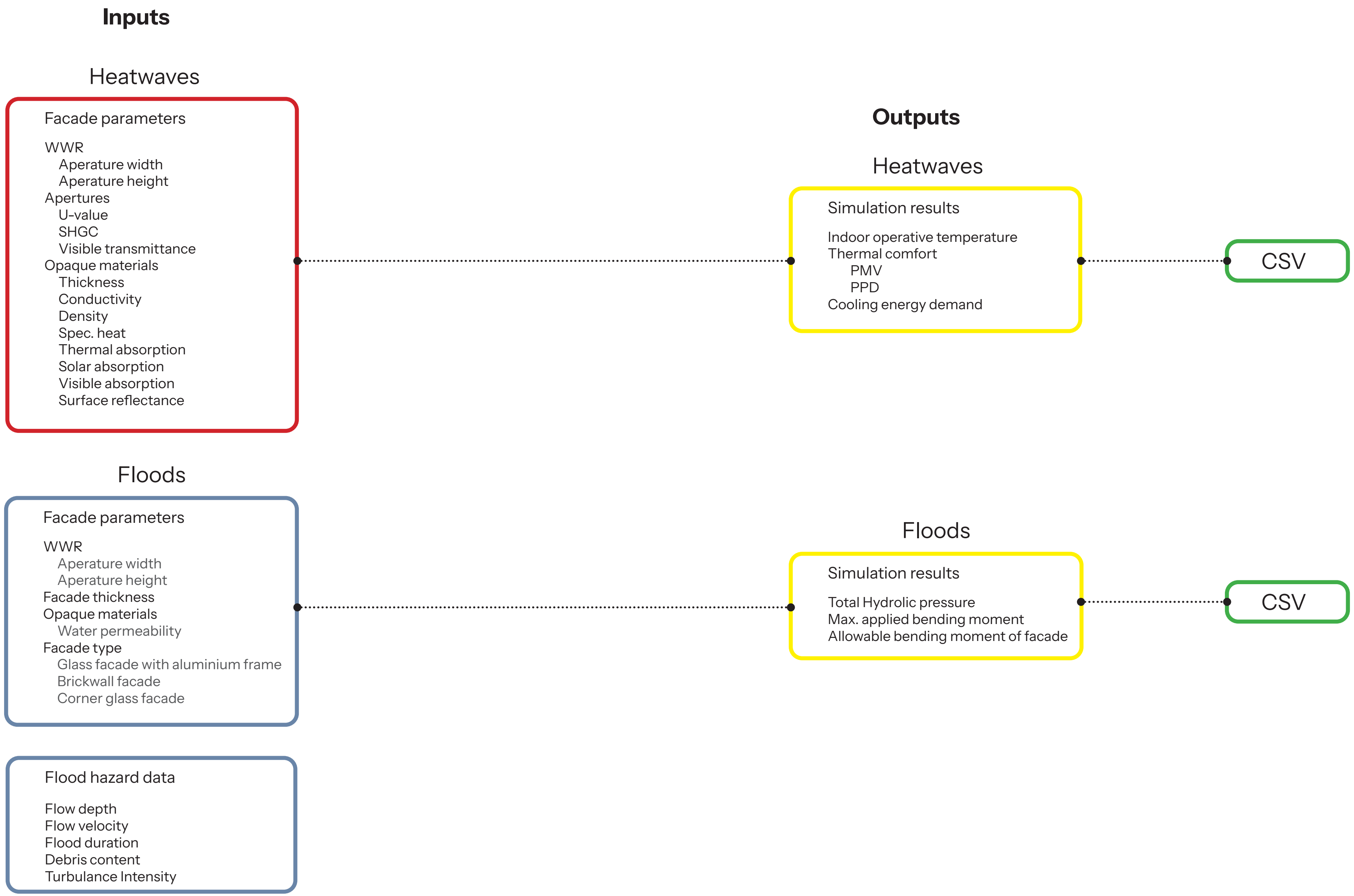
Simulation results

- Indoor operative temperature
- Thermal comfort
  - PMV
  - PPD
- Cooling energy demand

Floods

Simulation results

- Total Hydrolic pressure
- Max. applied bending moment
- Allowable bending moment of facade


Inputs
Heatwaves
Facade parameters
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Outputs
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Simulation results
Indoor operative temperature
Thermal comfort
PMV
PPD
Cooling energy demand
CSV
Floods
Simulation results
Total Hydrolic pressure
Max. applied bending moment
Allowable bending moment of facade
CSV

Machine learning regression models

To create a function between input and output variables for sensitivity analysis

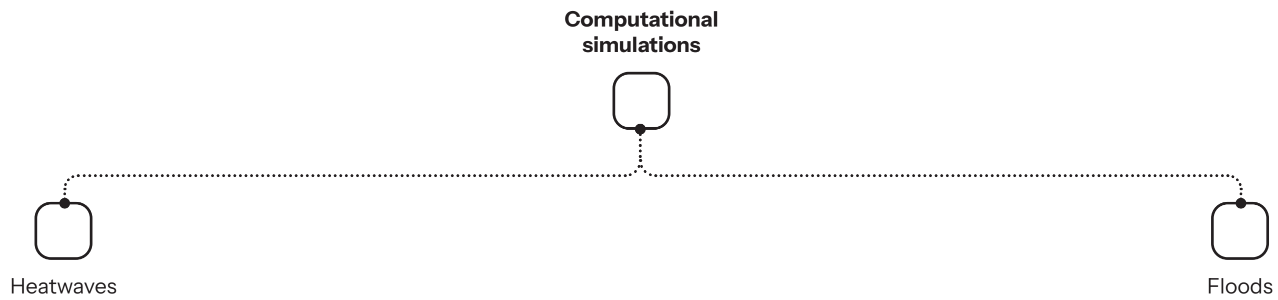
To create a function between input and output variables for sensitivity analysis

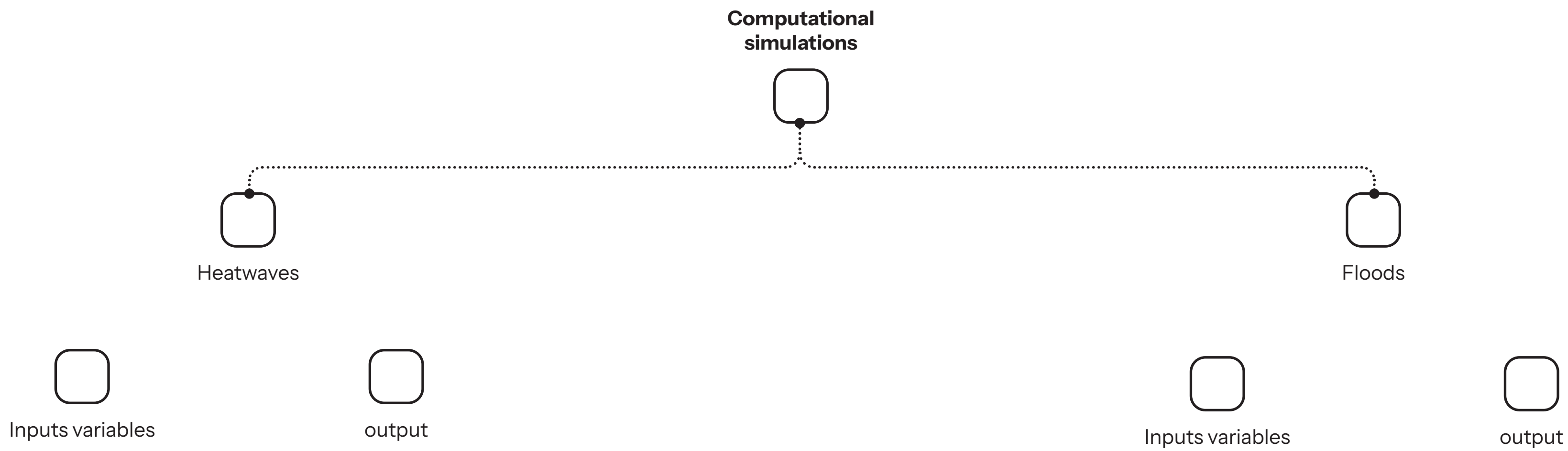
Reduce the time for long-running dynamic simulations

To create a function between input and output variables for sensitivity analysis

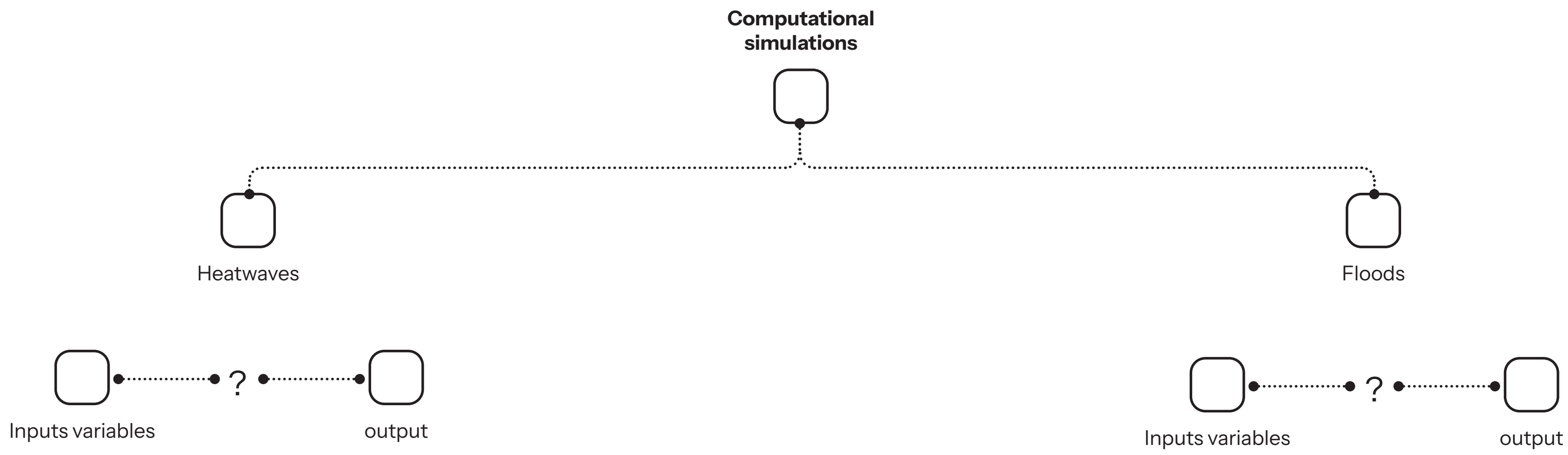
Reduce the time for long-running dynamic simulations

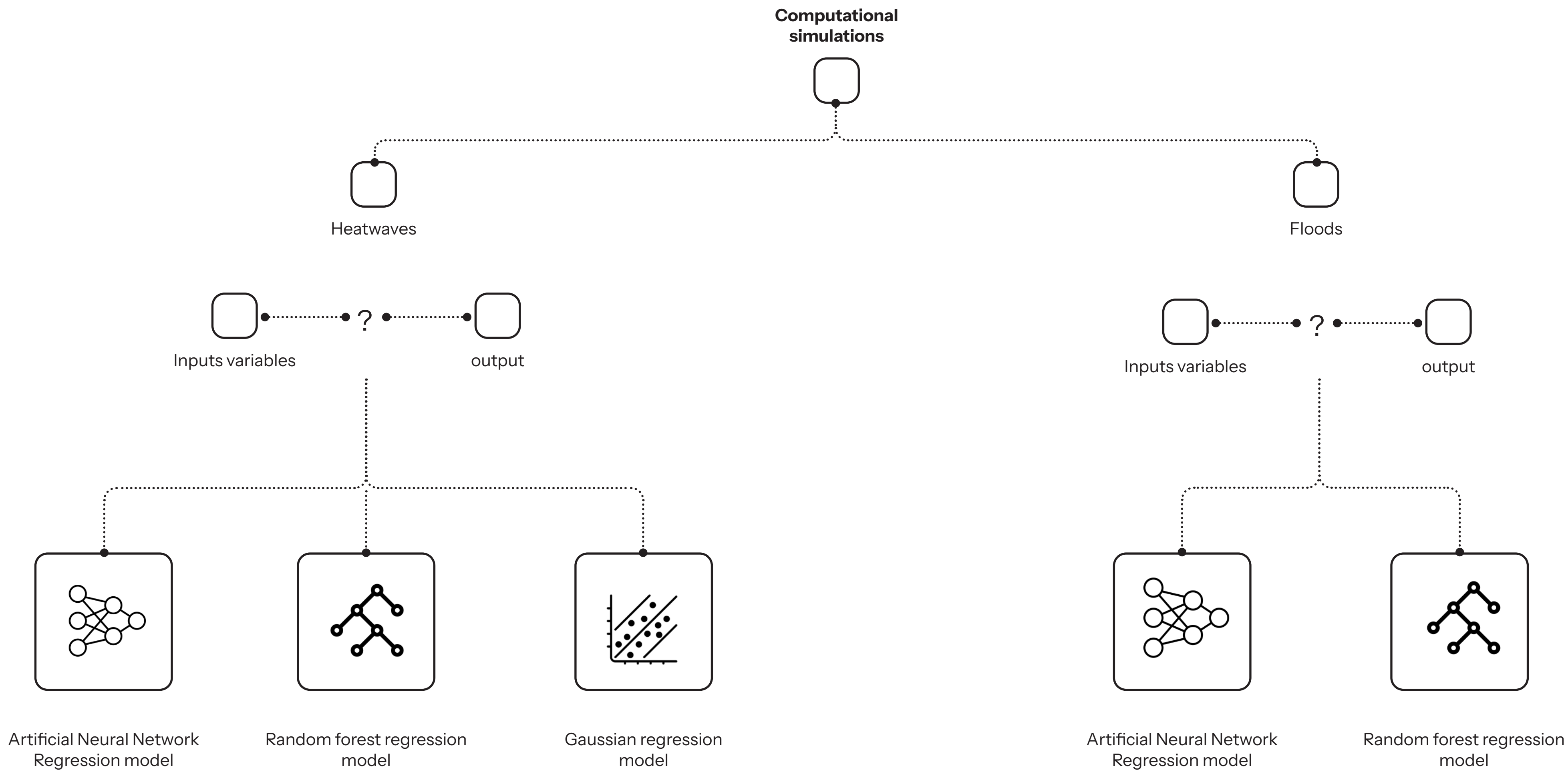
Increase the accuracy for sensitivity analysis

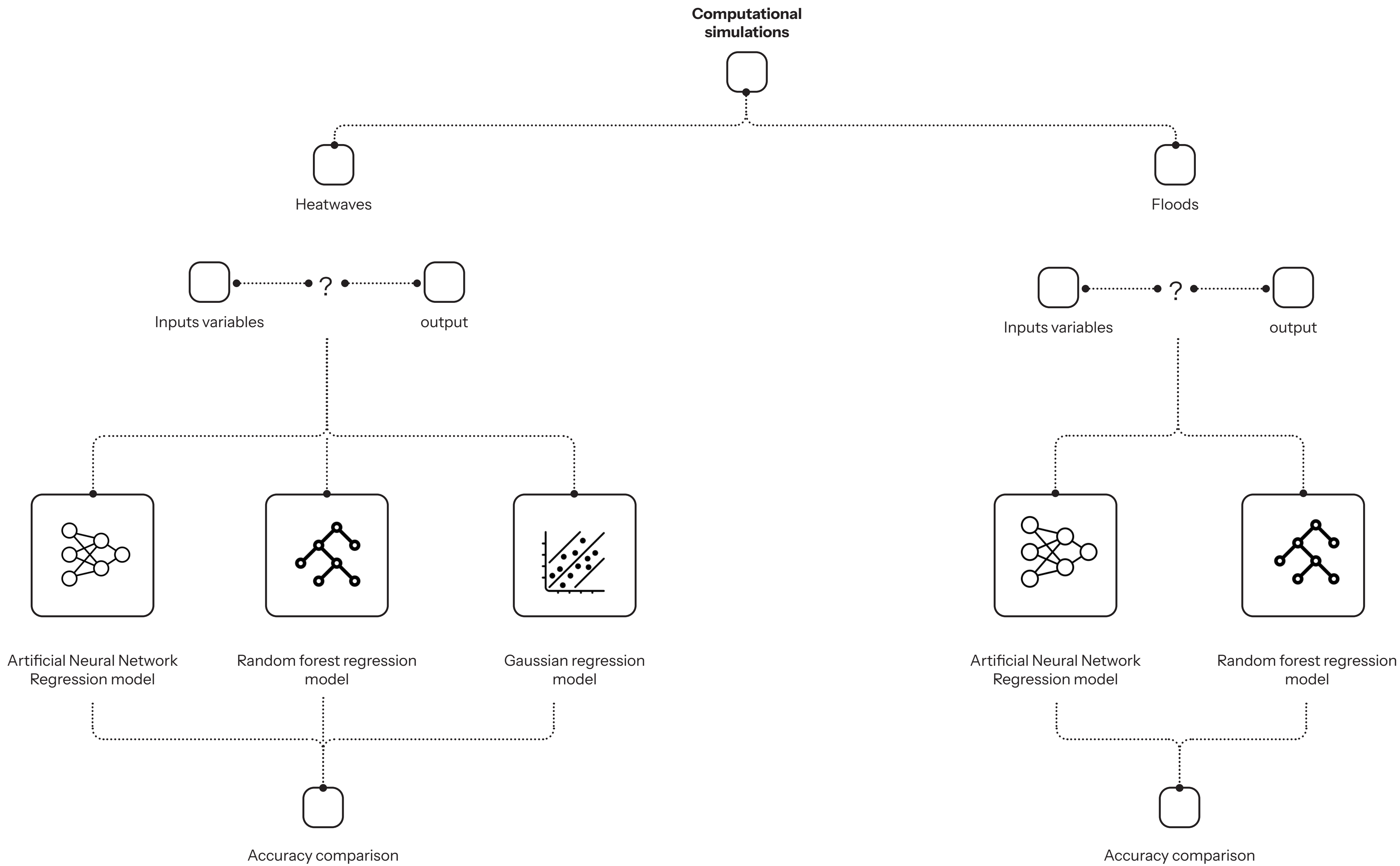

Computational
simulations
Heatwaves
Floods



Computational simulations
Heatwaves
Floods
Inputs variables
output
Inputs variables
output


Computational
simulations
Heatwaves
Floods
Inputs variables
?
output
Inputs variables
?
output

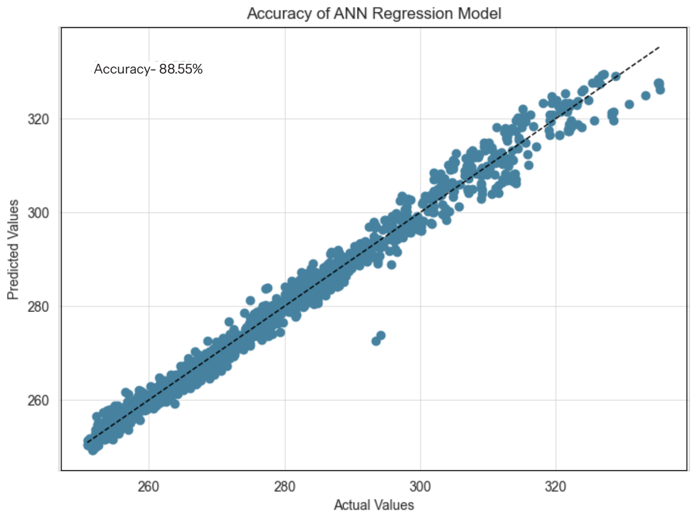

Computational simulations
Heatwaves
Floods
Inputs variables
?
output
Inputs variables
?
output
Artificial Neural Network Regression model
Random forest regression model
Gaussian regression model
Artificial Neural Network Regression model
Random forest regression model


Computational simulations
Heatwaves
Floods
Inputs variables
?
output
Inputs variables
?
output
Artificial Neural Network Regression model
Random forest regression model
Gaussian regression model
Artificial Neural Network Regression model
Random forest regression model
Accuracy comparison
Accuracy comparison

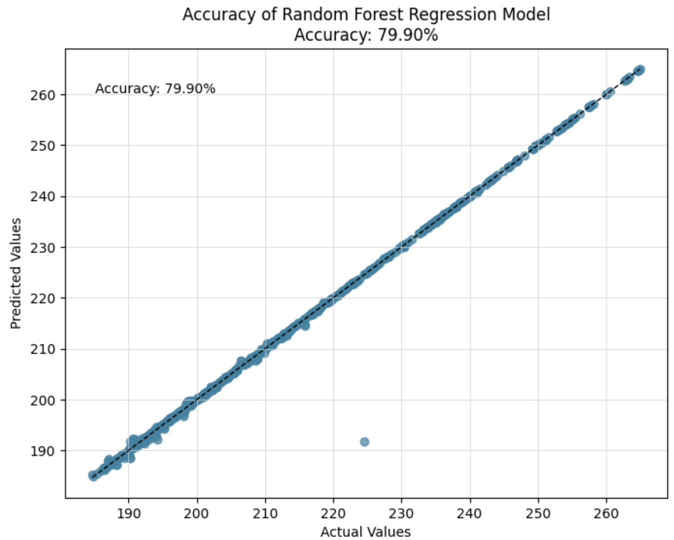
Heatwaves dataset

Inputs variables output

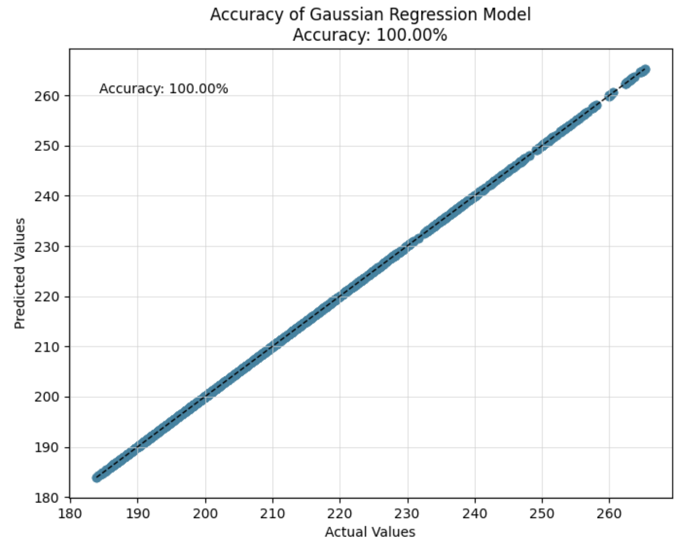
Artificial Neural Network
Regression model



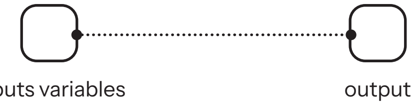
Random forest regression
model



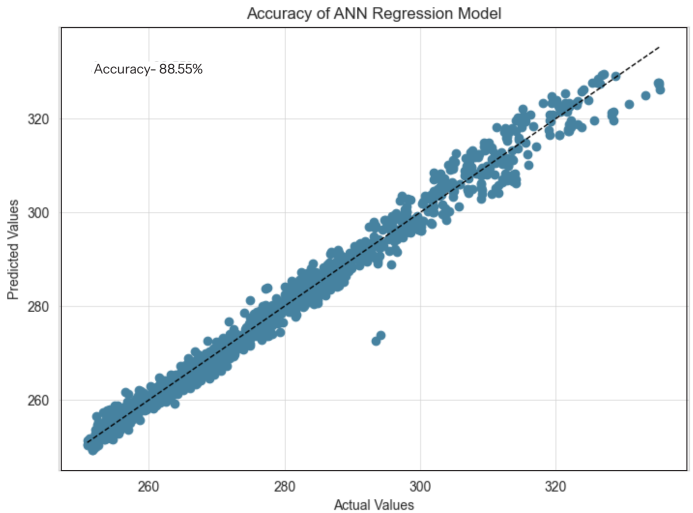
Gaussian regression
model



Heatwaves dataset

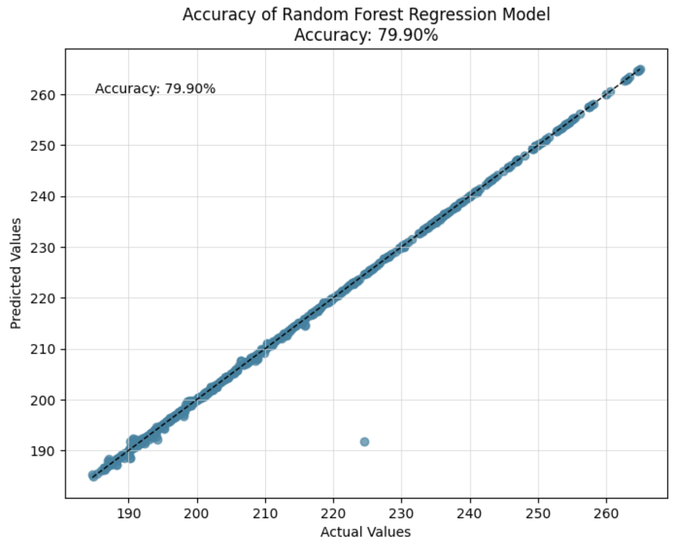


Artificial Neural Network
Regression model



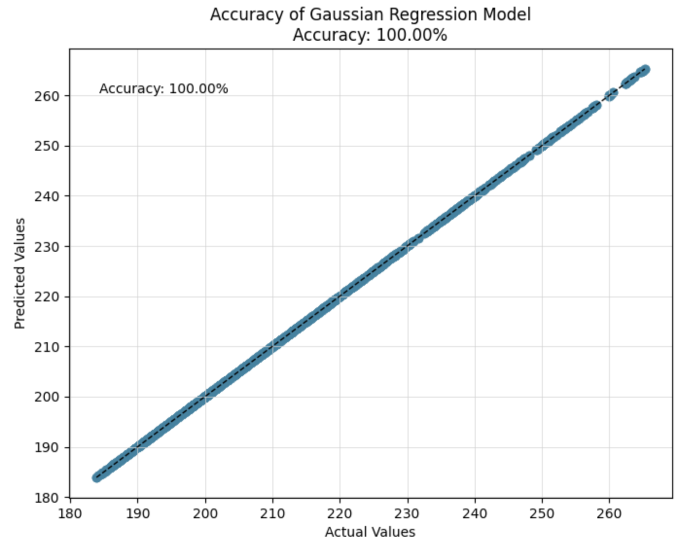
Prediction accuracy - 88.55%

Random forest regression
model



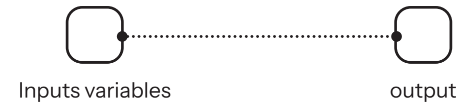
Prediction accuracy - 79.90%

Gaussian regression
model

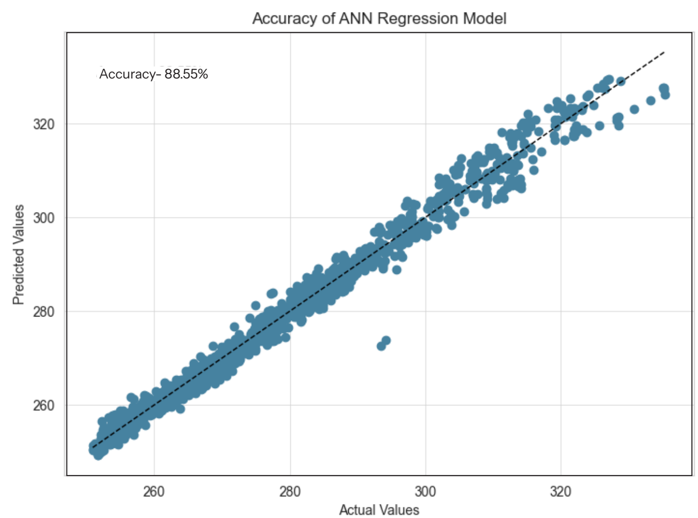


Prediction accuracy - 100%

Heatwaves dataset



Artificial Neural Network
Regression model



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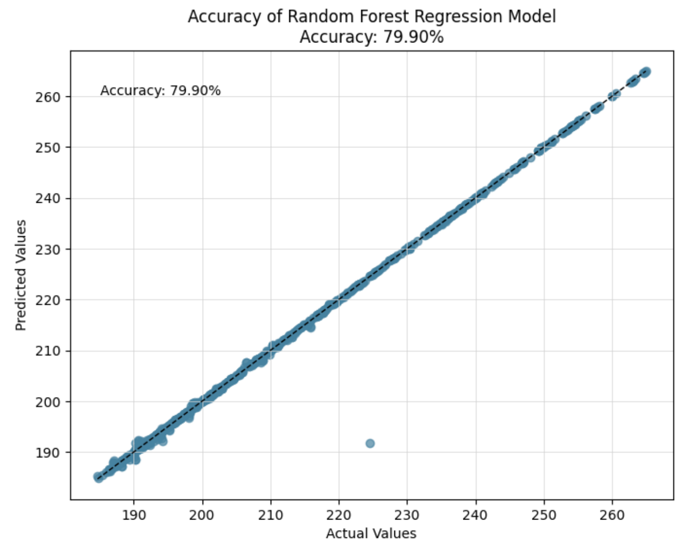

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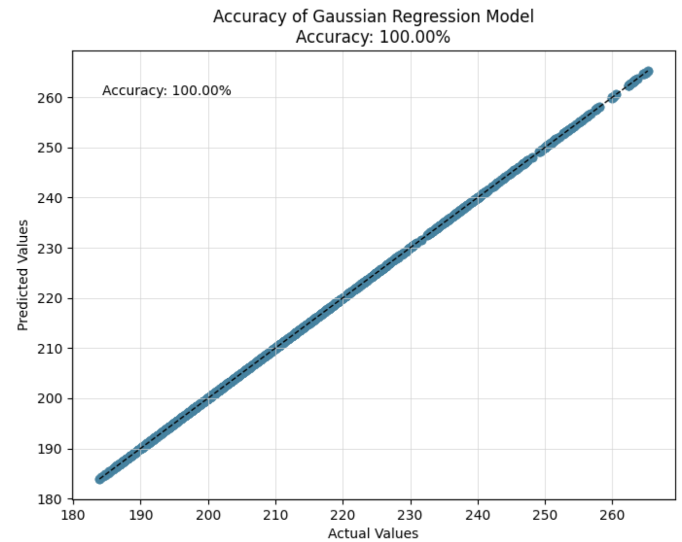
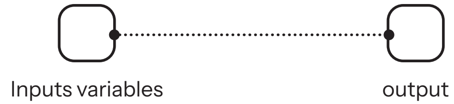


Prediction accuracy - 100%

Floods dataset

Floods dataset



Artificial Neural Network
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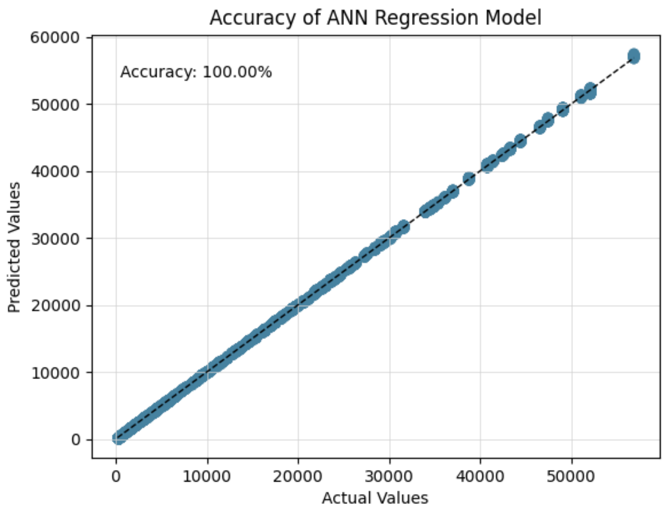

Prediction accuracy - 100%

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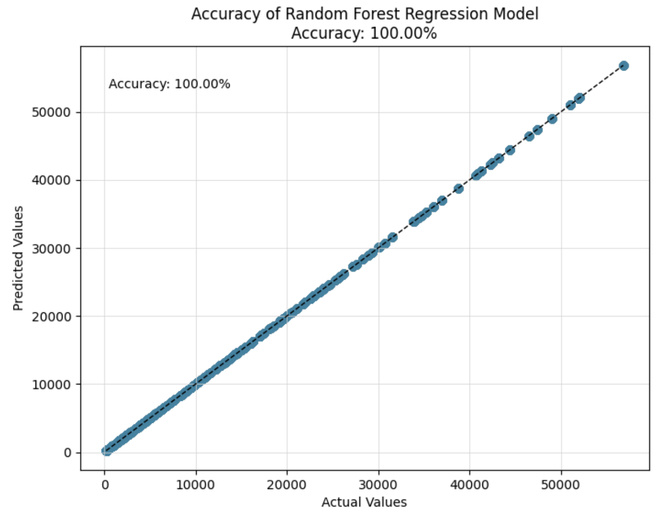

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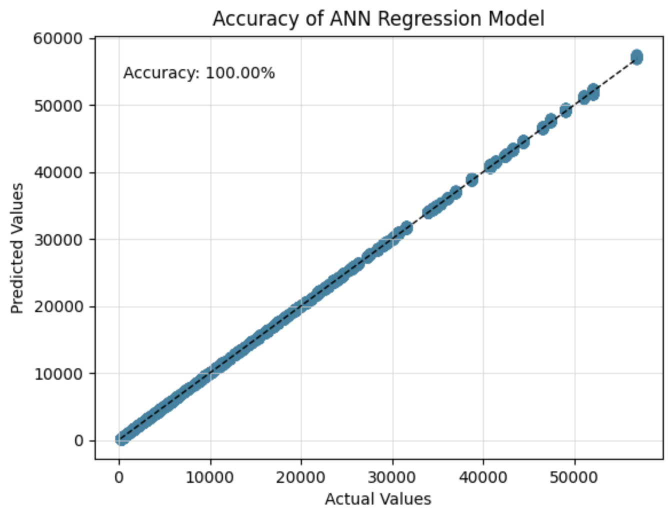

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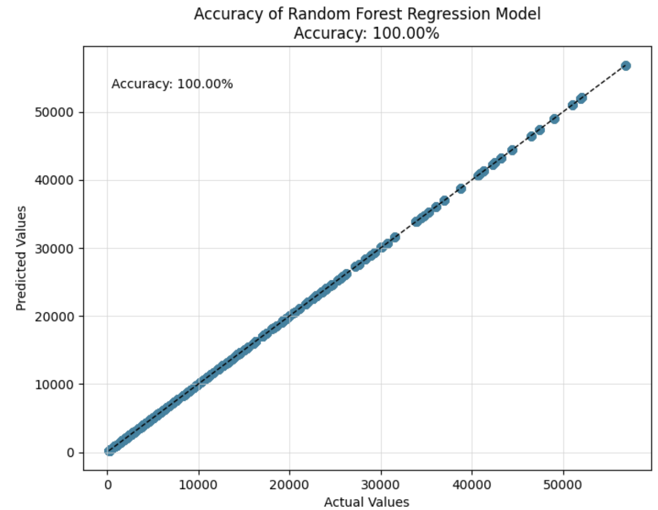
Random forest regression
model



Prediction accuracy - 100%

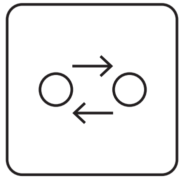
Sensitivity analysis

To find out how each input variable impacts the output

To find out how each input variable impacts the output

To find out how the interaction between two inputs impacts the output

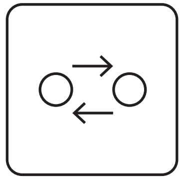
To find out how each input variable impacts the output



To find out how the interaction between two inputs impacts the output

Based on sensitivity analysis, designers can prioritize the input parameters while designing a resilient facade

To find out how each input variable impacts the output



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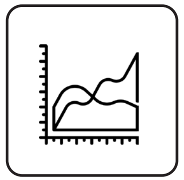
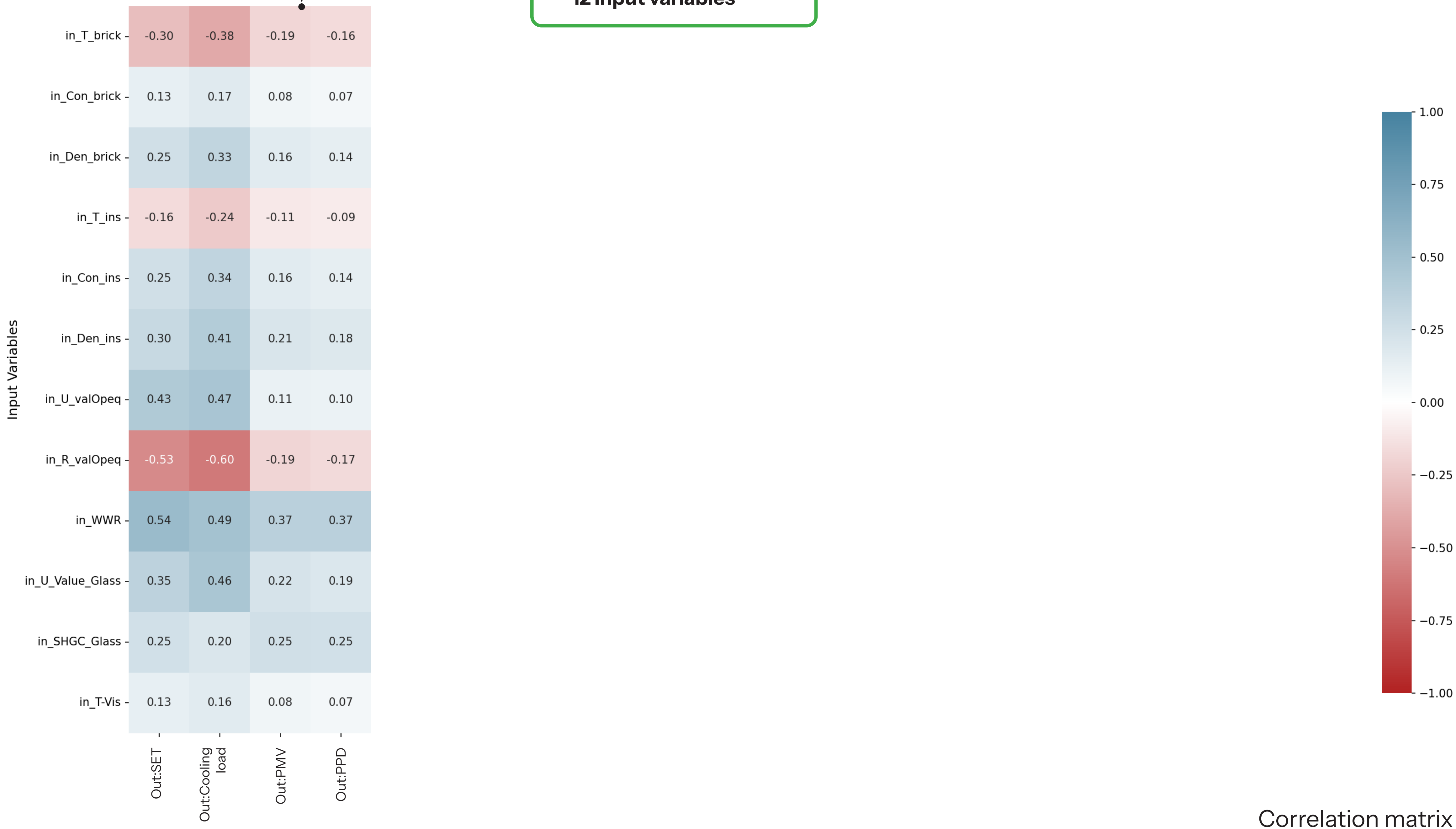


Sensitivity analysis helps in creating a resilience matrix by identifying the most influential input variables.

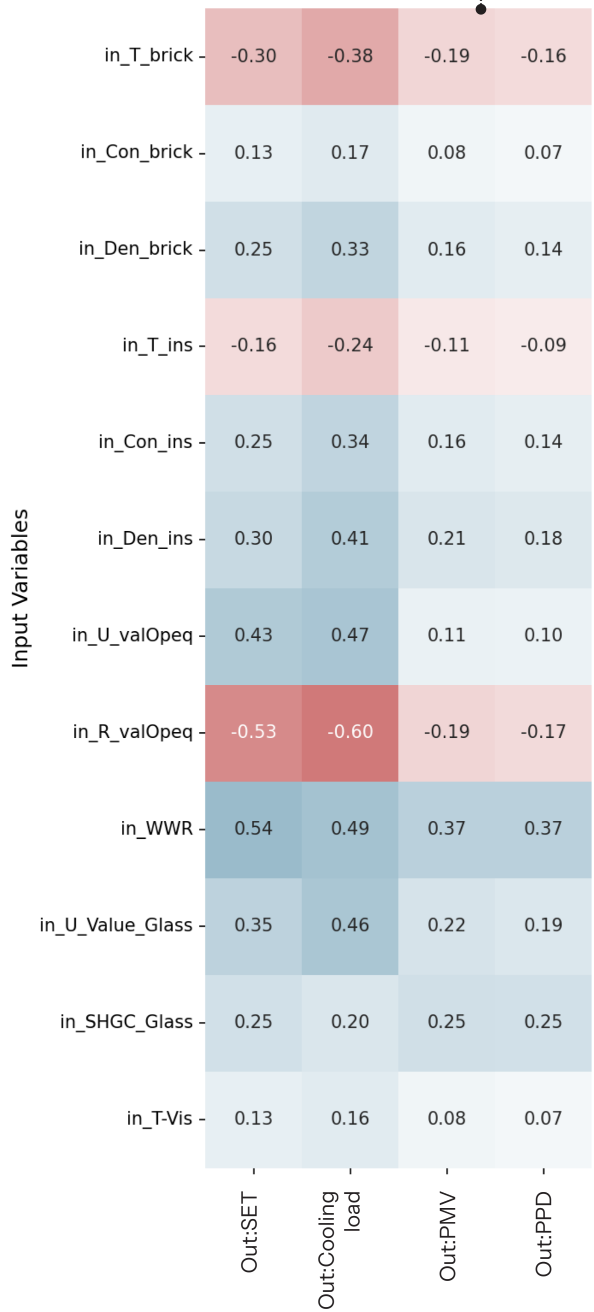
12 Input variables



Correlation matrix

12 Input variables

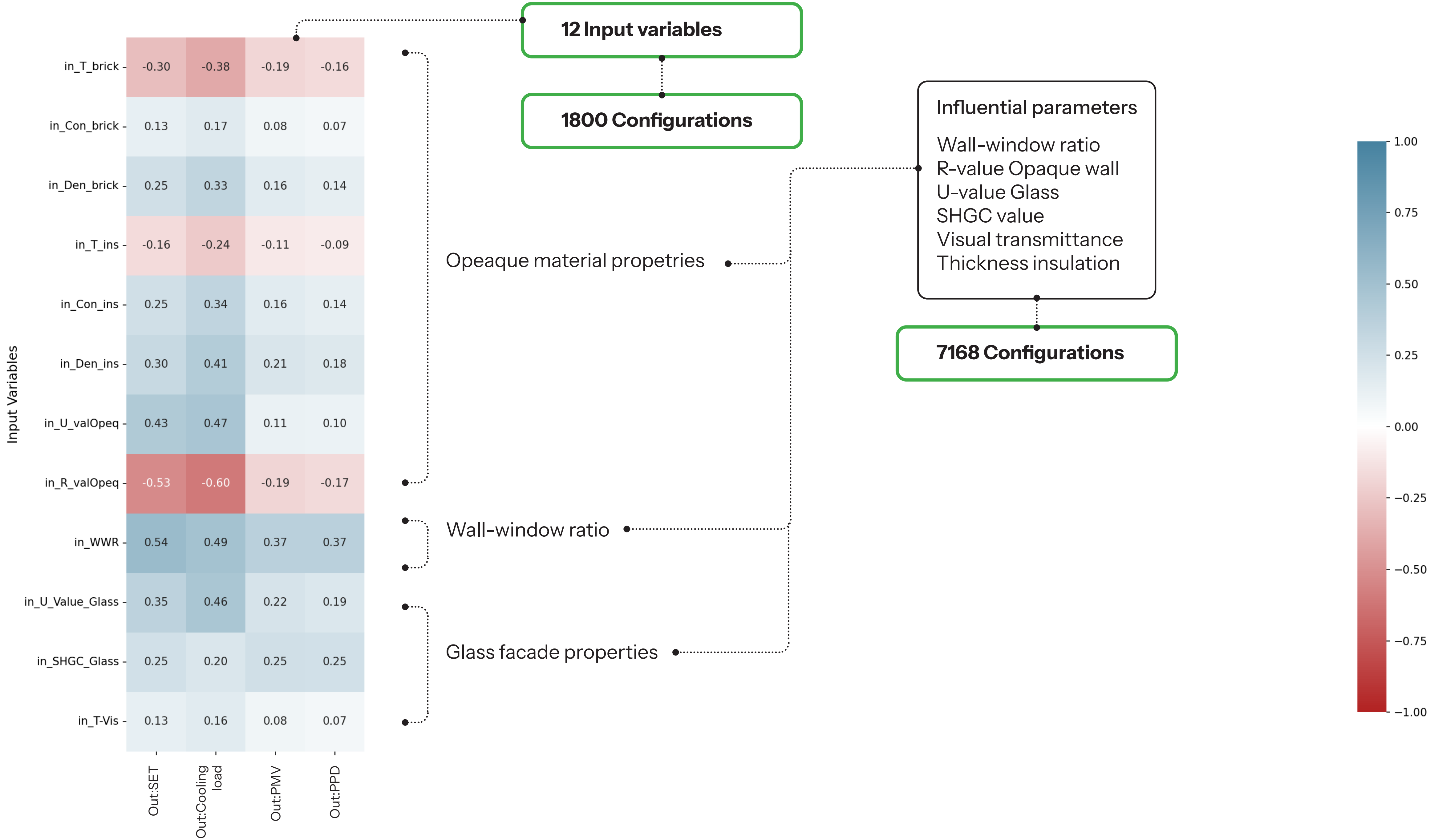
1800 Configurations



Opeaque material propetries

Wall-window ratio

Glass facade properties



12 Input variables
1800 Configurations
Influential parameters
Wall-window ratio
R-value Opaque wall
U-value Glass
SHGC value
Visual transmittance
Thickness insulation
7168 Configurations
Opeaque material propetries
Wall-window ratio
Glass facade properties
Input Variables
in_T_brick -0.30 -0.38 -0.19 -0.16
in_Con_brick 0.13 0.17 0.08 0.07
in_Den_brick 0.25 0.33 0.16 0.14
in_T_ins -0.16 -0.24 -0.11 -0.09
in_Con_ins 0.25 0.34 0.16 0.14
in_Den_ins 0.30 0.41 0.21 0.18
in_U_valOpeq 0.43 0.47 0.11 0.10
in_R_valOpeq -0.53 -0.60 -0.19 -0.17
in_WWR 0.54 0.49 0.37 0.37
in_U_Value_Glass 0.35 0.46 0.22 0.19
in_SHGC_Glass 0.25 0.20 0.25 0.25
in_T-Vis 0.13 0.16 0.08 0.07
Out:SET
Out:Cooling load
Out:PMV
Out:PPD
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00

Sobol's method Sensitivity analysis

Saltelli Sampling method

N * (2D+2) = 7168 Samples ,N= 6
,D = 512

Heatwaves

Saltelli Sampling method

N * (2D+2) = 7168 Samples ,N= 6
,D = 512

Input variables (x_i)

?

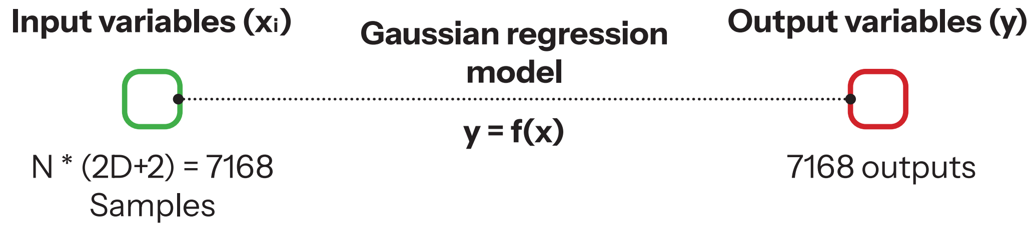
Output variables (y)

N * (2D+2) = 7168 Samples

7168 outputs

Saltelli Sampling method

N * (2D+2) = 7168 Samples ,N= 6 ,D = 512



Saltelli Sampling method

N * (2D+2) = 7168 Samples ,N= 6
,D = 512

Input variables (x_i)

Gaussian regression model

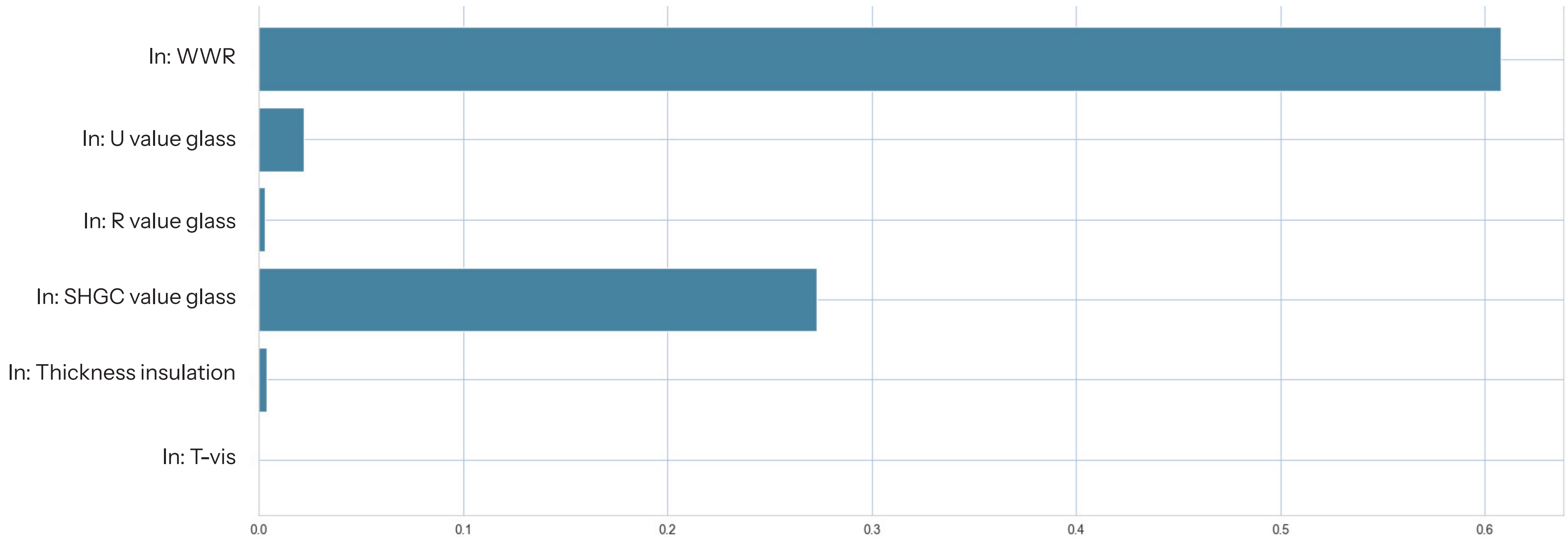
Output variables (y)

y = f(x)

N * (2D+2) = 7168 Samples

7168 outputs

First-Order indices



Heatwaves

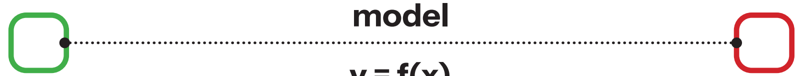
Saltelli Sampling method

N * (2D+2) = 7168 Samples ,N= 6
,D = 512

Input variables (x_i)

Gaussian regression model

Output variables (y)

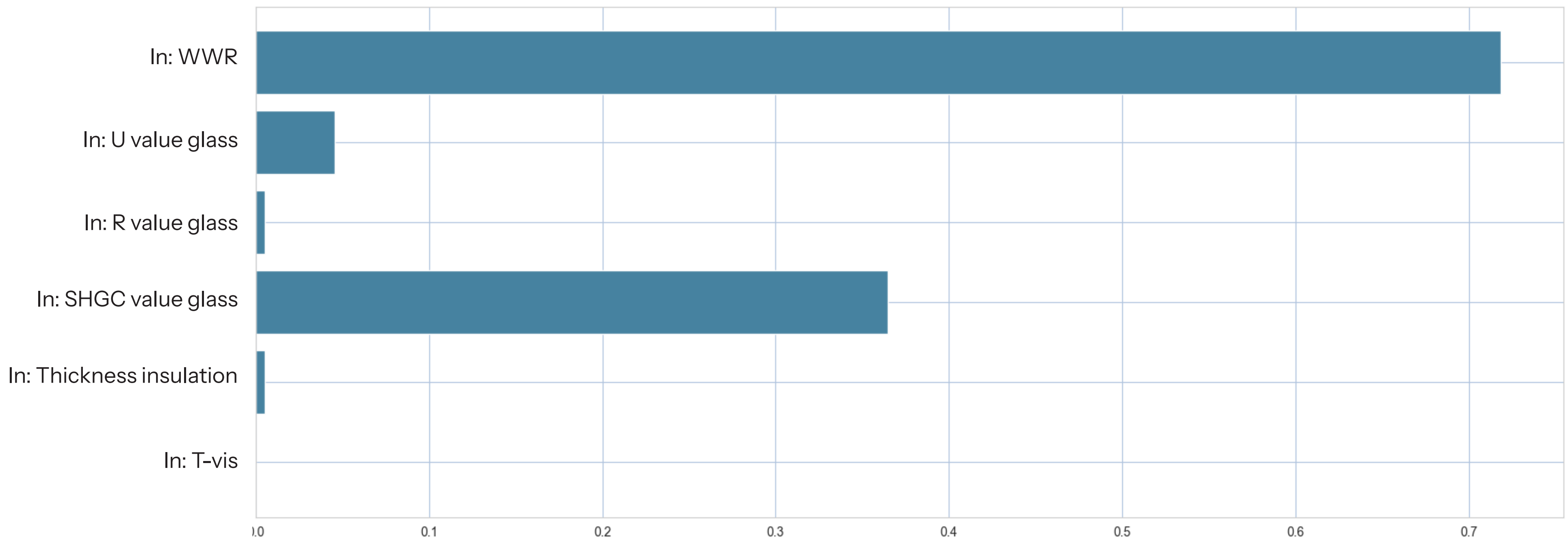


y = f(x)

N * (2D+2) = 7168 Samples

7168 outputs

Total-Order indices



Heatwaves

Saltelli Sampling method

N * (2D+2) = 131072 Samples ,N= 7 ,D = 8192

Saltelli Sampling method

N * (2D+2) = 131072 Samples ,N= 7
,D = 8192

Input variables (x_i)

Output variables (y)

N * (2D+2) = 131072 Samples

131072 X 3 outputs

Saltelli Sampling method

N * (2D+2) = 131072 Samples ,N= 7
,D = 8192

Input variables (x_i)

Mathematical equation

Output variables (y)

y =f(x)

N * (2D+2) = 131072 Samples

131072 X 3 outputs

Saltelli Sampling method

N * (2D+2) = 131072 Samples ,N= 7
,D = 8192

Input variables (x_i)

Mathematical equation

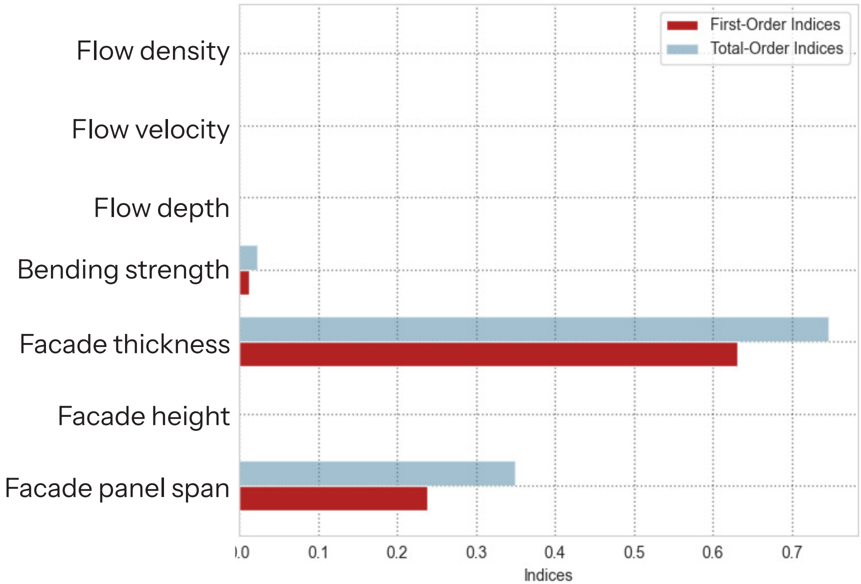
Output variables (y)

N * (2D+2) = 131072 Samples

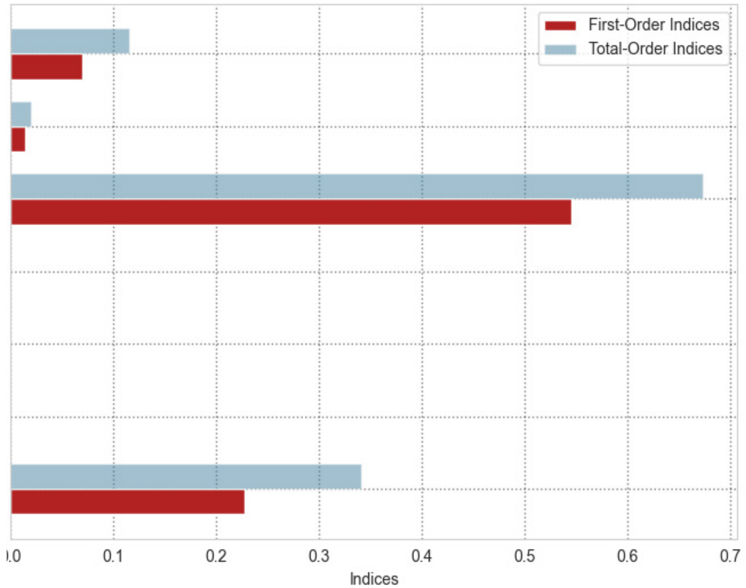
y =f(x)

131072 X 3 outputs

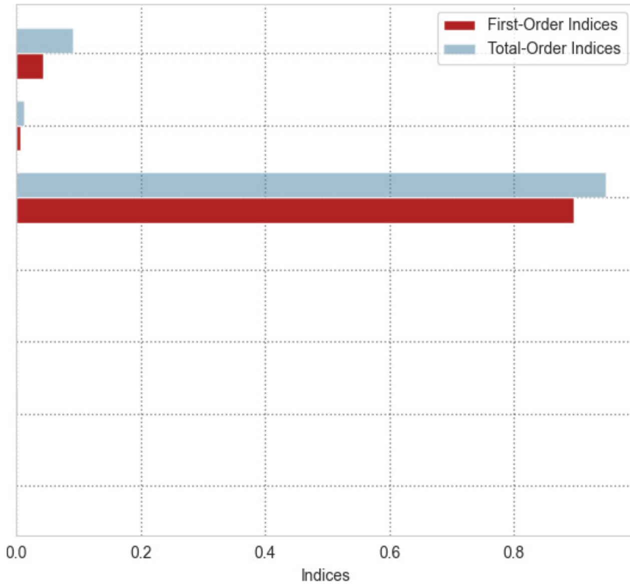
Allowable bendiing moment



Total hydraulic pressure



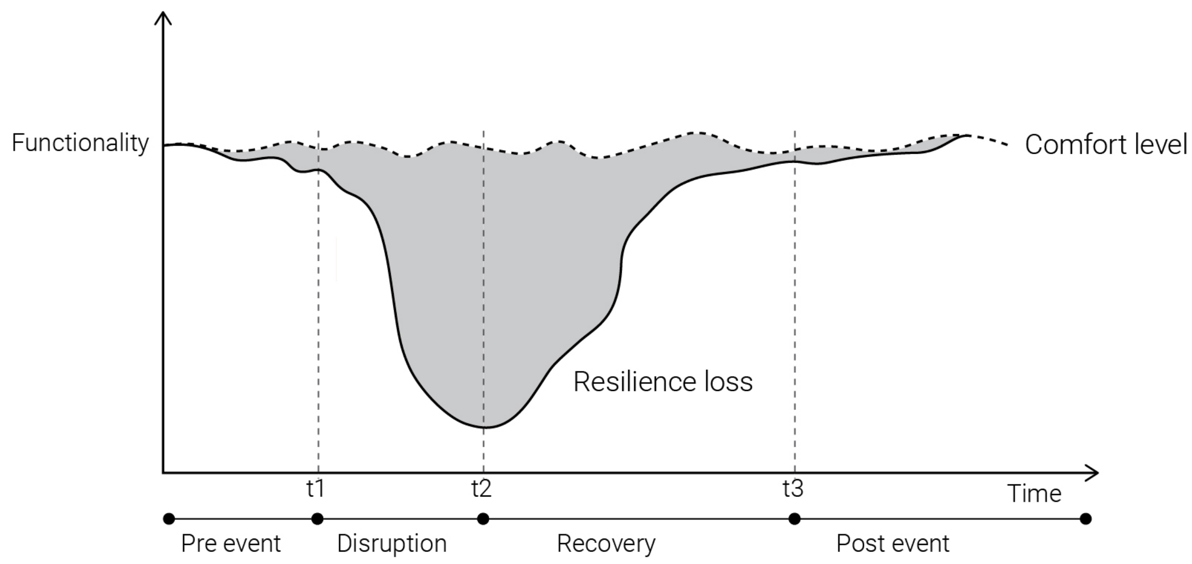
Max. applied bending moment



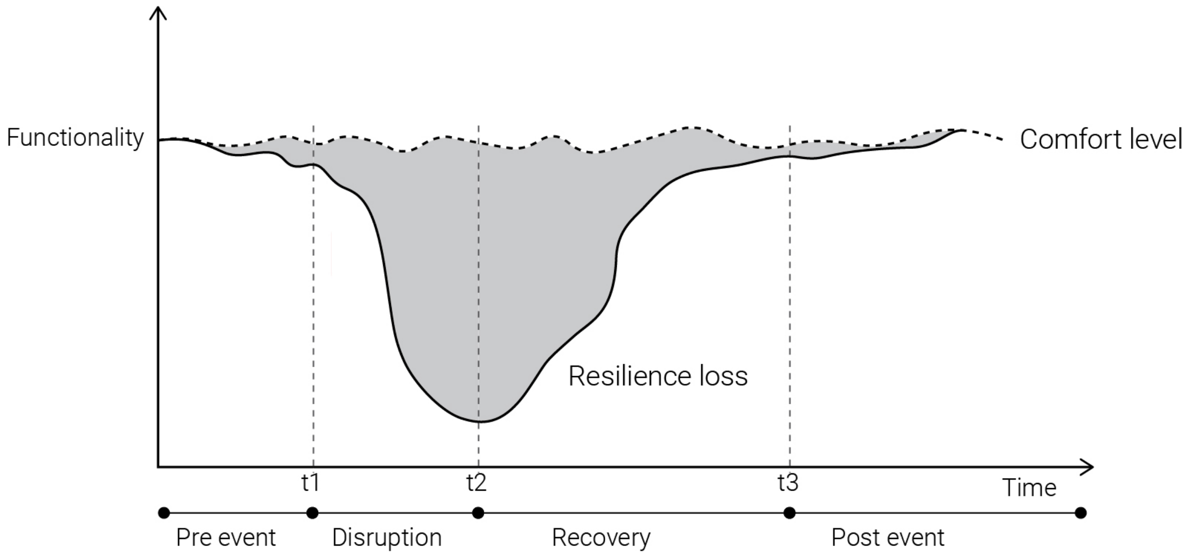
Floods

Resilience matrics

Resilience graph



Resilience graph

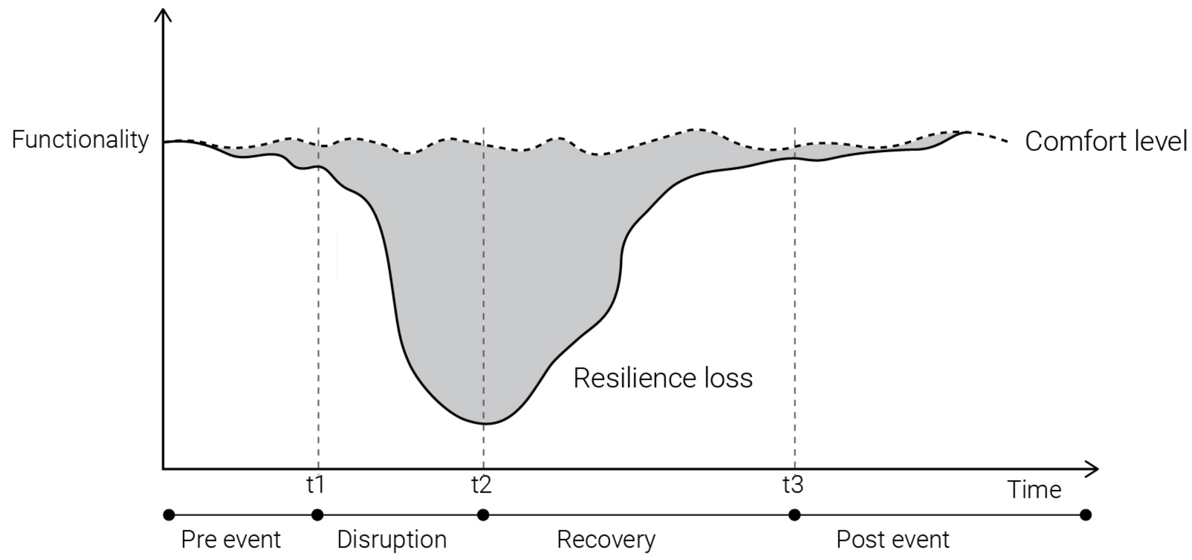


Resilience indicator

Heatwaves

Cooling energy demand

Resilience graph



Resilience indicator

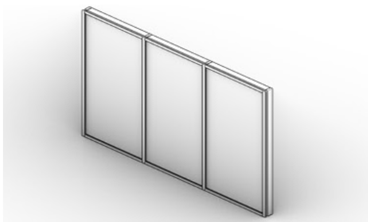
Heatwaves

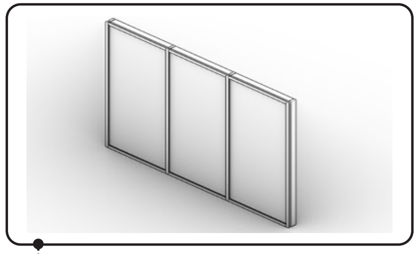
Cooling energy demand

Floods

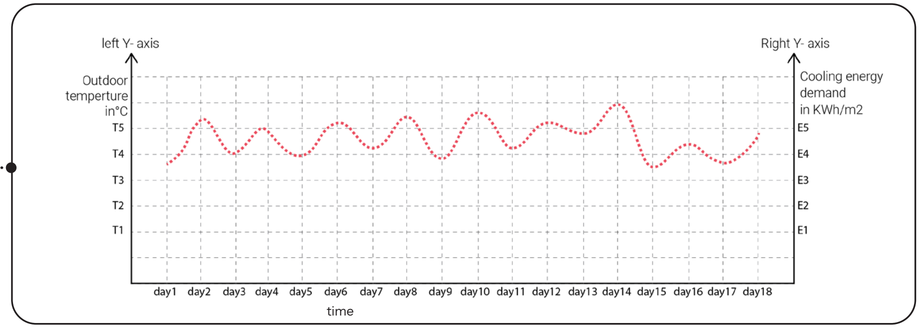
Bending moment

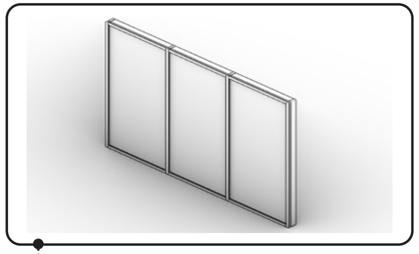
Thermal resilience quantification





Outdoor temperature before hazard: temperature in comfort-able range (18-27°C)





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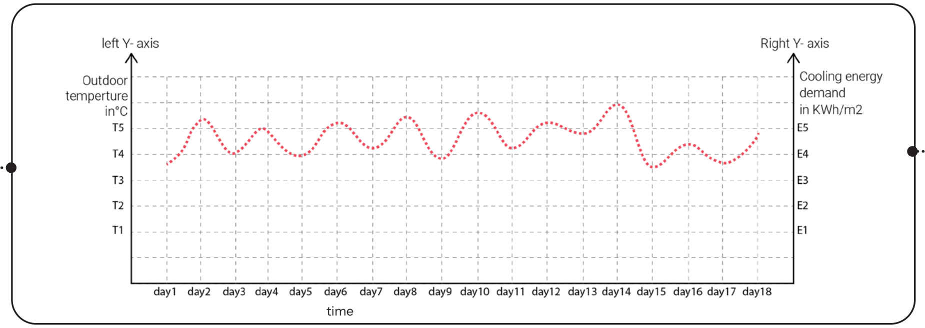
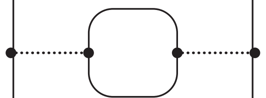
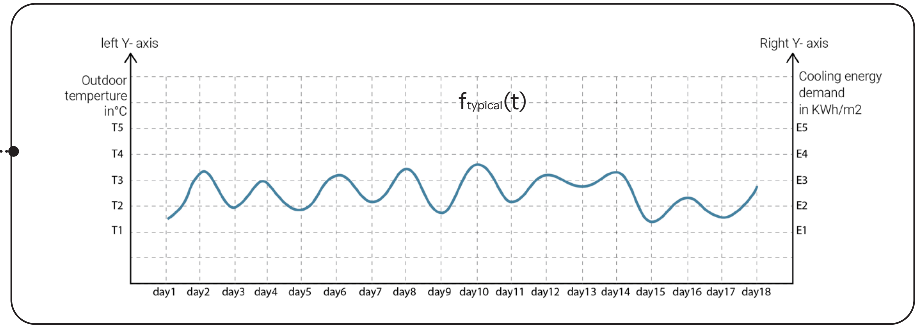
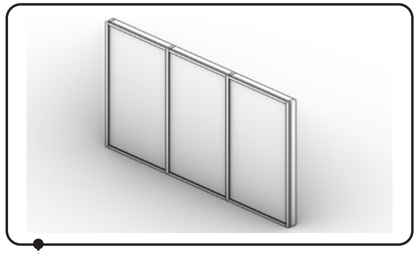




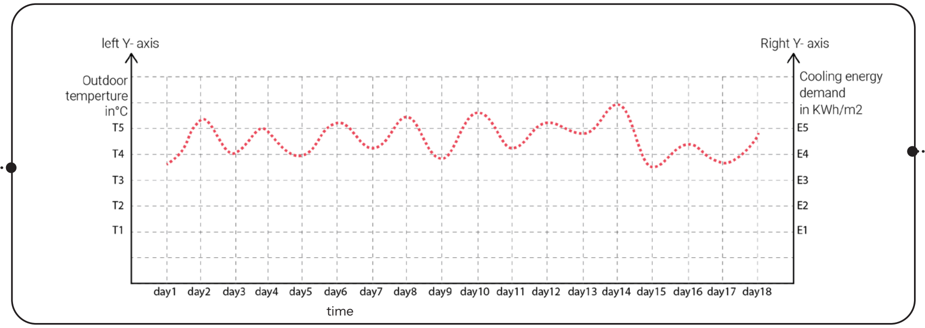
Simulation

Cooling energy demand

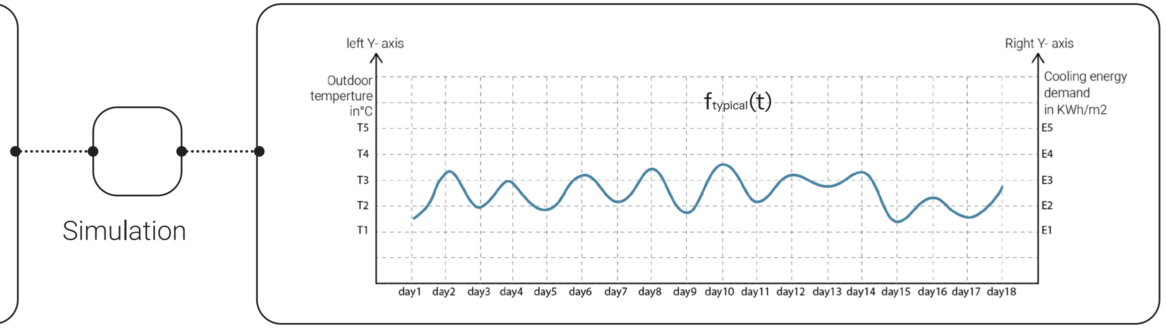




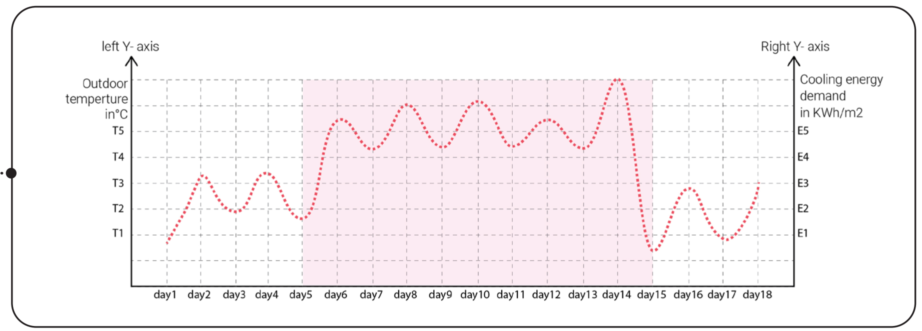
Outdoor temperature before hazard: temperature in comfortable range (18-27°C)

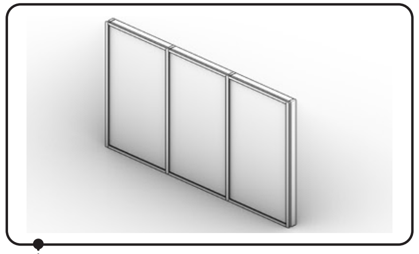


Cooling energy demand

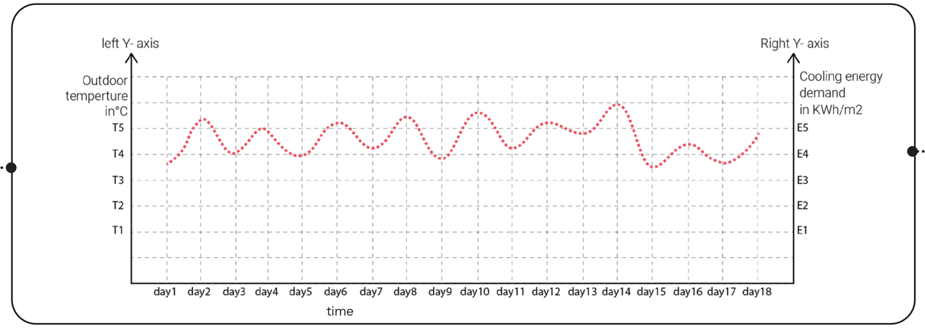


Outdoor temperature during heatwaves: temperature range (>40°C)



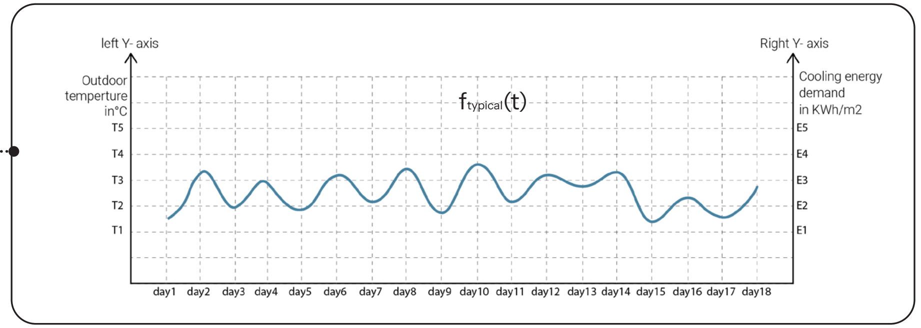


Outdoor temperature before hazard: temperature in comfort-able range (18-23°C)

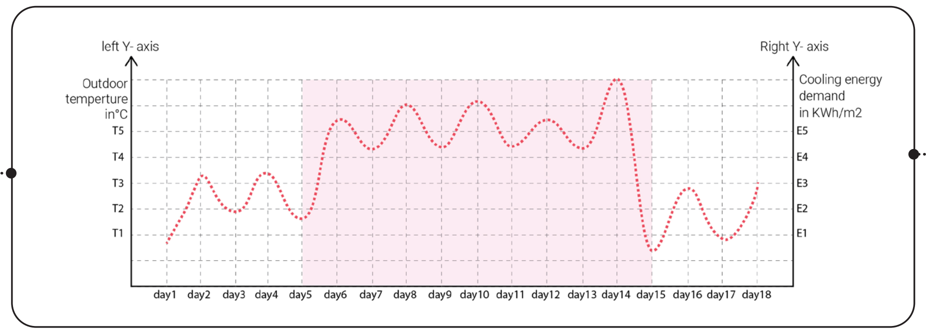


Simulation

Cooling energy demand

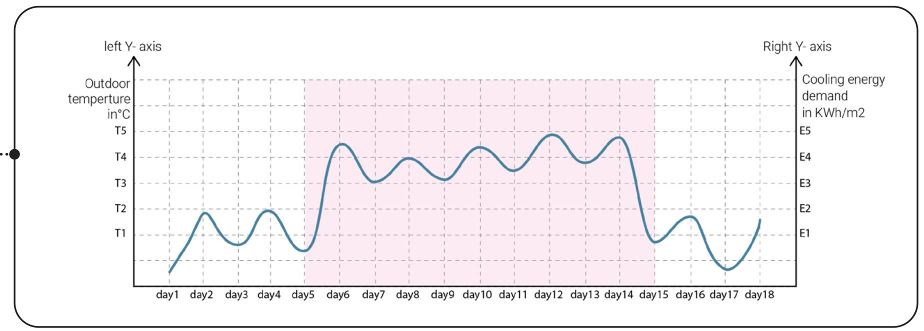


Outdoor temperature during heatwaves: temperature range (>40°C)

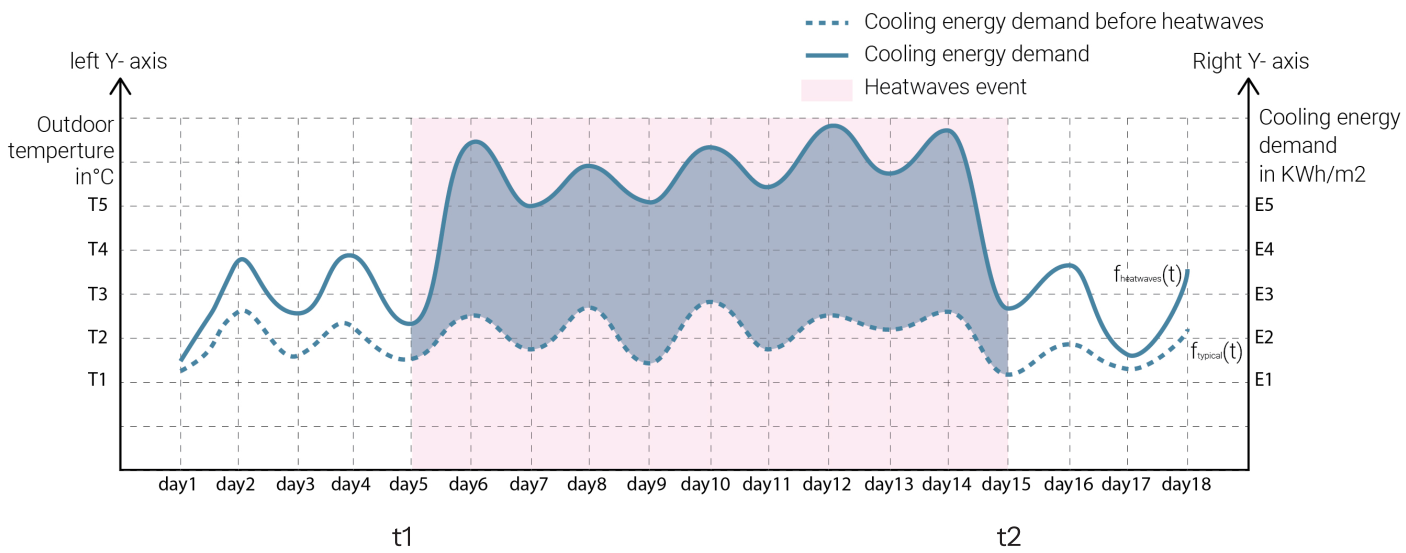


Simulation

Cooling energy demand during heatwaves

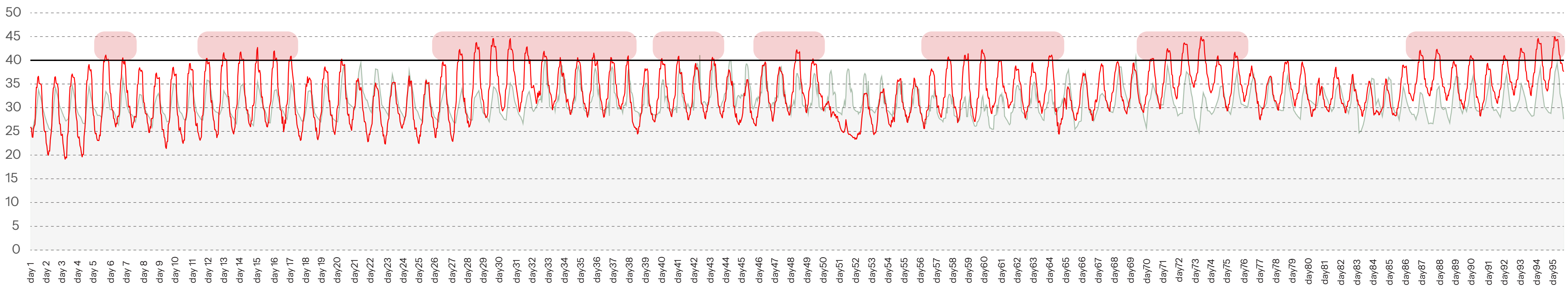


The area between the two cooling energy demand functions represents resilience loss.



$$\text{Resilience loss} = \int_{t_1}^{t_2} \left(f_{\text{heatwaves}}(t) - f_{\text{typical}}(t)\right)\, dt$$

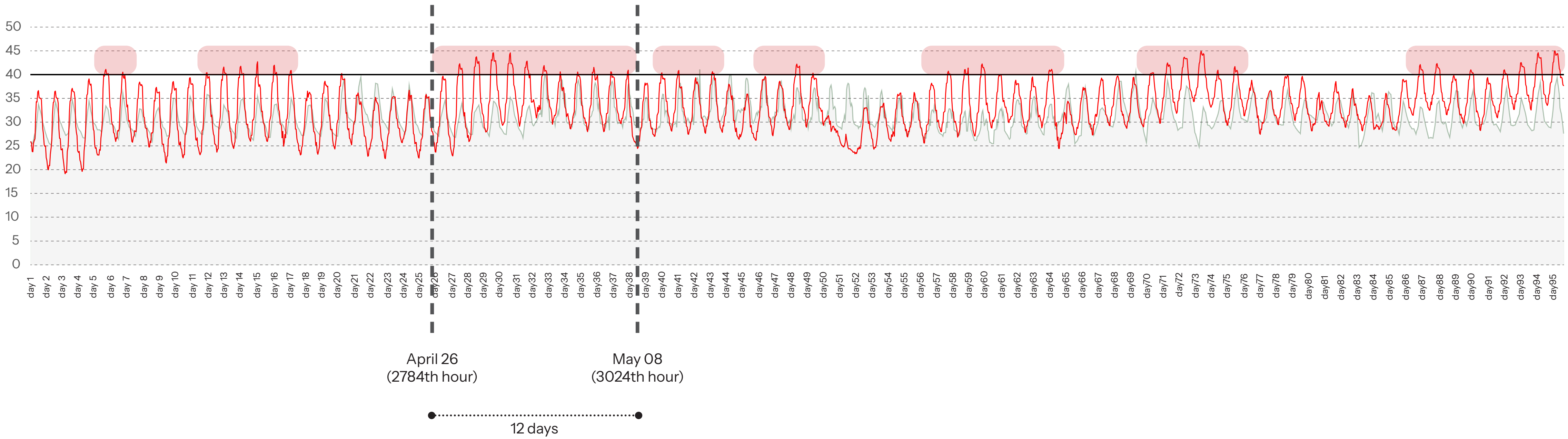
Heatwaves 2021- Chennai,India (April - June)



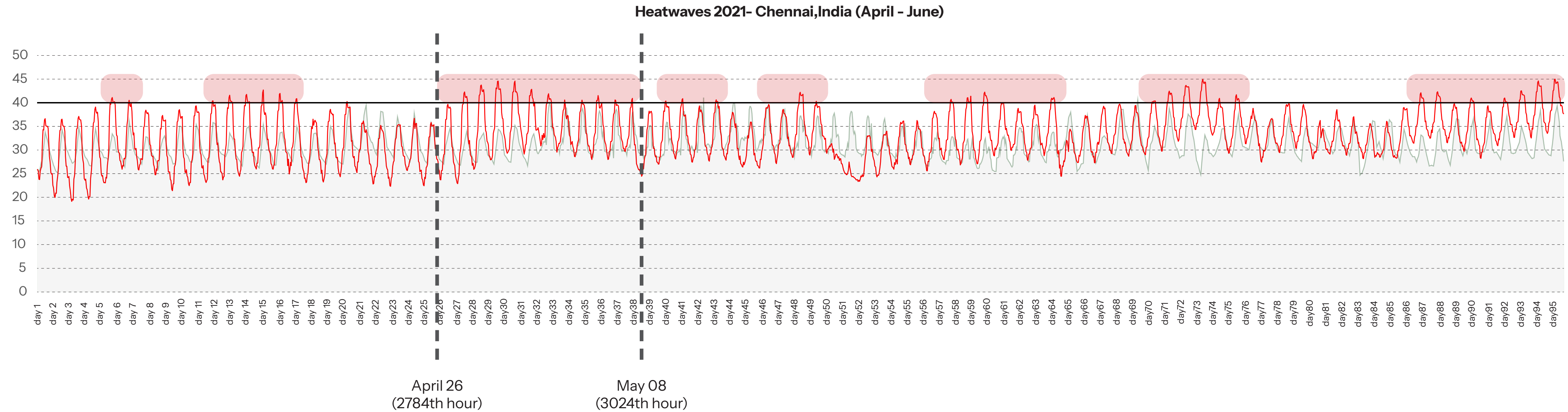
Casestudy- Chennai, India

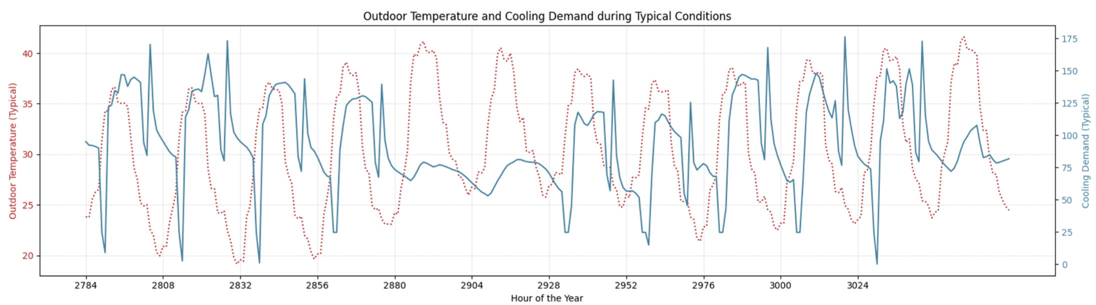
26 June 2024

Heatwaves 2021- Chennai,India (April - June)



Casestudy- Chennai, India

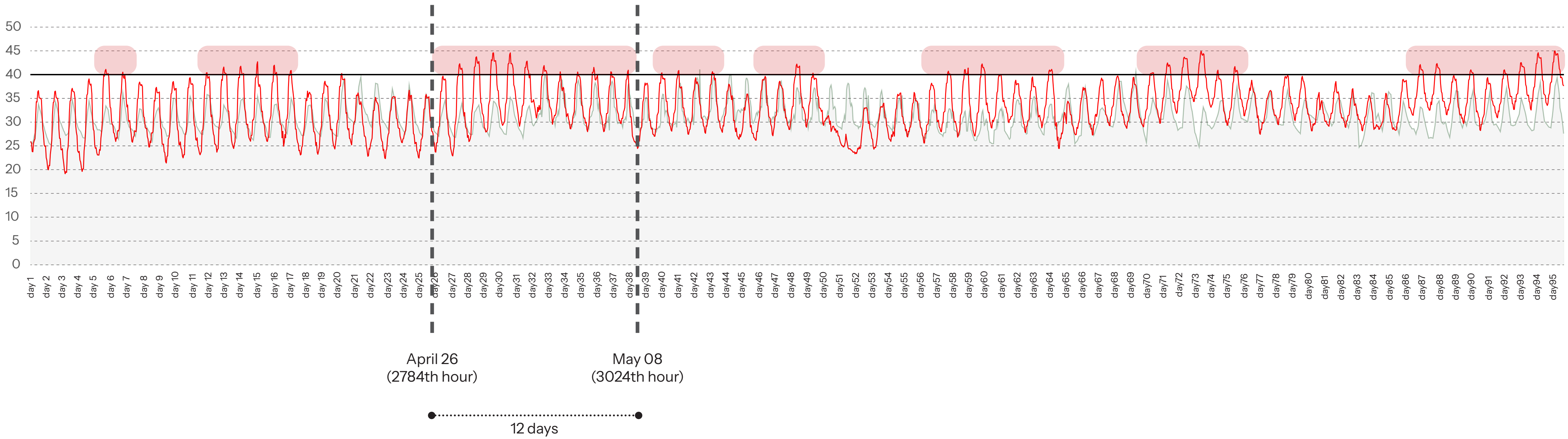


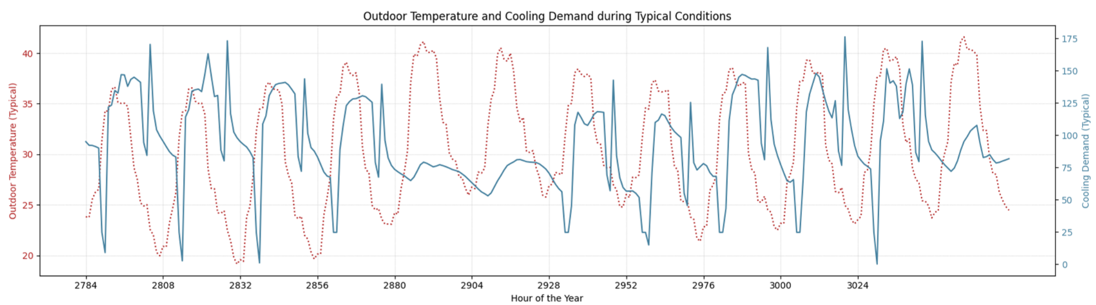


Typical weather condition

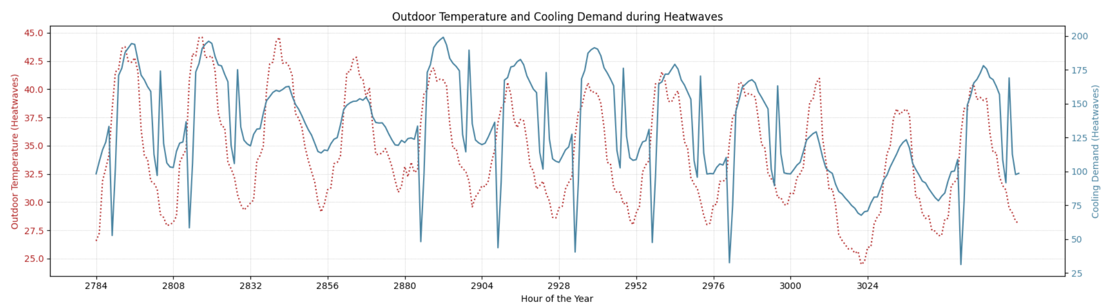
Casestudy- Chennai, India

Heatwaves 2021- Chennai,India (April - June)



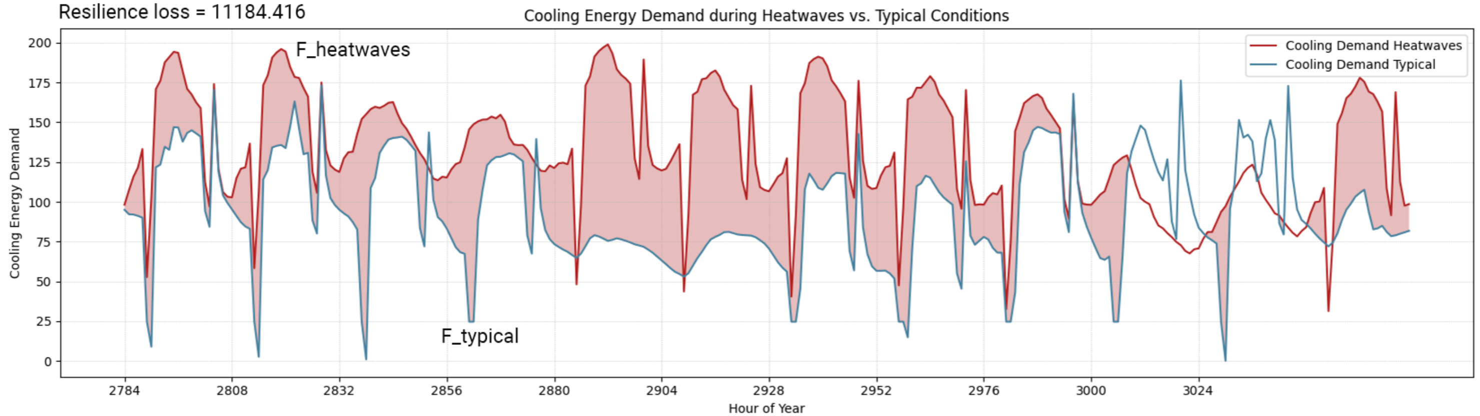


Typical weather condition



Heatwave (April 26-May08 2021)

F_heatwaves = 37931.638
F_typical= 26747.222
Resilience loss = 11184.416



Casestudy- Chennai, India

F_heatwaves = 37931.638
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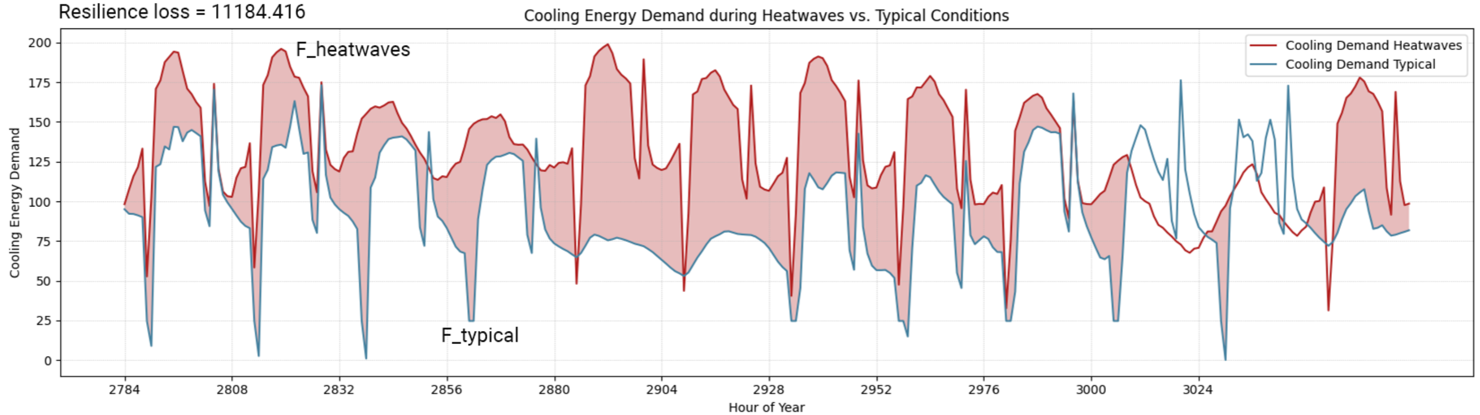


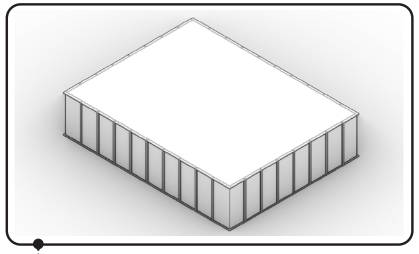
$$\text{Resilience loss} = \int_{t_1}^{t_2} \left(f_{\text{heatwaves}}(t) - f_{\text{typical}}(t)\right)\, dt$$

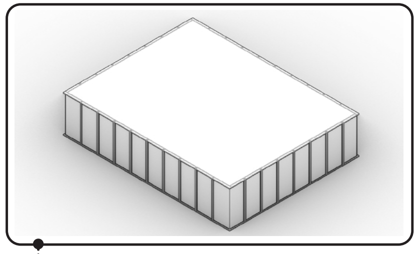
$$= 37931.638 - 26747.222$$

$$= 11184.416$$ **(29.5 % Thermal resilience loss)**

Casestudy- Chennai, India

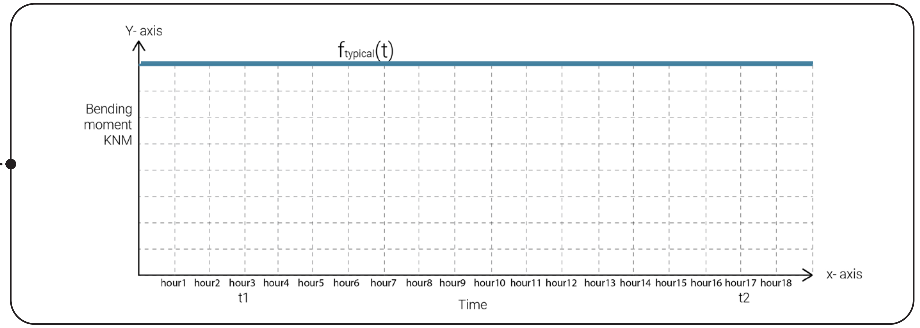
Flood resilience quantification

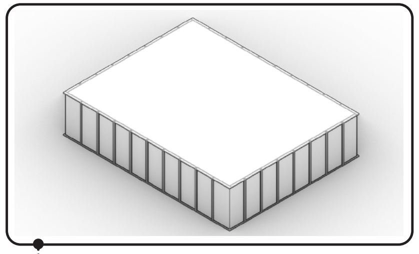




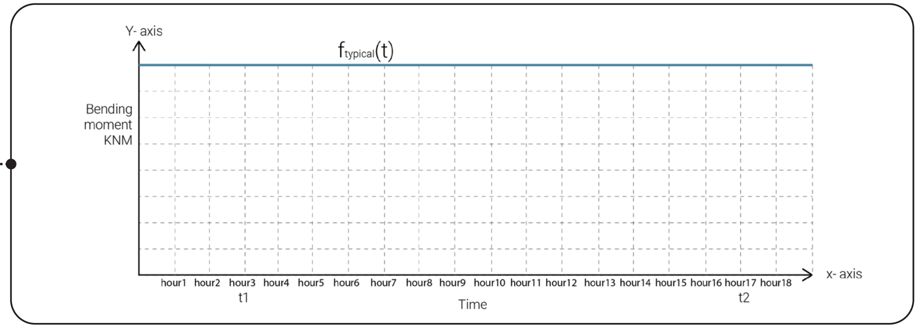
Mathematical calculations

Allowable bending moment of the facade



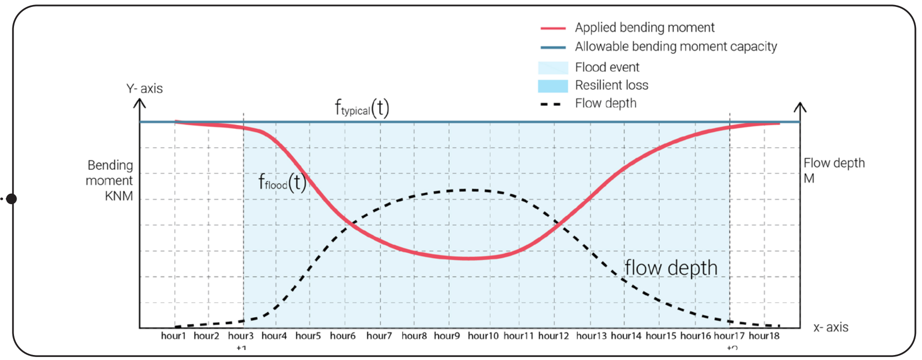


Allowable bending moment of the facade



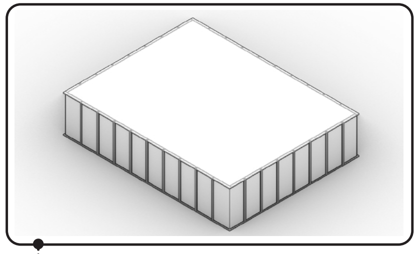
Mathematical calculations

Applied bending moment on facade due to flood with chaning flow depth



Flood intensity

Computation simulation/
Mathematical calculations

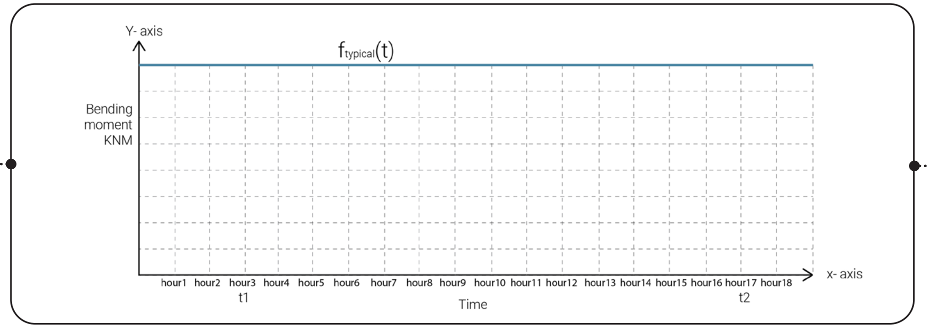


Mathematical calculations

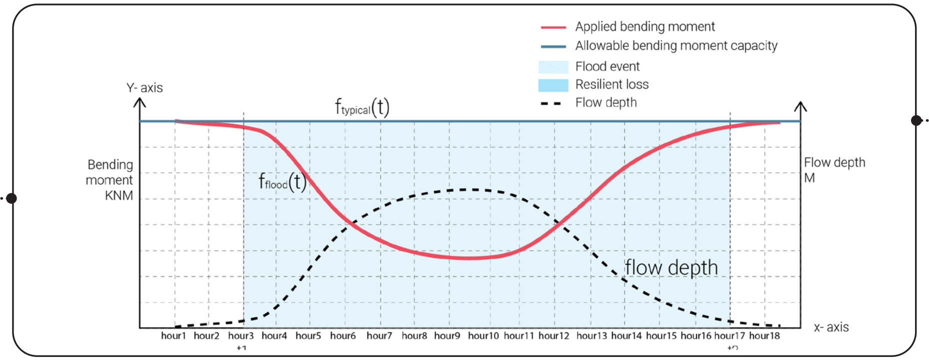
Flood intensity

Computation simulation/ Mathematical calculations

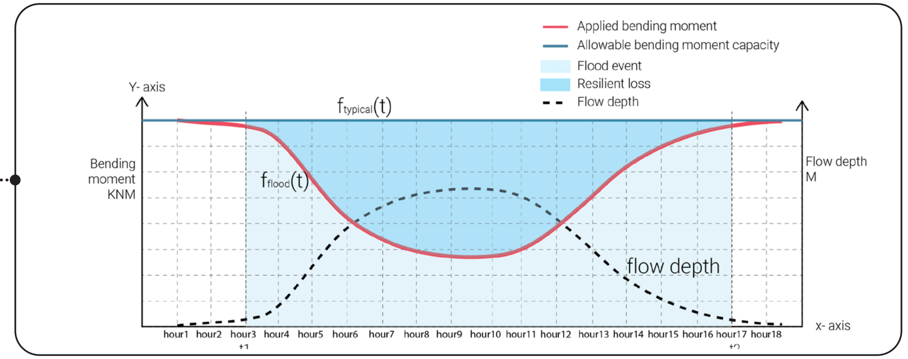
Allowable bending moment of the facade



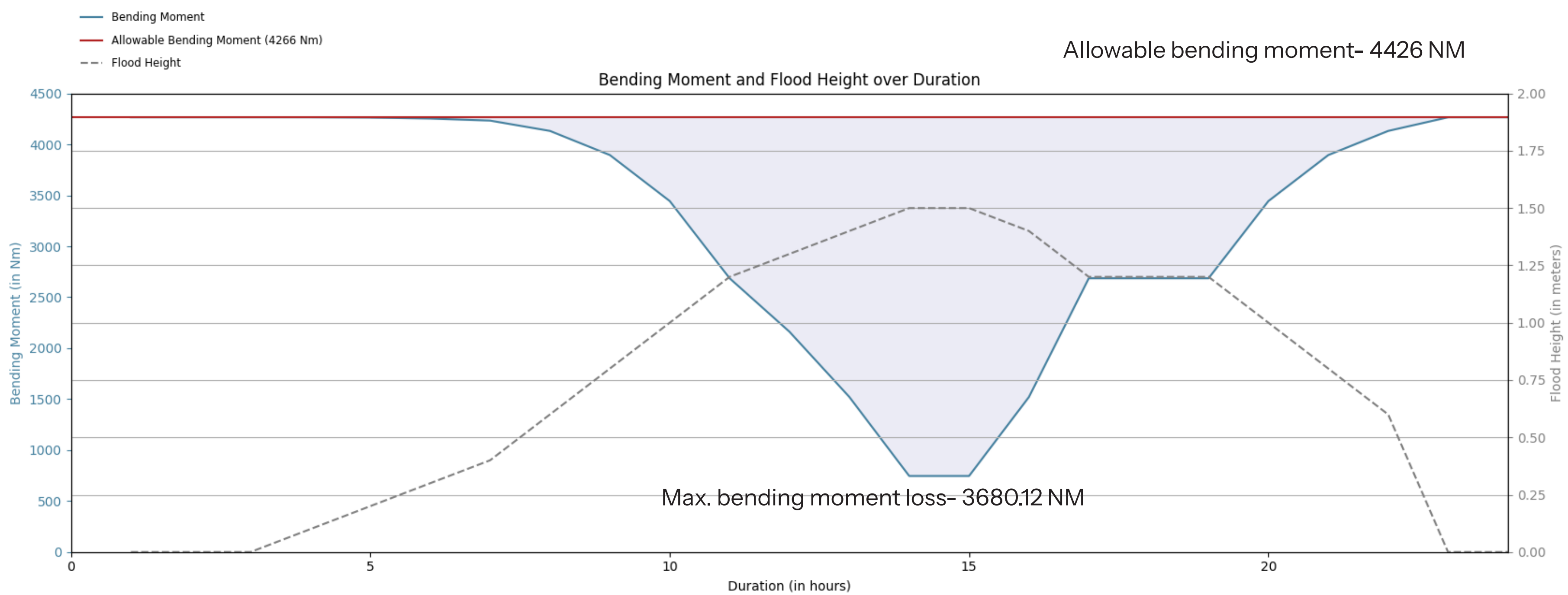
Applied bending moment on facade due to flood with chaning flow depth



The area between the bending moment functions represents resilience score for the facade



$$\text{Resilience loss} = \int_{t_1}^{t_2} \left(f_{\text{typical}}(t) - f_{\text{flood}}(t)\right)\, dt$$



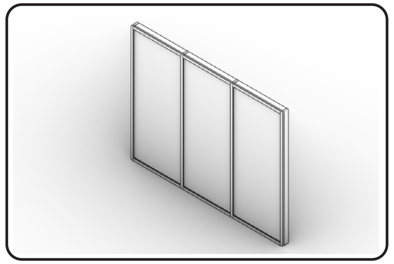
$$\text{Resilience loss} = \int_{t_1}^{t_2} \left(f_{\text{typical}}(t) - f_{\text{flood}}(t)\right)\, dt$$

$$= 76788.0 - 53145.4$$

$$= 23642.6$$ **(30.78 % Flood resilience loss)**

Casestudy- Chennai, India

Multi-hazard resilience loss



Facade input parameters

Geometrical propeties

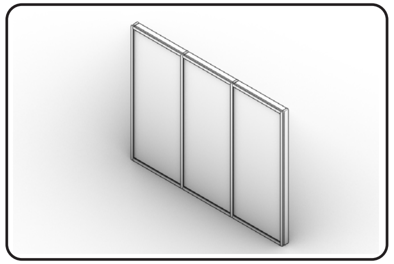
Facade span
Facade Height
Facade thickness
Moment of intertia
WWR

Material properties

U- value of facade
SHGC value
Visual transmittance
Thermal conductivity
Density

Structural parameters

- Bending stress
- Young's modulus
- Max. bending moment capacity
- Allowable deflection limit



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Visual transmittance
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Density

Structural parameters

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- Max. bending moment capacity
- Allowable deflection limit

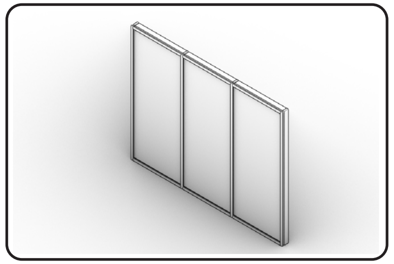
Hazard stressors

Heatwaves stressors

Outdoor temperature
Relative humidity
Duration
Wind speed

Flood stressors

Flow depth
Flow velocity
Flood duration
Debris content
Turbulance intensity



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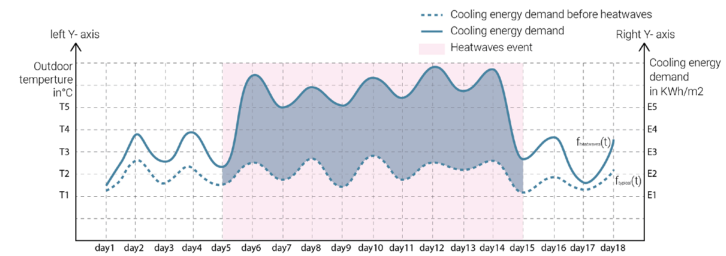
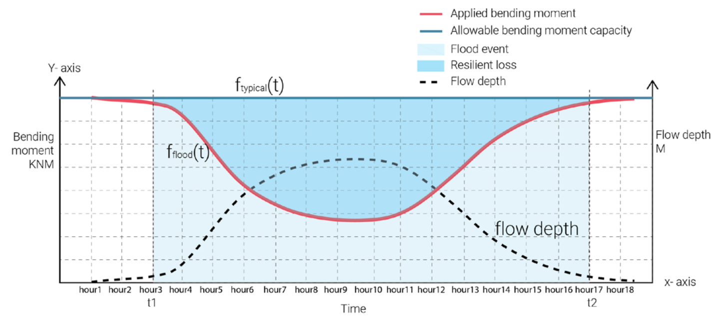
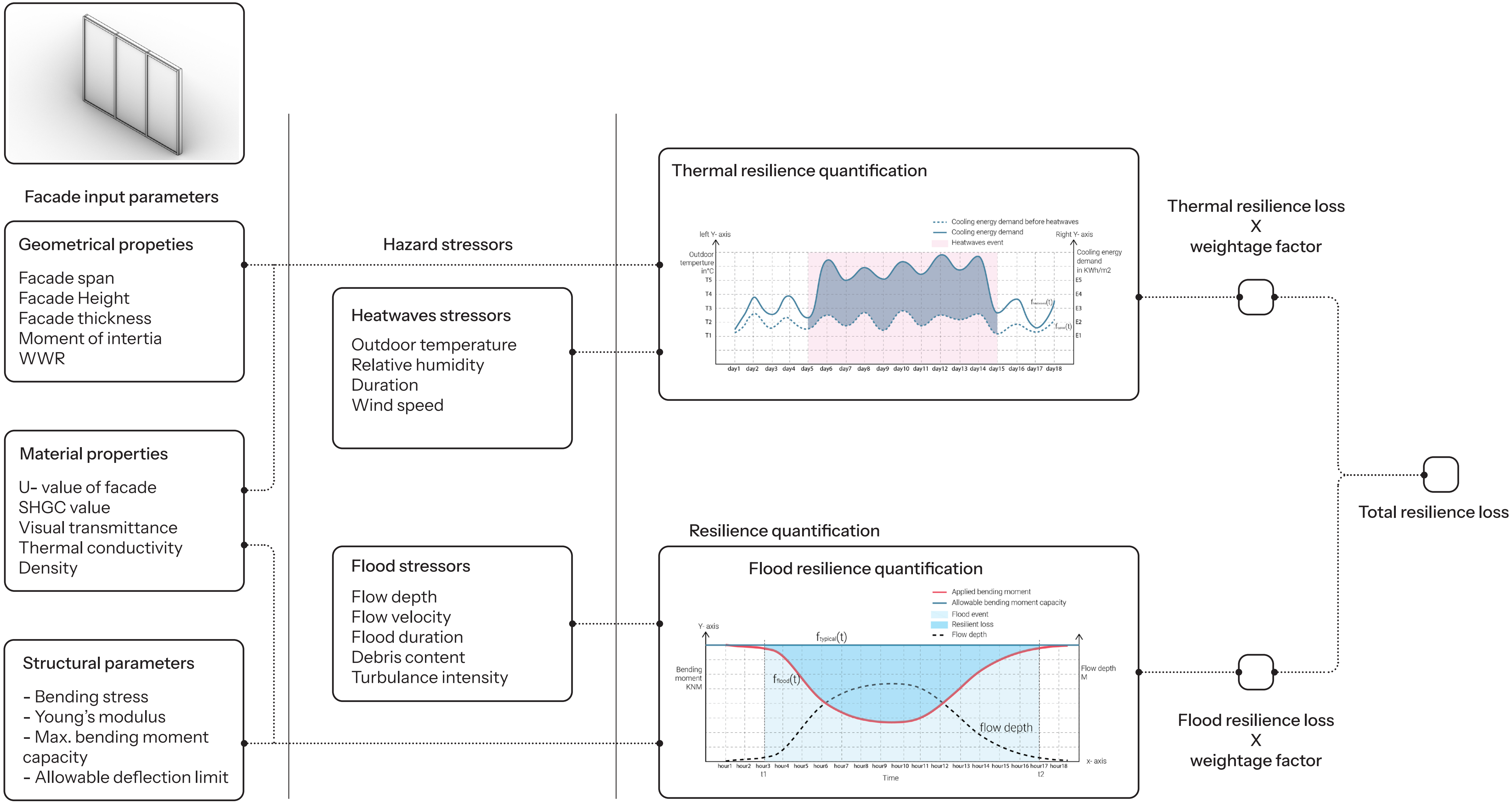
Thermal resilience quantification



Resilience quantification

Flood resilience quantification





Facade input parameters
Geometrical propeties
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Facade Height
Facade thickness
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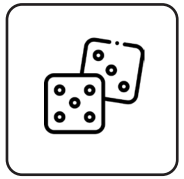
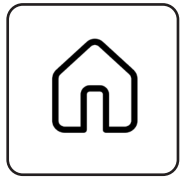
Relative humidity
Duration
Wind speed
Flood stressors
Flow depth
Flow velocity
Flood duration
Debris content
Turbulance intensity
Thermal resilience quantification
Cooling energy demand before heatwaves
Cooling energy demand
Heatwaves event
left Y- axis
Outdoor temperture in°C
T5
T4
T3
T2
T1
Right Y- axis
Cooling energy demand in KWh/m2
E5
E4
E3
E2
E1
$f_{heatwaves}(t)$
$f_{typical}(t)$
day1 day2 day3 day4 day5 day6 day7 day8 day9 day10 day11 day12 day13 day14 day15 day16 day17 day18
Resilience quantification
Flood resilience quantification
Applied bending moment
Allowable bending moment capacity
Flood event
Resilient loss
Flow depth
Y- axis
Bending moment KNM
$f_{typical}(t)$
$f_{flood}(t)$
flow depth
Flow depth M
x- axis
hour1 hour2 hour3 hour4 hour5 hour6 hour7 hour8 hour9 hour10 hour11 hour12 hour13 hour14 hour15 hour16 hour17 hour18
t1
t2
Time
Thermal resilience loss
X
weightage factor
Flood resilience loss
X
weightage factor
Total resilience loss

How to define weightage factor?

Liklihood of the hazard events



Liklihood of the hazard events

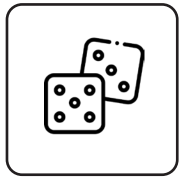


Building functionality

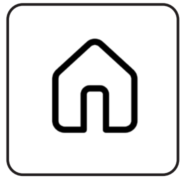
Liklihood of the hazard events

Building functionality

Building location

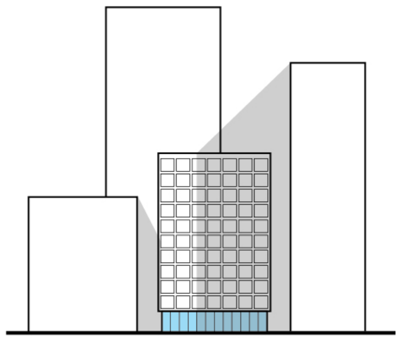


Liklihood of the hazard events



Building functionality

Building location



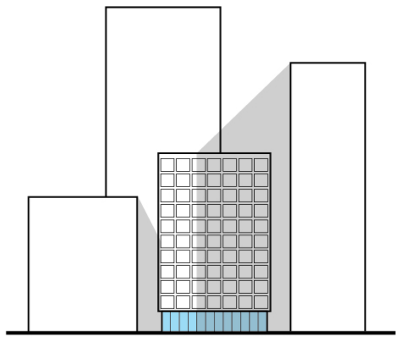
- Ground floor facade
- Facade is shaded by surrounding buildings

Flood resilience weightage factor > **Thermal resilience weightage factor**

Liklihood of the hazard events

Building functionality

Building location



- Ground floor facade
- Facade is shaded by surrounding buildings

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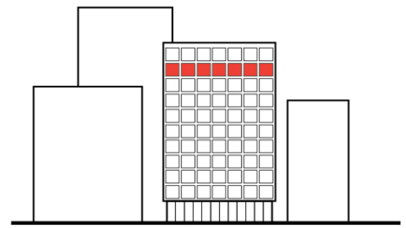

- Upper flood facade

Total resilience loss = Thermal resilience loss

Main research question

How can we **identify** the **optimal facade combination** that is **resilient against heatwaves** and **floods**?

Facade 1 - Single glazed facade

Facade input parameters

Geometrical propeties

- Facade span	3 m
- Facade Height	3.5 m
- Facade thickness	0.016m
- Moment of intertia	0.000001024 m4
- WWR	75%

Material properties

- U- value of facade	5.2 W/m2.K
- SHGC value	0.9
- Visual transmittance	0.8
- Thermal conductivity	0.8 W/m.K

Structural parameters

- Bending stress	32 MPa
- Young's modulus	72 GPa
- Max. bending moment capacity	9.216 KNm

Facade 1 - Single glazed facade

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- Young's modulus	72 GPa
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Hazard intensity

Flood stressors

Flow depth	0 - 1.5m
Flow velocity	2 m/s
Flood duration	20 hours
Debris content	1800 kg/m3

Heatwaves stressors

Outdoor temperature	Chennai heatwaves
Relative humidity	2021 weather data
Duration	(EPW file)
Wind speed	

Facade 1 - Single glazed facade

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Outdoor temperature	Chennai heatwaves
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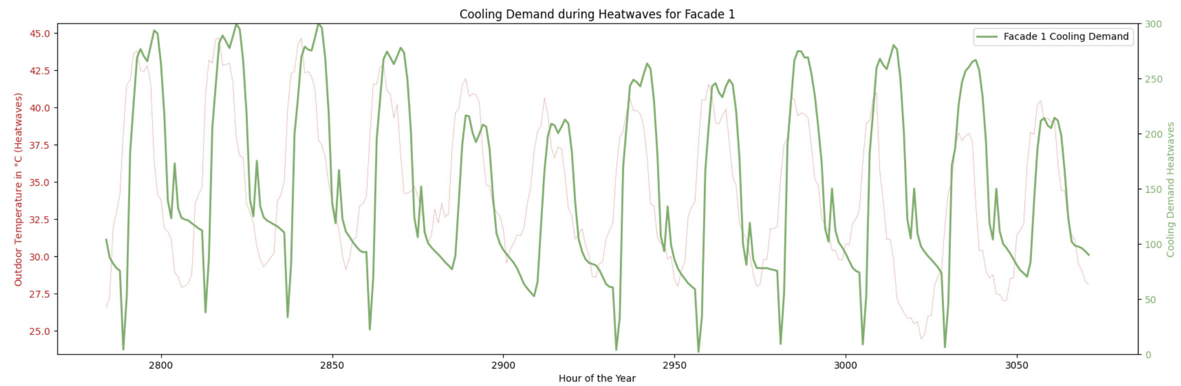
Duration	(EPW file)
Wind speed	



Thermal resilience loss = **14452** **(47.9%)**

Facade 1 - Single glazed facade

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- Facade span	3 m
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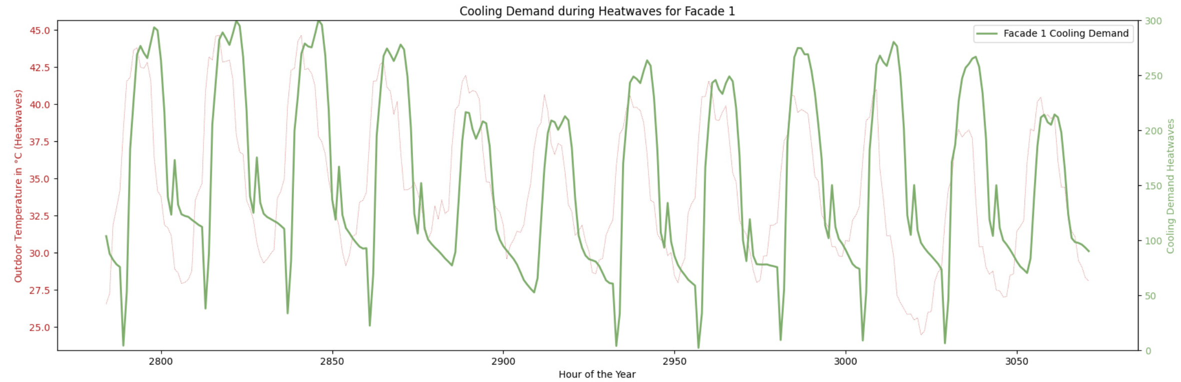
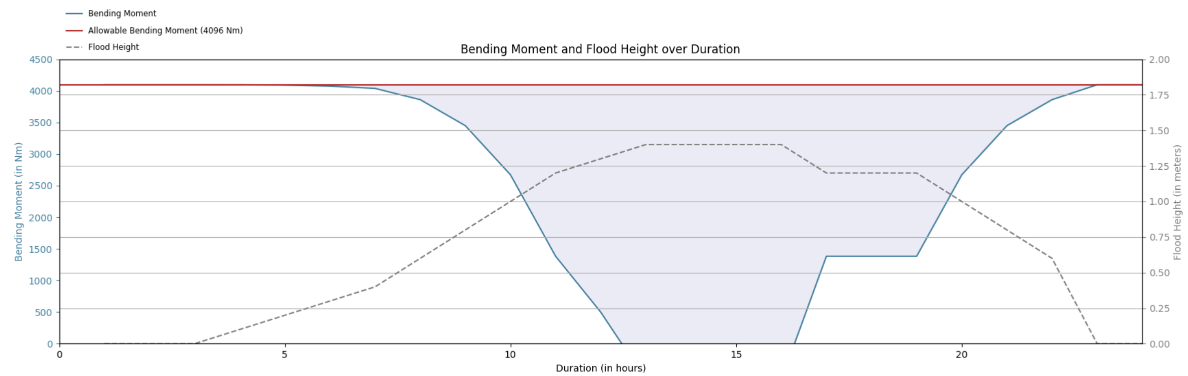
Relative humidity	2021 weather data
Duration	(EPW file)
Wind speed	



Thermal resilience loss = **14452** **(47.9%)**



Flood resilience loss = **not resilient** **(100%)**

Facade 1 - Single glazed facade

Facade input parameters

Geometrical propeties

- Facade span	3 m
- Facade Height	3.5 m
- Facade thickness	0.016m
- Moment of intertia	0.000001024 m4
- WWR	75%

Material properties

- U- value of facade	5.2 W/m2.K
- SHGC value	0.9
- Visual transmittance	0.8
- Thermal conductivity	0.8 W/m.K

Structural parameters

- Bending stress	32 MPa
- Young's modulus	72 GPa
- Max. bending moment capacity	9.216 KNm

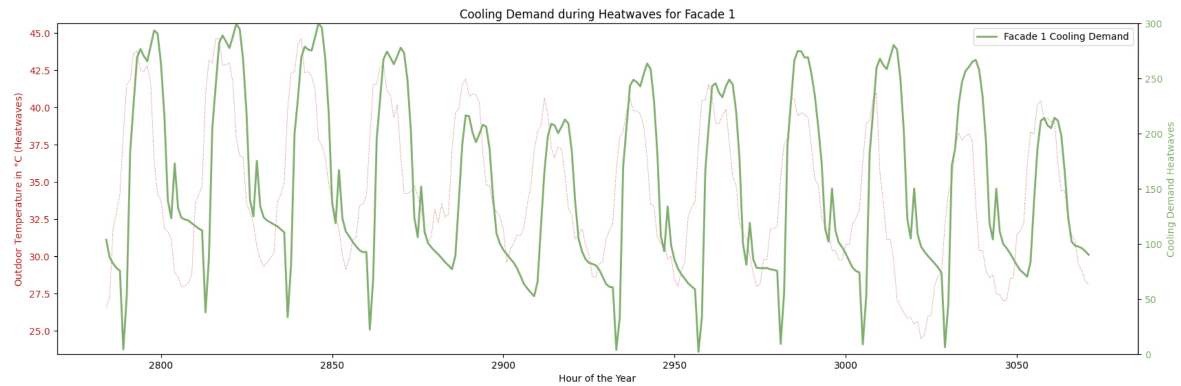
Hazard intensity

Flood stressors

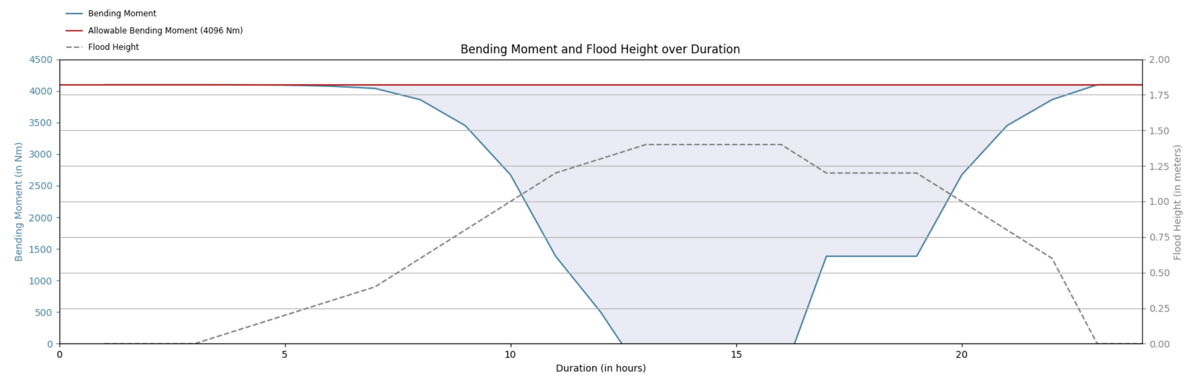
Flow depth	0 - 1.5m
Flow velocity	2 m/s
Flood duration	20 hours
Debris content	1800 kg/m3

Heatwaves stressors

Outdoor temperature	Chennai heatwaves
Relative humidity	2021 weather data
Duration	(EPW file)
Wind speed	



Thermal resilience loss = **14452** **(47.9%)**



Flood resilience loss = **not resilient** **(100%)**

Heatwaves resilience weightage factor	Flood resilience weightage factor	**Total resilience loss**
0.7	**0.3**	**63.55 %**
0.5	**0.5**	**73.95 %**
0.3	**0.7**	**84.37 %**

Facade 2 - Double glazed facade

Facade input parameters

Geometrical propeties

- Facade span — 2 m
- Facade Height — 4.5 m
- Facade thickness — 0.024m
- Moment of intertia — 0.000002304m4
- WWR — 75%

Material properties

- U- value of facade — 3.2 W/m2.K
- SHGC value — 0.5
- Visual transmittance — 0.5
- Thermal conductivity — 0.8 W/m.K

Structural parameters

- Bending stress — 34 MPa
- Young's modulus — 72 GPa
- Max. bending moment capacity — 6.528 KNm

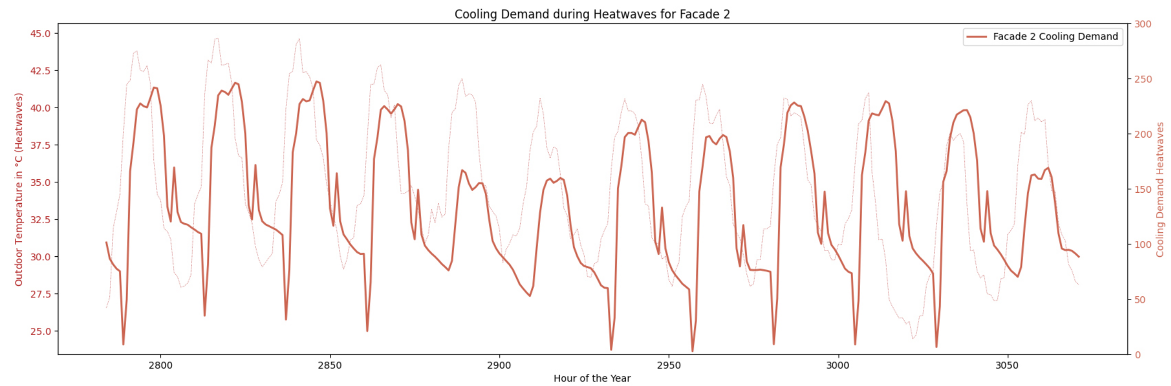
Hazard intensity

Flood stressors

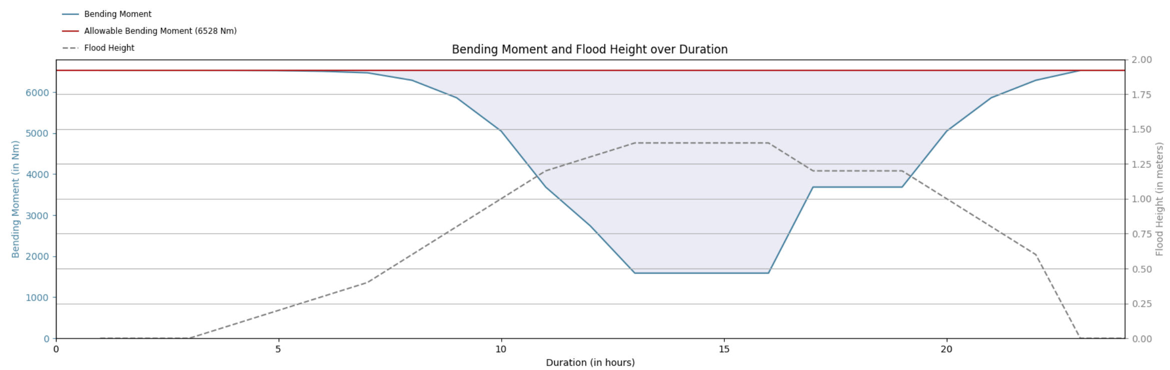
Flow depth	0 - 1.5m
Flow velocity	2 m/s
Flood duration	20 hours
Debris content	1800 kg/m3

Heatwaves stressors

Outdoor temperature	Chennai heatwaves
Relative humidity	2021 weather data
Duration	(EPW file)
Wind speed	



Thermal resilience loss = **14452** **(29.56%)**



Flood resilience loss = **39764.70** **(38%)**

Heatwaves resilience weightage factor	Flood resilience weightage factor	**Total resilience loss**
0.7	**0.3**	**32.09 %**
0.5	**0.5**	**33.78 %**
0.3	**0.7**	**35.46 %**

Facade 3 - Triple glazed facade

Facade input parameters

Geometrical propeties

- Facade span 1.2 m
- Facade Height 3 m
- Facade thickness 0.036m
- Moment of intertia 0.00000466 m4
- WWR 75%

Material properties

- U- value of facade 0.8 W/m2.K
- SHGC value 0.1
- Visual transmittance 0.1
- Thermal conductivity 0.8 W/m.K

Structural parameters

- Bending stress 36 MPa
- Young's modulus 72 GPa
- Max. bending moment capacity 9.331 KNm

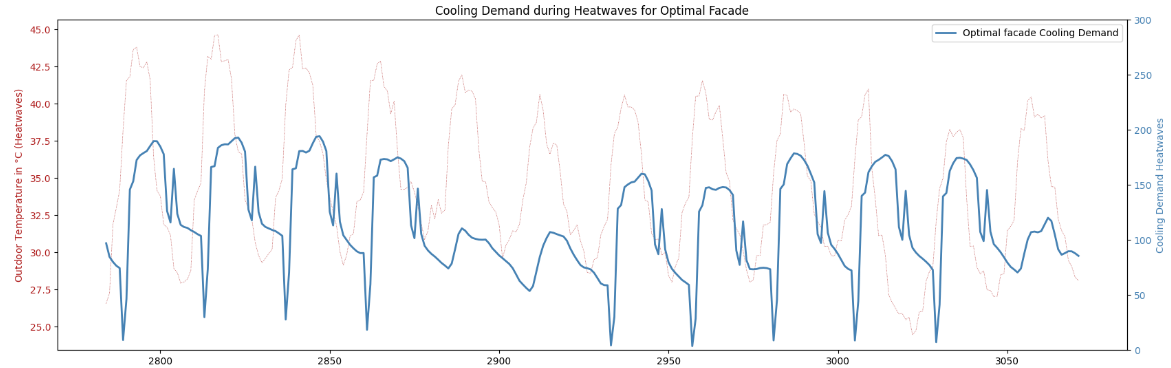
Hazard intensity

Flood stressors

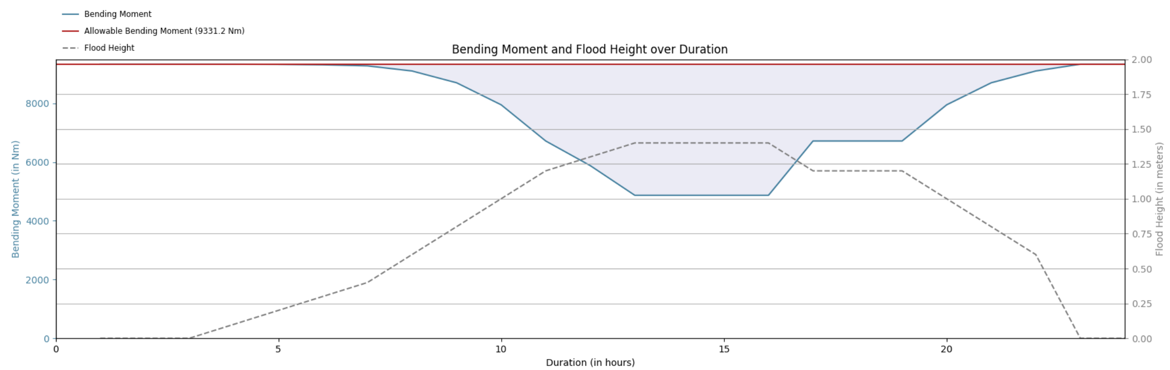
Flow depth 0 - 1.5m
Flow velocity 2 m/s
Flood duration 20 hours
Debris content 1800 kg/m3

Heatwaves stressors

Outdoor temperature Chennai heatwaves
Relative humidity 2021 weather data
Duration (EPW file)
Wind speed

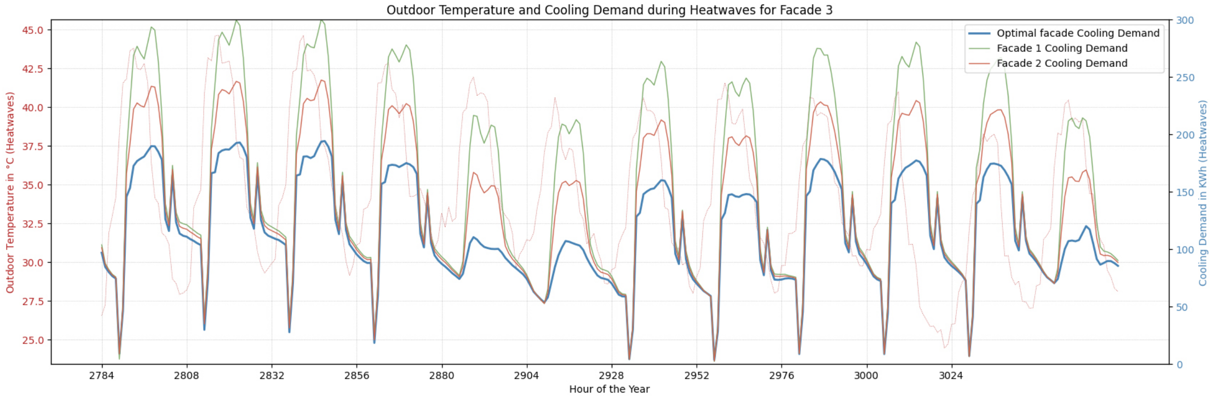


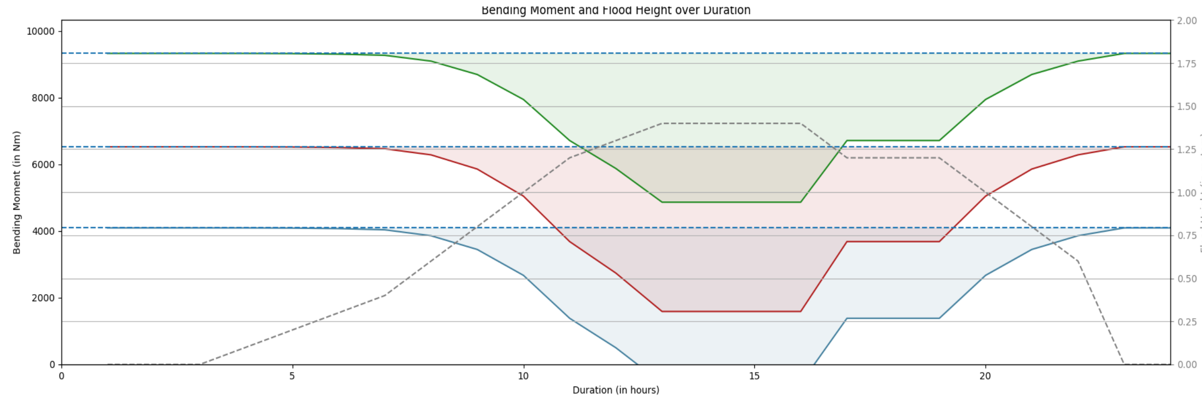
Thermal resilience loss = **2770** **(9.19 %)**

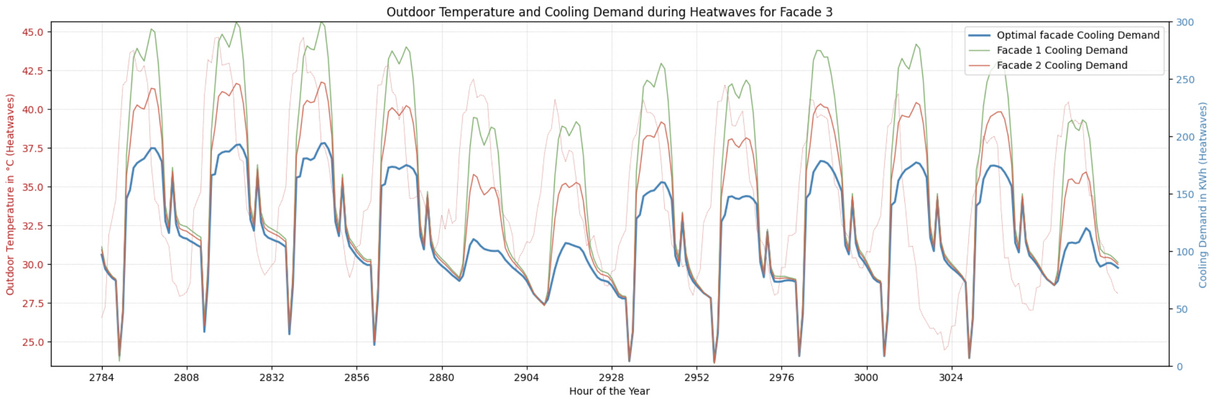


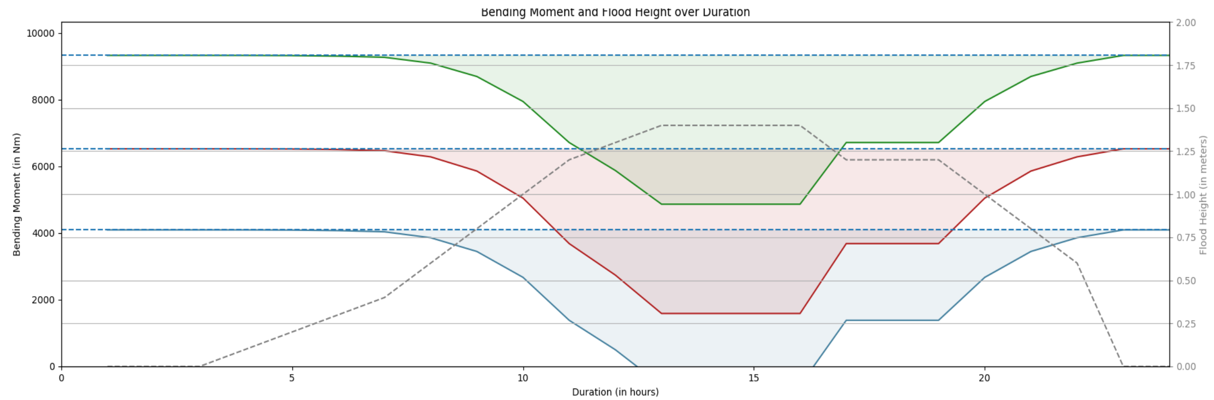
Flood resilience loss = **36328.40** **(21.6 %)**

Heatwaves resilience weightage factor	Flood resilience weightage factor	**Total resilience loss**
0.7	**0.3**	**12.91 %**
0.5	**0.5**	**15.39 %**
0.3	**0.7**	**17.81 %**

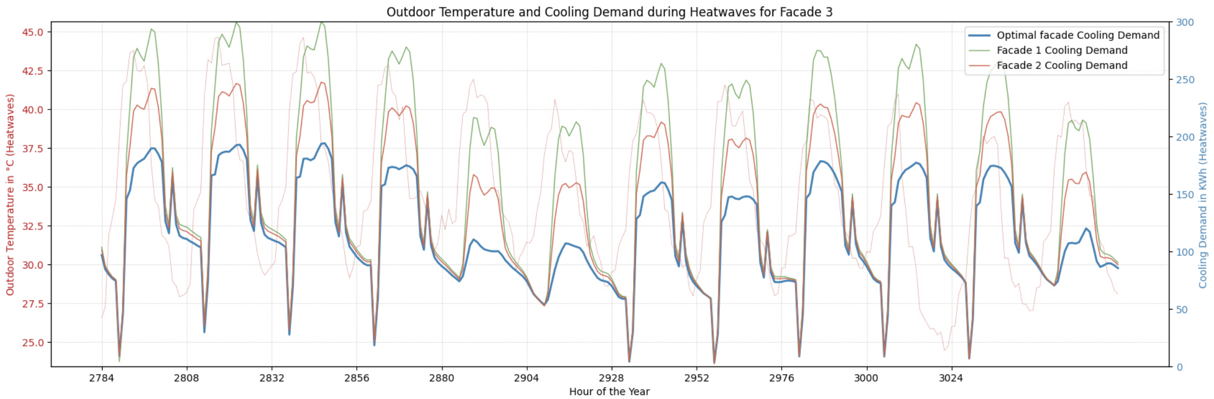

Outdoor Temperature and Cooling Demand during Heatwaves for Facade 3
Optimal facade Cooling Demand
Facade 1 Cooling Demand
Facade 2 Cooling Demand
Outdoor Temperature in °C (Heatwaves)
Cooling Demand in KWh (Heatwaves)
Hour of the Year

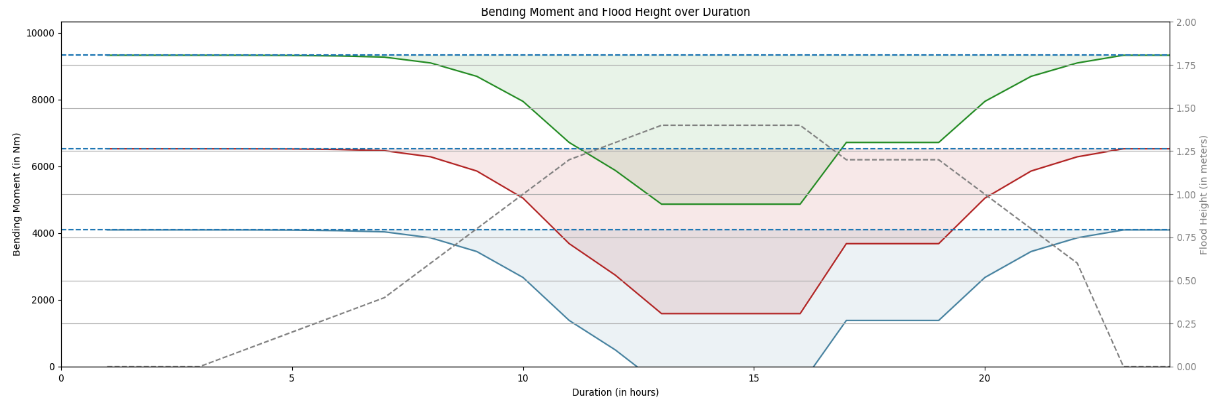

Bending Moment and Flood Height over Duration
Bending Moment (in Nm)
Flood Height (in meters)
Duration (in hours)





Facade type	Heatwaves resilience loss	Flood resilience loss	**Total resilience loss**	
Facade 1 (Single glazed facade)	**47.9 %**	**100 %**	**63.55 %**	**(HR: FR = 0.7 : 0.3)**
			73.95 %	**(HR: FR = 0.5 : 0.5)**
			84.37 %	**(HR: FR = 0.3 : 0.7)**
Facade 2 (Double glazed facade)	**29.56 %**	**38 %**	**32.09 %**	**(HR: FR = 0.7 : 0.3)**
			33.78 %	**(HR: FR = 0.5 : 0.5)**
			35.46 %	**(HR: FR = 0.3 : 0.7)**
Facade 3 (Triple glazed facade)	**9.19 %**	**21.6 %**	**12.91 %**	**(HR: FR = 0.7 : 0.3)**
			15.39 %	**(HR: FR = 0.5 : 0.5)**
			17.81 %	**(HR: FR = 0.3 : 0.7)**

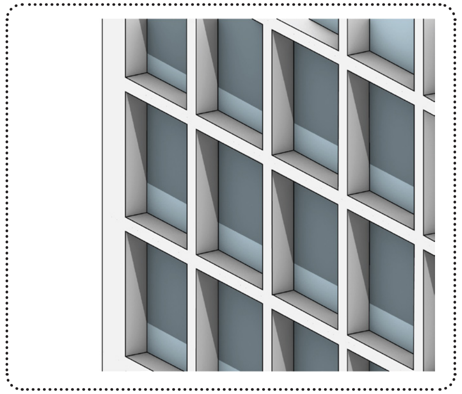




Facade type	Heatwaves resilience loss	Flood resilience loss	**Total resilience loss**		
Facade 1 (Single glazed facade)	47.9 %	100 %	63.55 %	(HR: FR = 0.7 : 0.3)	
			73.95 %	(HR: FR = 0.5 : 0.5)	
			84.37 %	(HR: FR = 0.3 : 0.7)	
Facade 2 (Double glazed facade)	29.56 %	38 %	32.09 %	(HR: FR = 0.7 : 0.3)	
			33.78 %	(HR: FR = 0.5 : 0.5)	
			35.46 %	(HR: FR = 0.3 : 0.7)	
Facade 3 (Triple glazed facade)	**9.19 %**	**21.6 %**	**12.91 %**	**(HR: FR = 0.7 : 0.3)**	**Optimal facade**
			15.39 %	**(HR: FR = 0.5 : 0.5)**	
			17.81 %	**(HR: FR = 0.3 : 0.7)**	

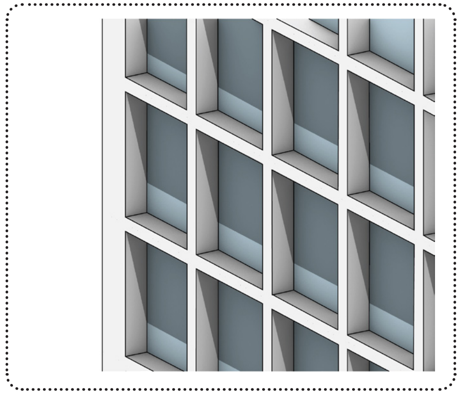
Design recommandations

Thermal resilience design

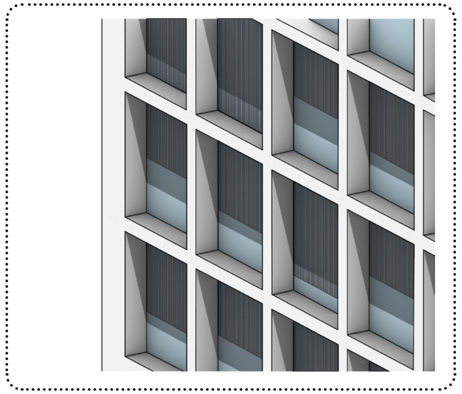


Use Horizontal and Vertical Shading Devices

Thermal resilience design

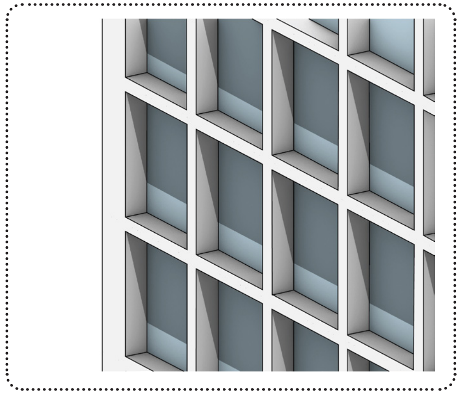


Use Horizontal and Vertical Shading Devices

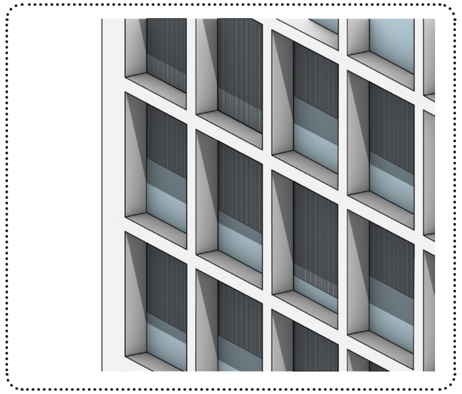


Use Automated blinds

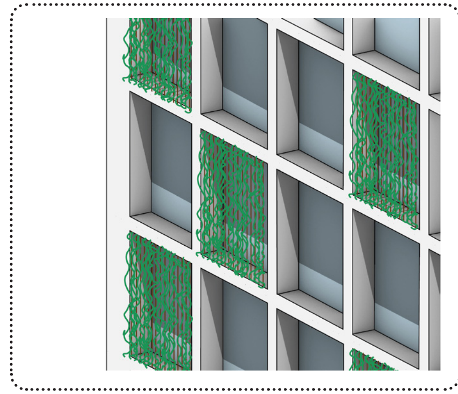
Thermal resilience design



Use Horizontal and Vertical Shading Devices

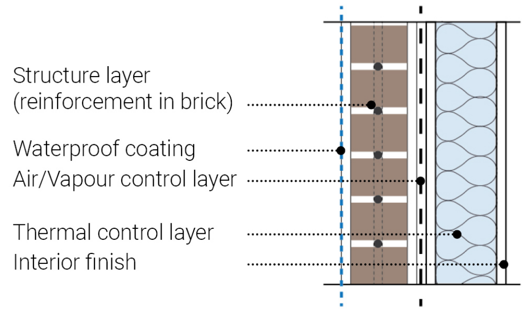


Use Automated blinds



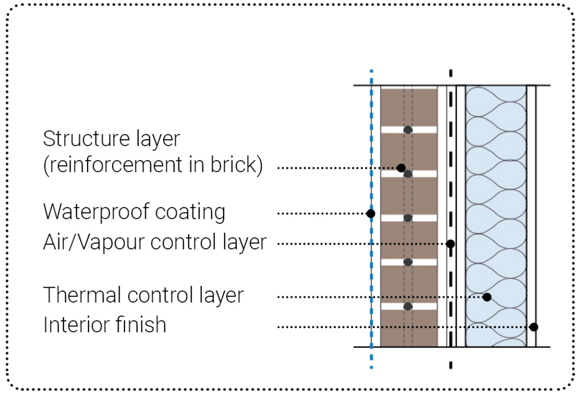
Green facade

Flood resilience design

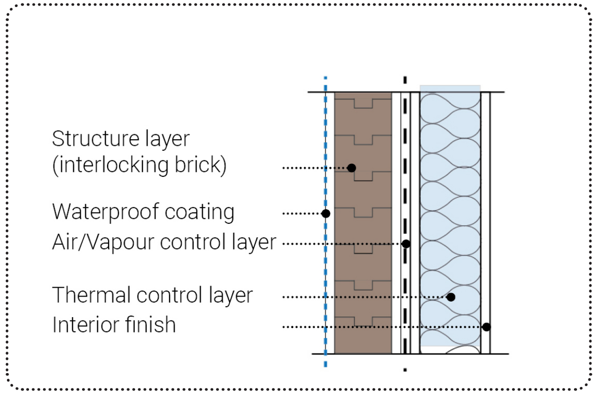


Use reinforcement in opeaque wall

Flood resilience design

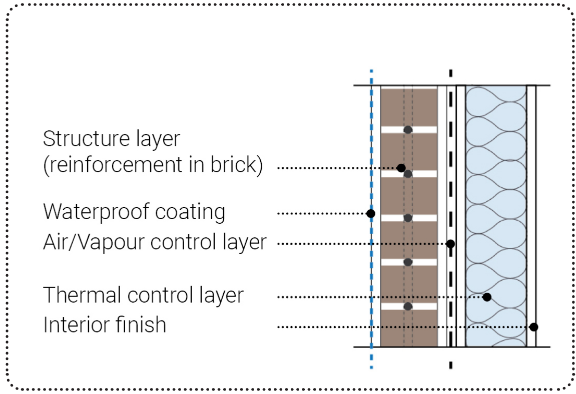


Use reinforcement in opeaque wall



Use interlocking blocks

Flood resilience design



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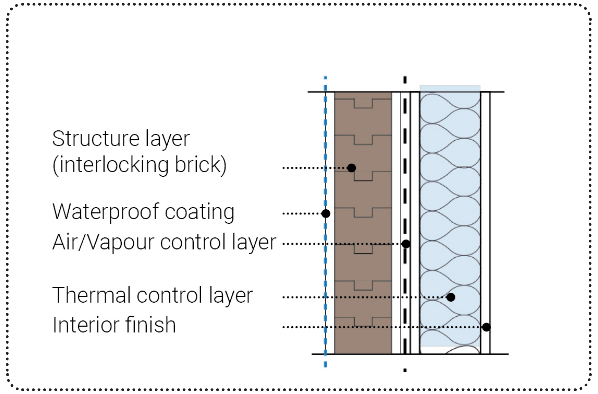
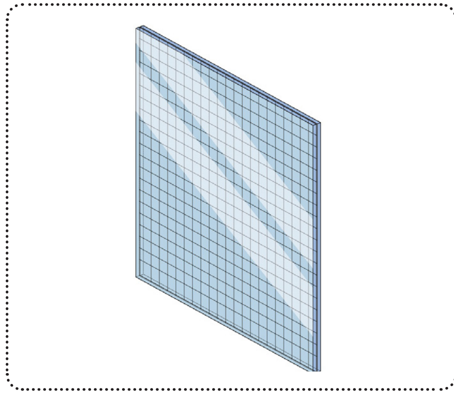
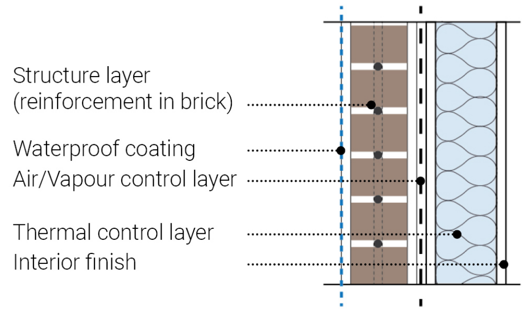


Use interlocking blocks

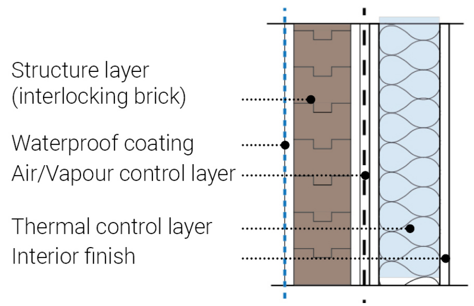


Use laminated reinforced glass

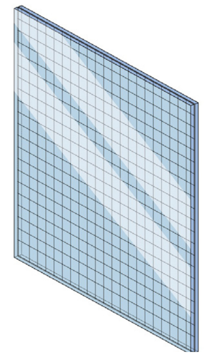
Flood resilience design



Use reinforcement in opeaque wall



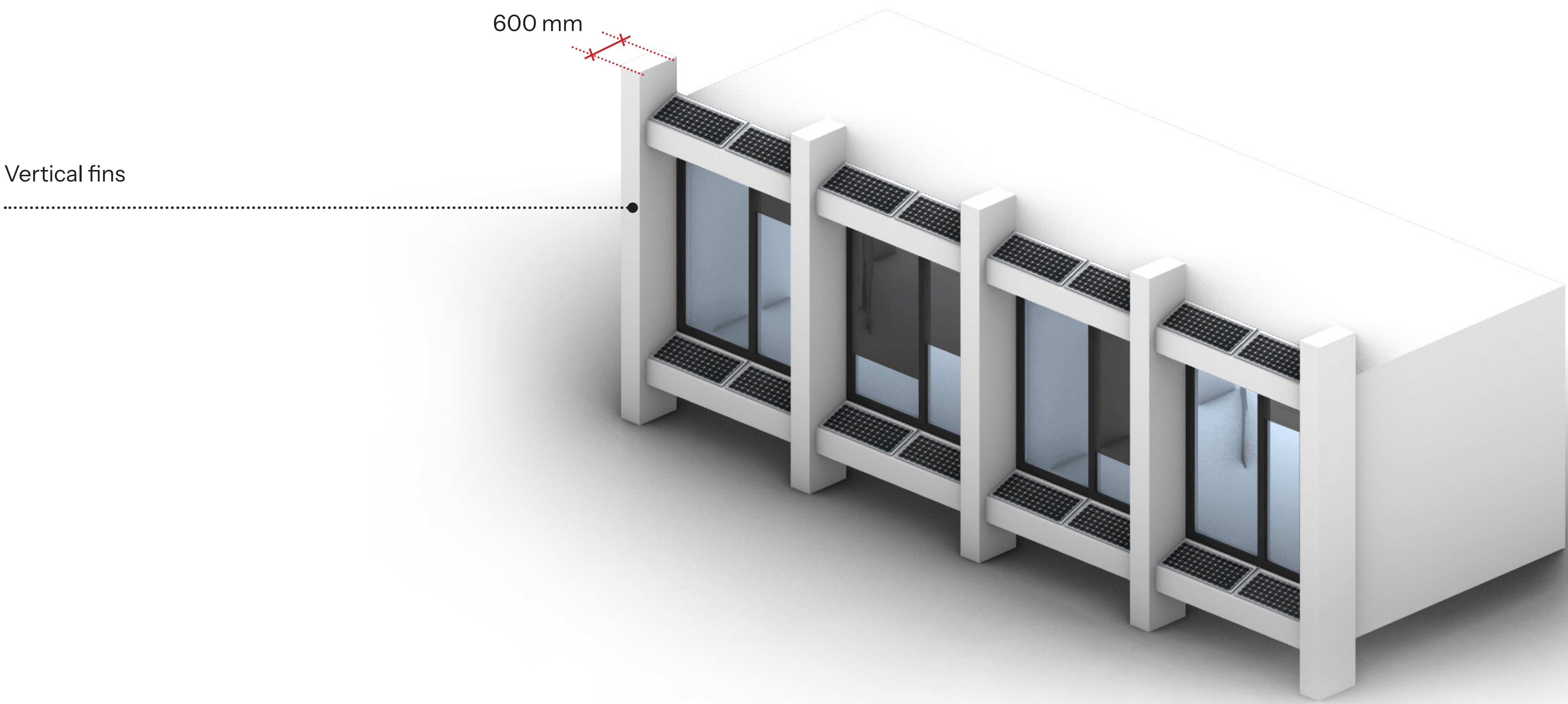
Use interlocking blocks



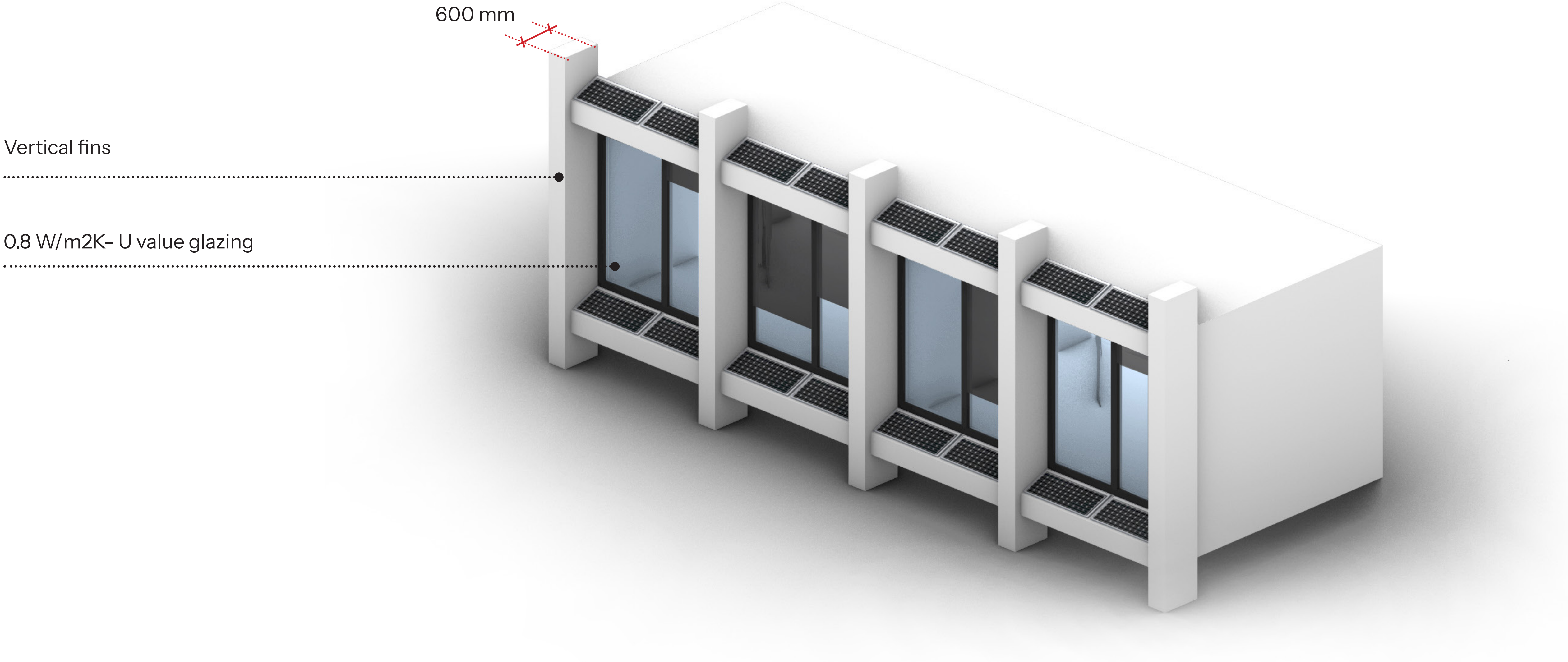
Use laminated reinforced glass

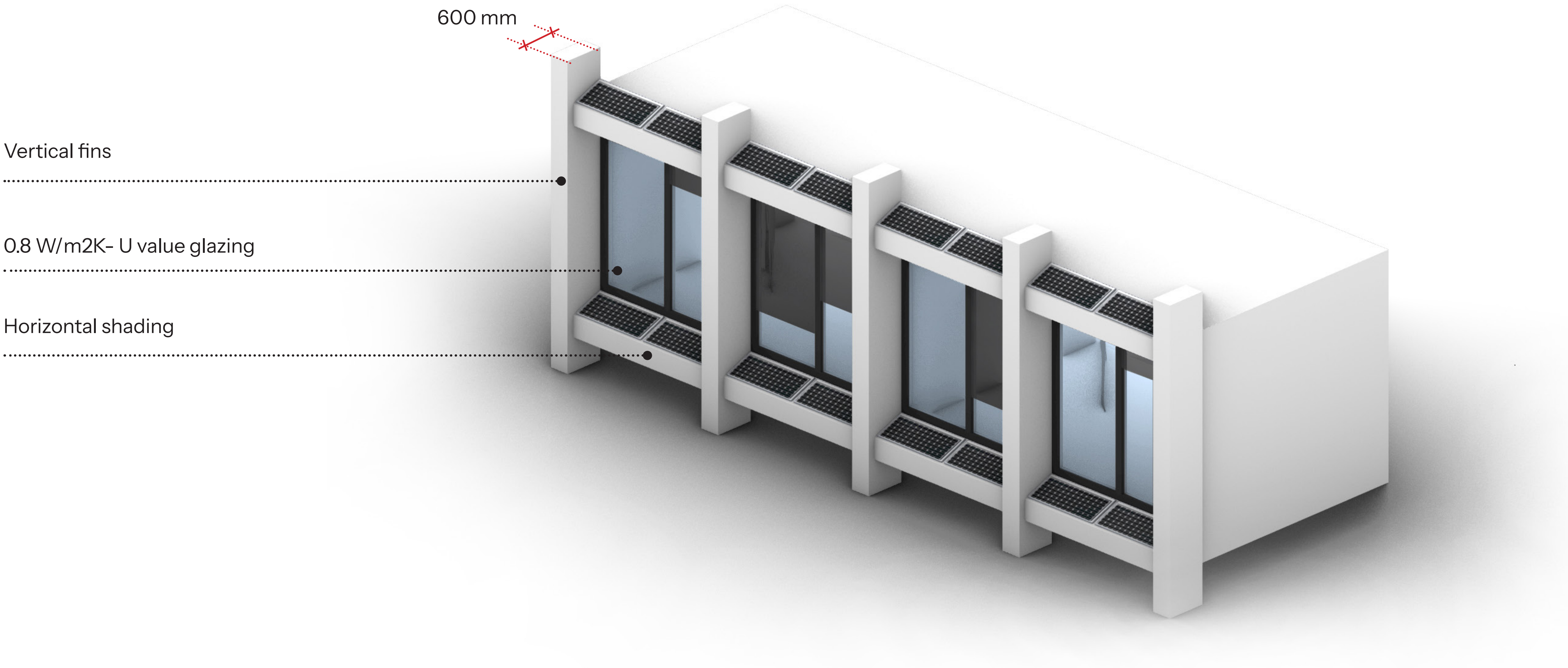
Use flood protection system in vulnerable points of the building

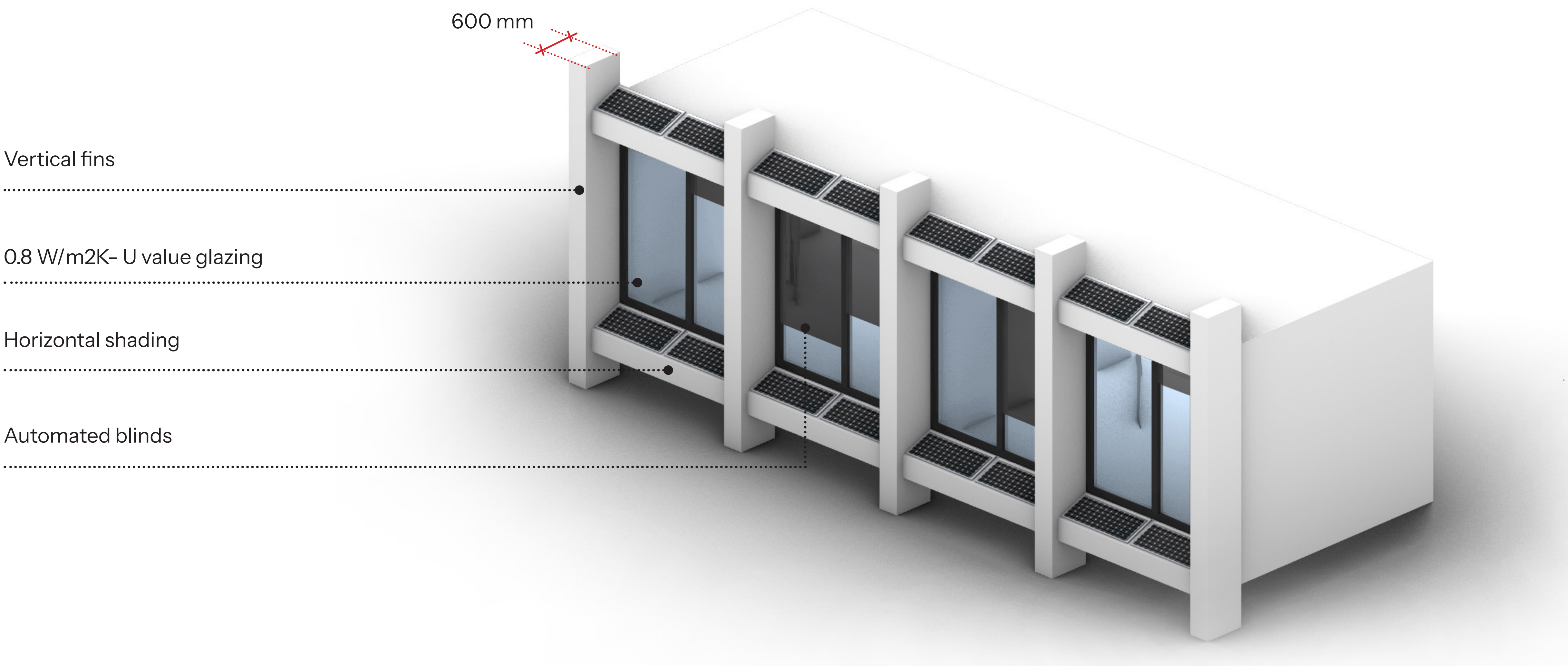
Resilient facade design

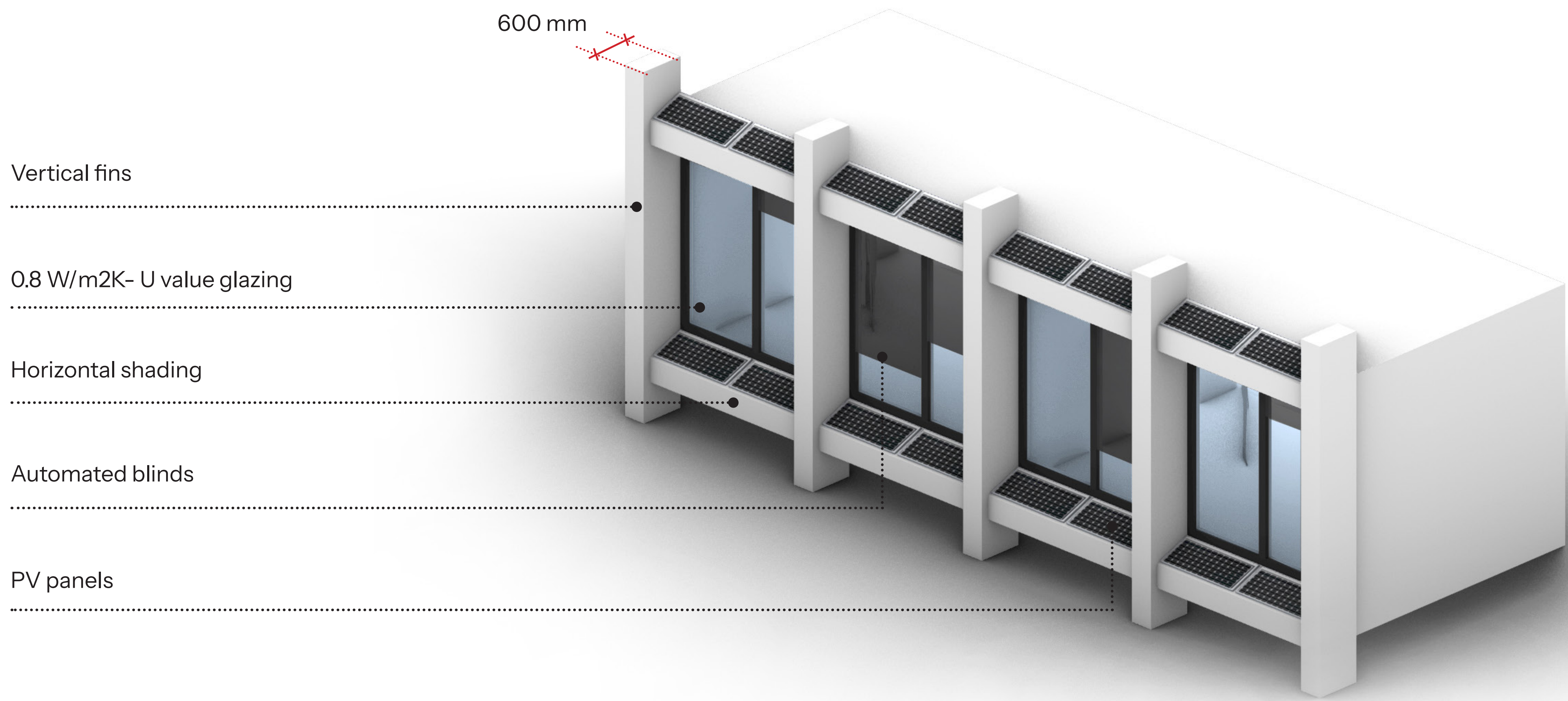


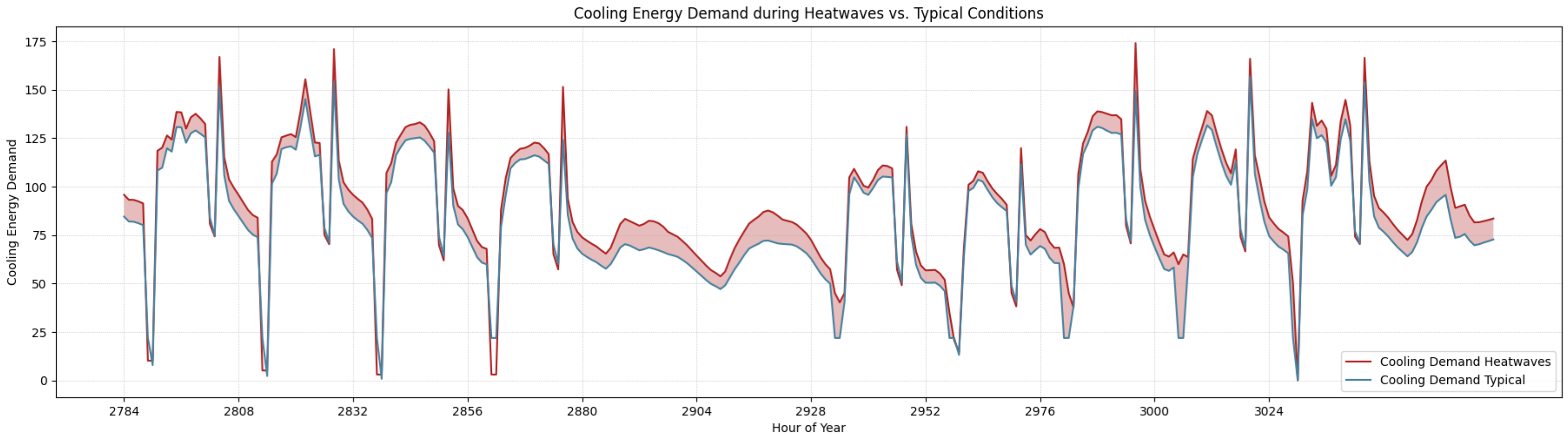
600 mm
Vertical fins


600 mm
Vertical fins
0.8 W/m2K- U value glazing


600 mm
Vertical fins
0.8 W/m2K- U value glazing
Horizontal shading


600 mm
Vertical fins
0.8 W/m2K- U value glazing
Horizontal shading
Automated blinds


600 mm
Vertical fins
0.8 W/m2K- U value glazing
Horizontal shading
Automated blinds
PV panels



Resilience loss in designed facade

$$\text{Resilience loss} = \int_{t_1}^{t_2} \left(f_{\text{heatwaves}}(t) - f_{\text{typical}}(t)\right)\, dt$$
$$= 26173.94 - 23805.02$$
$$= 2368.92 \quad \text{(around 11\% resilience loss)}$$

Key findings

Providing a framework for designers to assess the resilience of facades against floods and heatwaves.

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- [ ] Providing a resilience matrix for multi-hazard scenarios.

Further research

A tool/webpage can be developed for a simplified workflow

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- [ ] Can be implemented to the urban scale

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- [ ] More hazards can be included in order to quantify the resilience.

Thank you | Q&A

Presentation- 4

Graduation Project
Msc Building Technology track
Delft University of Technology

Student
Aashish Sadaphal

Mentor
Dr. Simona Bianchi (First Mentor)
Dr. Alessandra Luna Navarro (Second Mentor)

Delegate
Henriette H. Bier