Quantification of thermal resilience in buildings

Evaluation of Building Envelope Performance and Operational Parameters

Building Technology Graduation Project

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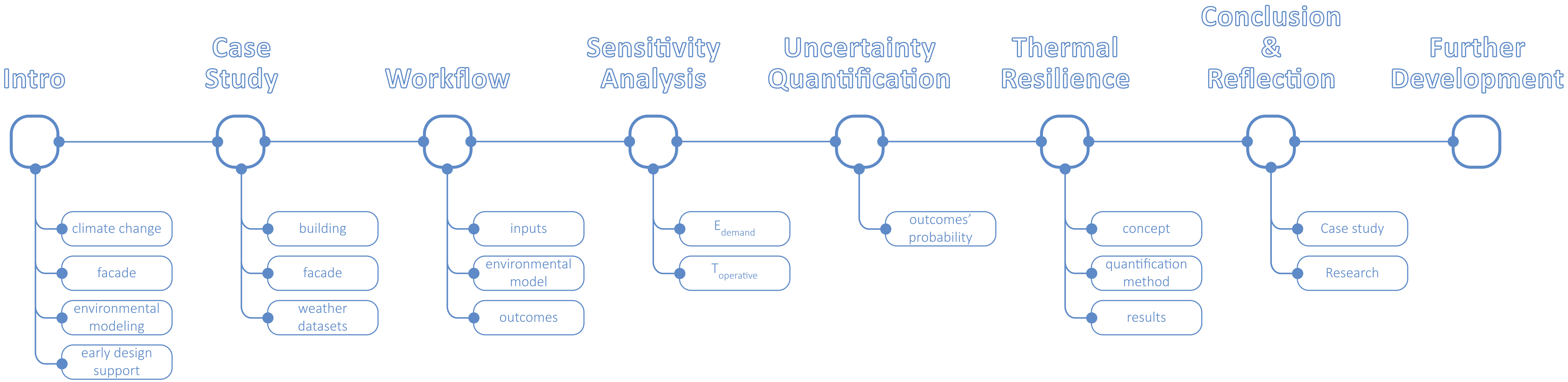
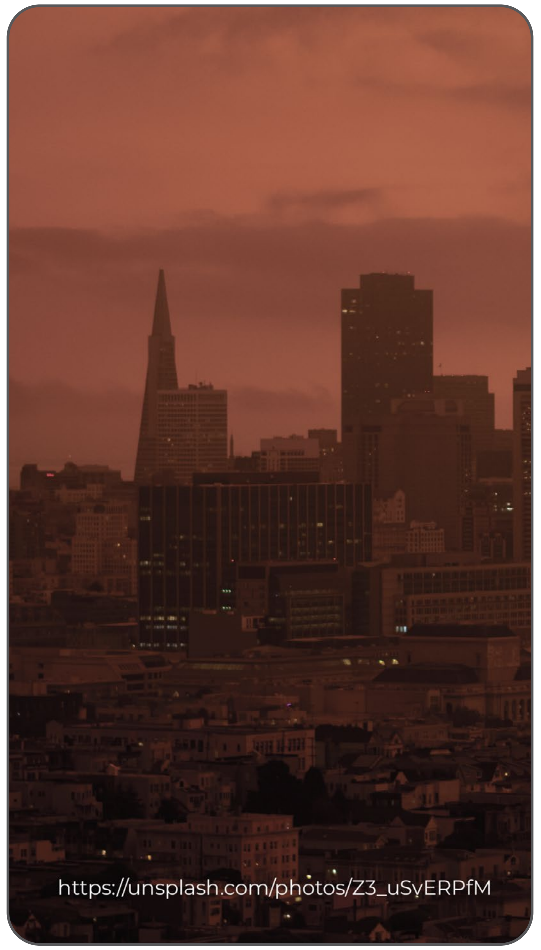
"I am developing a **dynamic** computational **workflow**, that can be utilized at the **early stage** of the design process, for assessing the **thermal resilience** of buildings against extreme over heat stresses, by alternating building's and material **properties**."


Intro
climate change
facade
environmental modeling
early design support
Case Study
building
facade
weather datasets
Workflow
inputs
environmental model
outcomes
Sensitivity Analysis
E_{demand}
$T_{operative}$
Uncertainty Quantification
outcomes' probability
Thermal Resilience
concept
quantification method
results
Conclusion & Reflection
Case study
Research
Further Development

Climate Change
&
Early Design Support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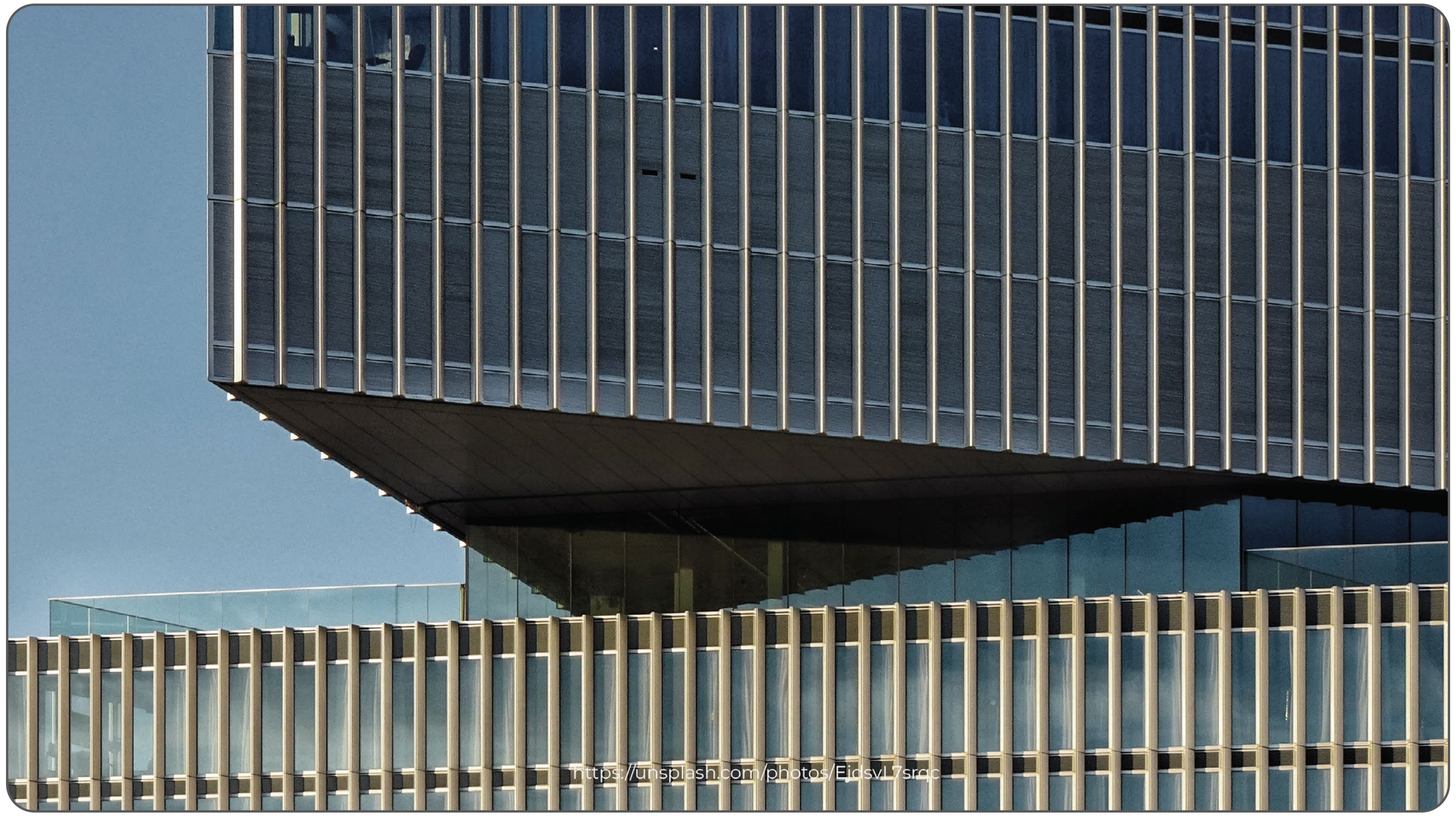
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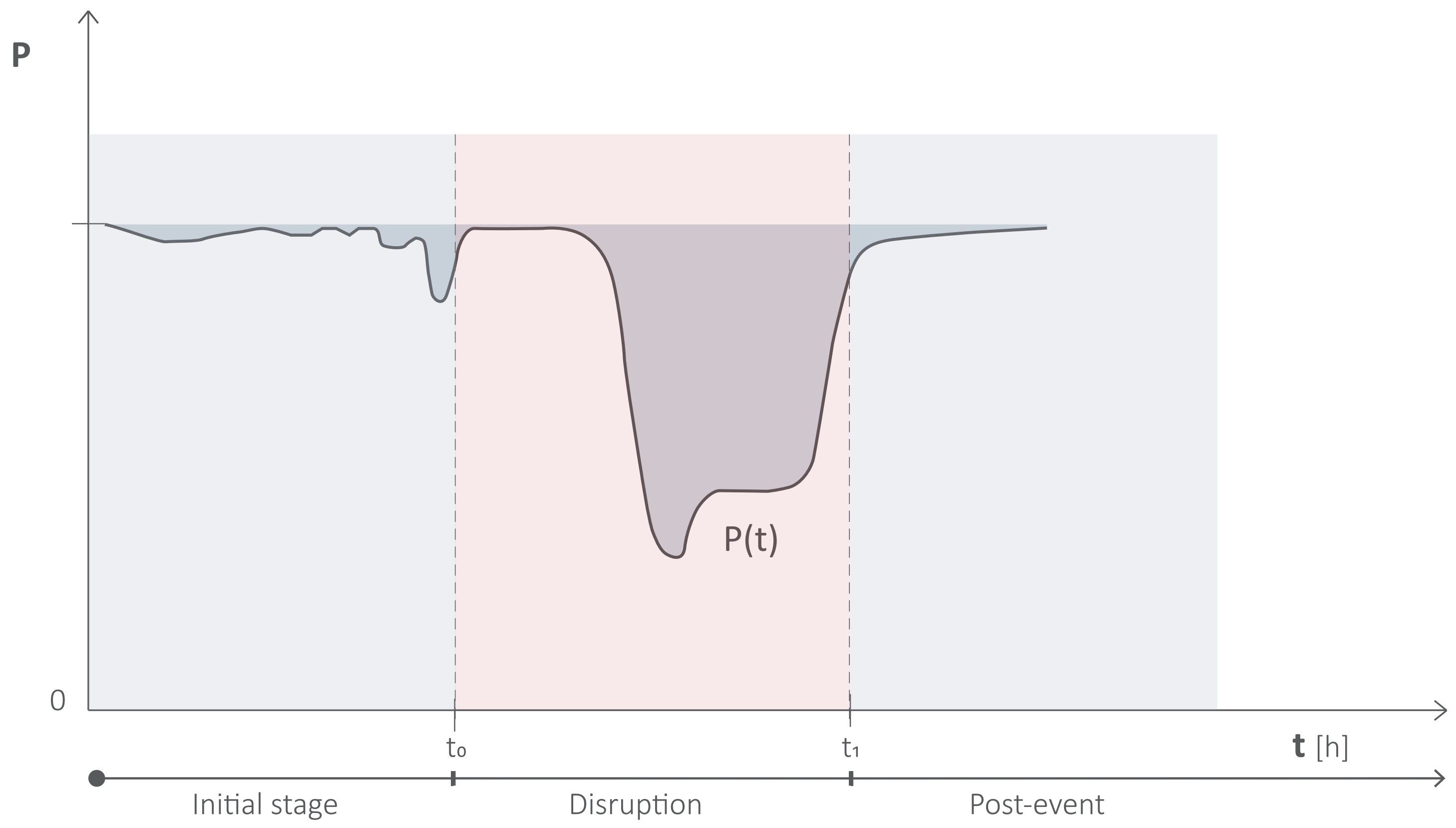
Definition

"Thermal resilience is the capability of the building to prepare, absorb, adapt and recover from overheating events."



Definition

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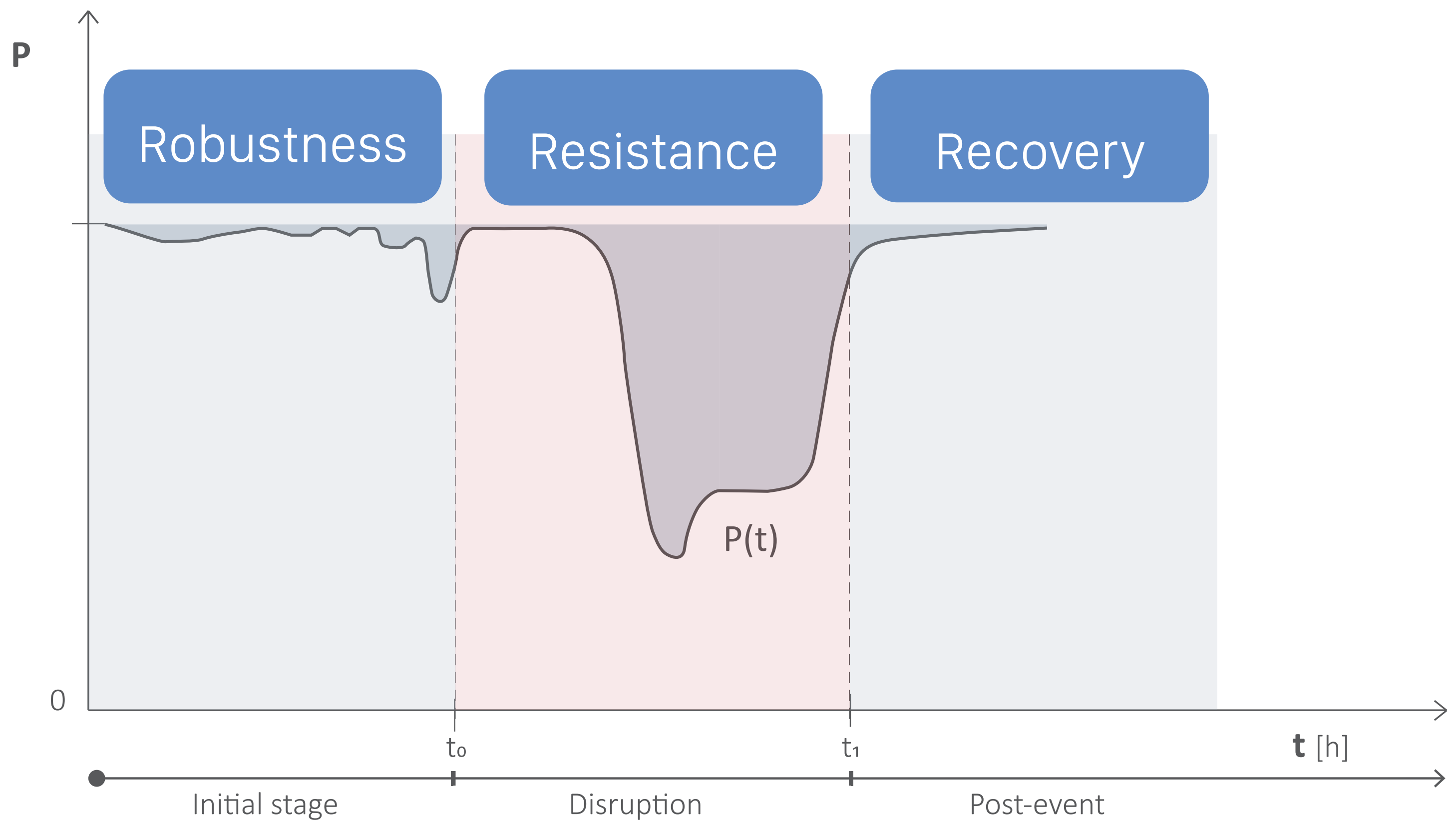
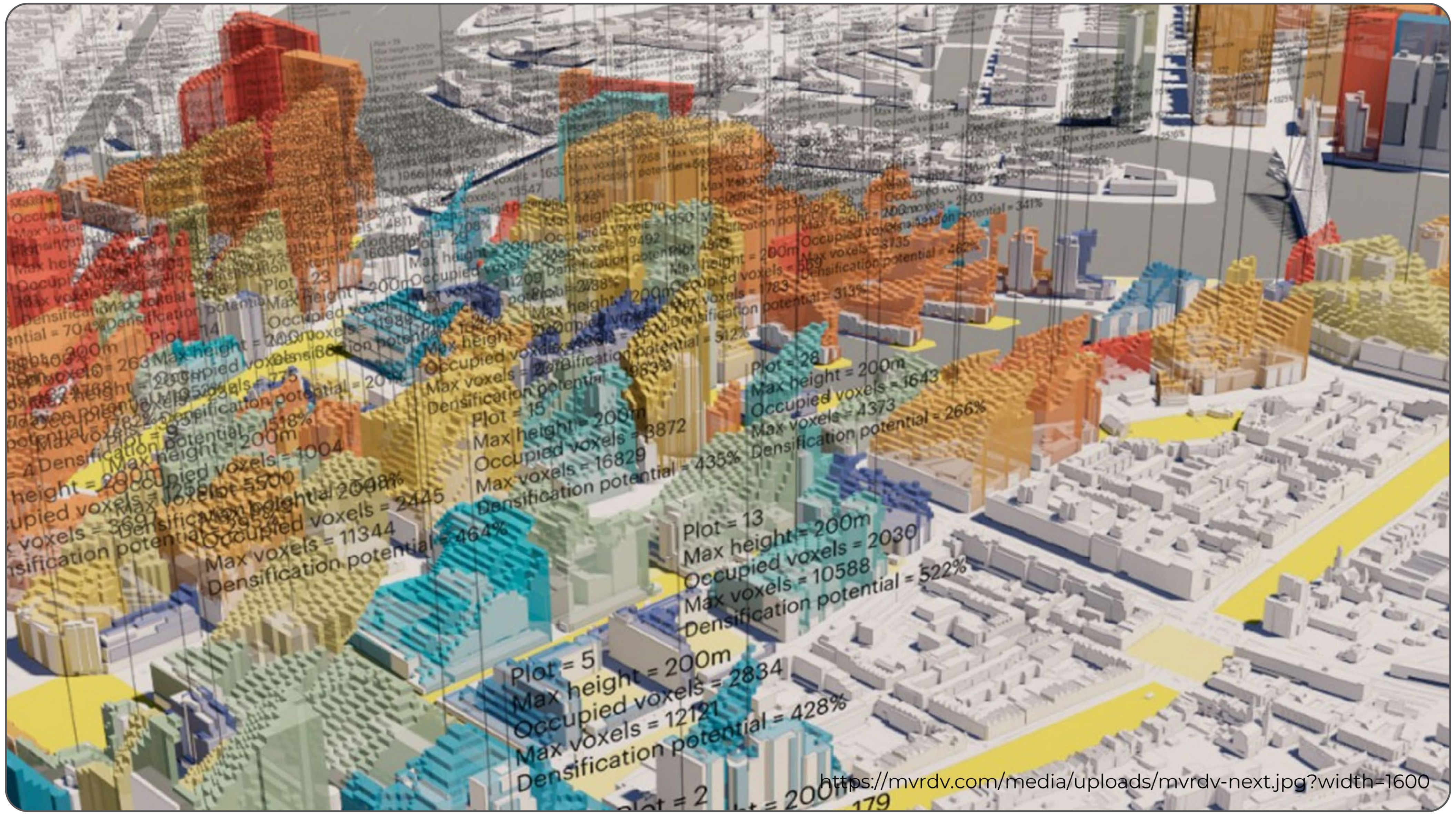
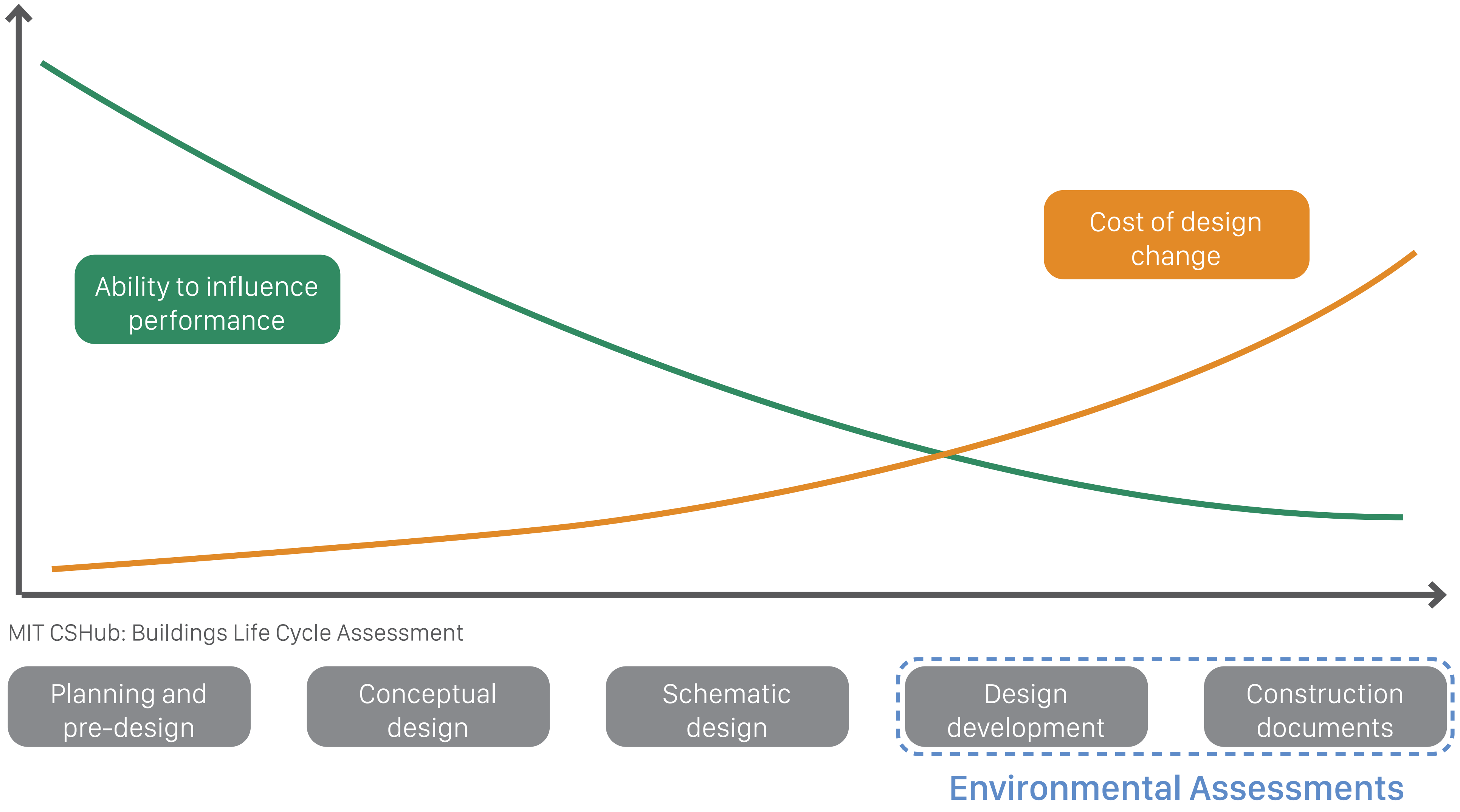


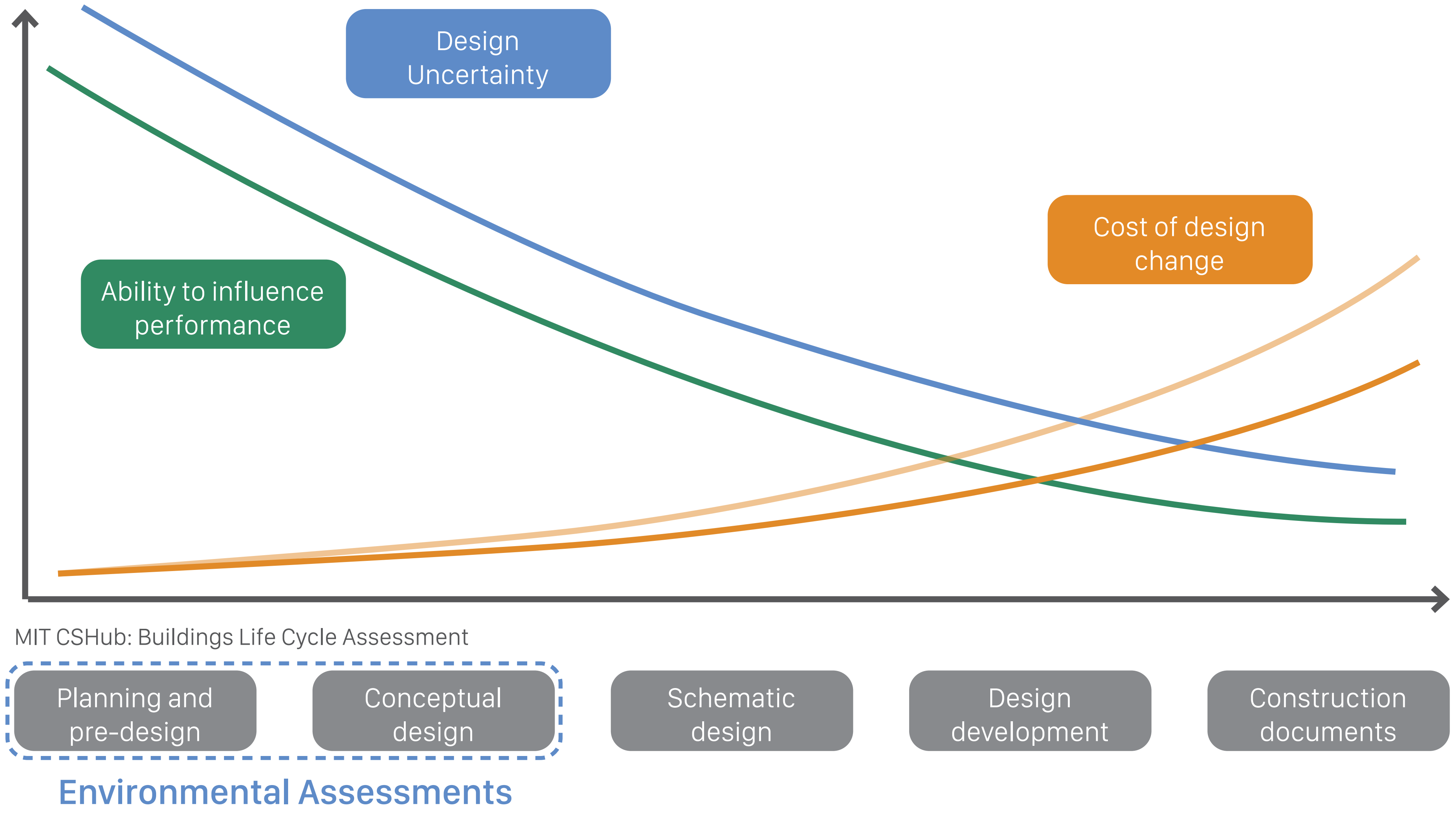
Key Performance Indicators

Indoor comfort

Energy Demand




Ability to influence performance
Cost of design change
MIT CSHub: Buildings Life Cycle Assessment
Planning and pre-design
Conceptual design
Schematic design
Design development
Construction documents
Environmental Assessments


Design
Uncertainty
Ability to influence
performance
Cost of design
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MIT CSHub: Buildings Life Cycle Assessment
Planning and
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Conceptual
design
Schematic
design
Design
development
Construction
documents
Environmental Assessments

gain new knowledge regarding the field of **thermal resilience** in buildings by pointing out the thermal resilience **definition** and its **indicators** that should be quantified

implement **uncertainty quantification** method in order to point out the **probability of results**

define a **computational workflow** for assessing thermal resilience of buildings against overheating via dynamic environmental simulation method

bridge the gap between qualitative and **quantitative assessment** of thermal resilience in buildings and indicate the **influence** of facade and buildings systems **parameters** to **performance**

"In what manner can a digital design **workflow** be devised to assess the **thermal resilience** of buildings against **extreme heat wave** stresses, and how it can support designers and engineers in the **decision-making** process during the **early** design **stage**?"

Definition
Indicators
Metrics

Climate change
Historical Data

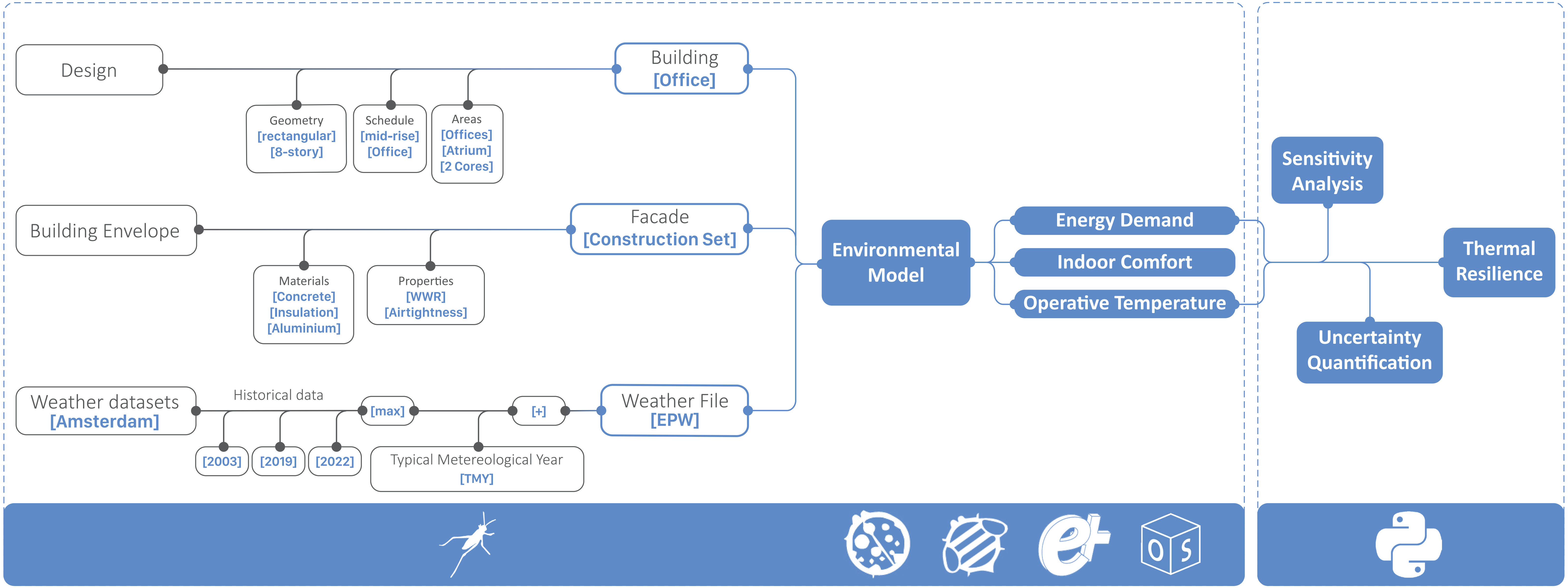
Dynamic building
simulation

Facade & Building
libraries

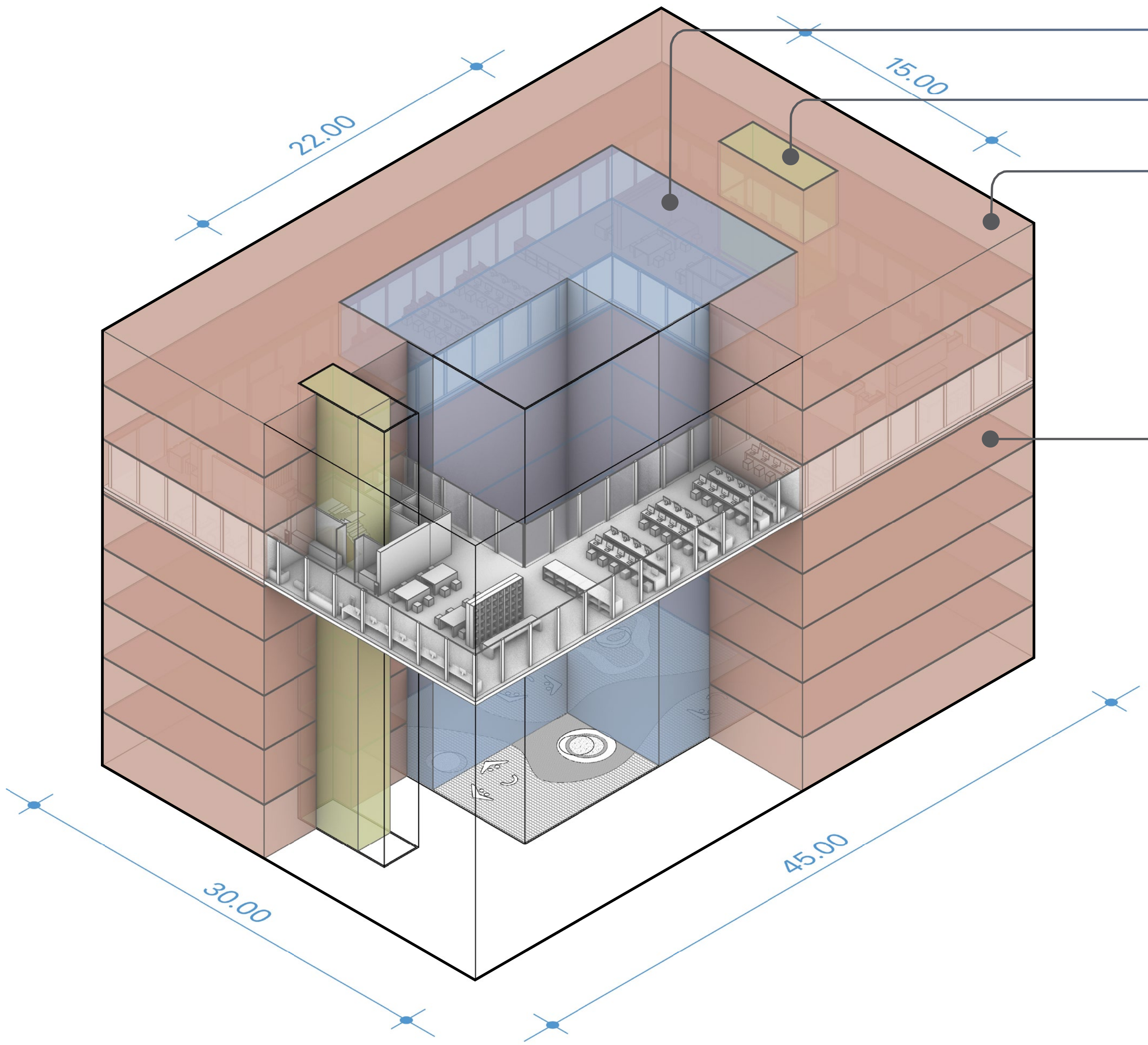
Influential parameters
Probabilistic approach

Case Study

Case study set-up



Case study set-up



Offices
Atrium
Cores
Thermal Zones
Environmental GH Model
Building

Design Choices

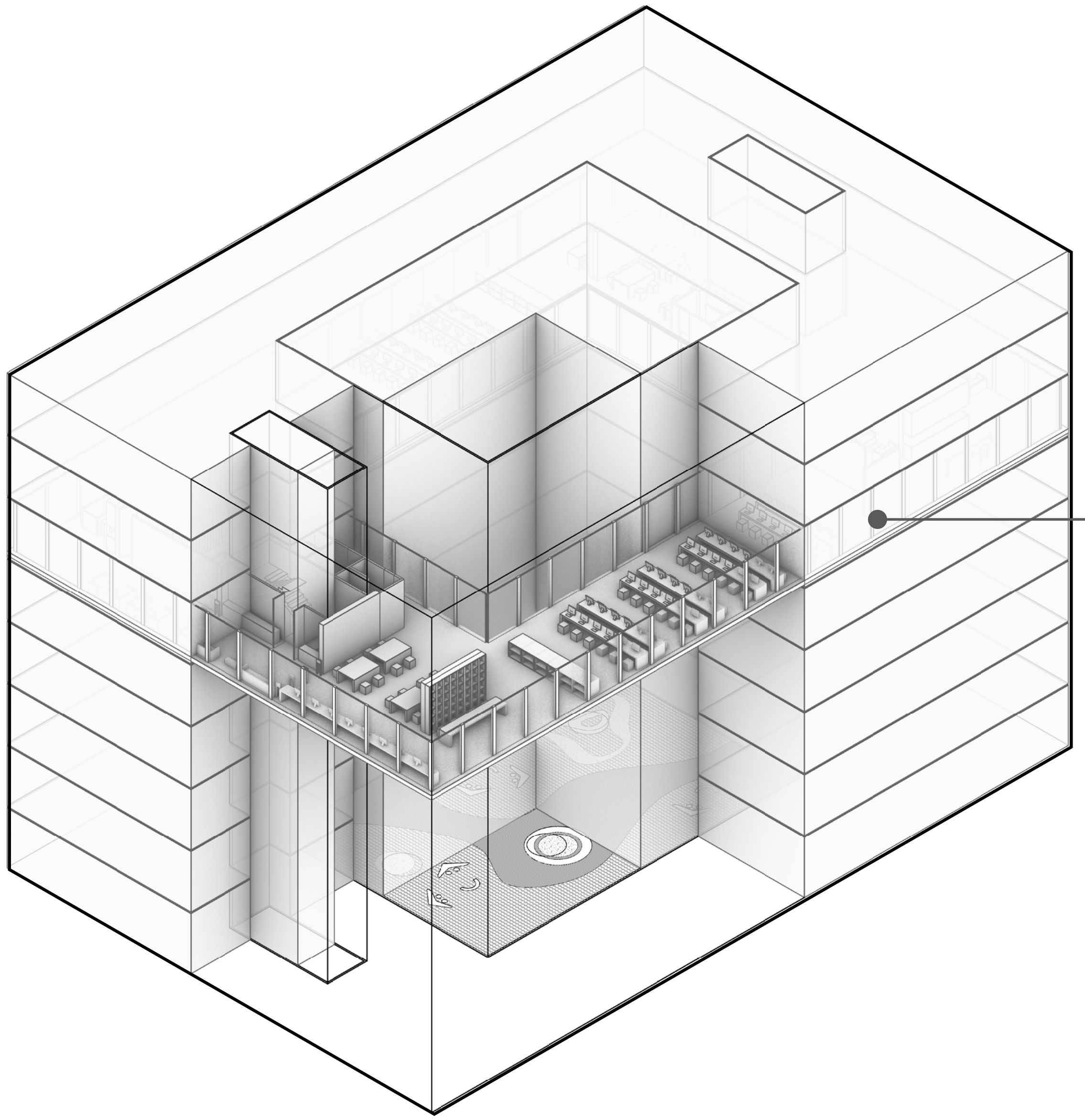
Plan Dimensions	[45x30m]
Building Type	[mid-rise office]
Building Height	[32m]
Floor Height	[4m]
Facade Surface	[5040m²]
Main Areas	[3]
GFA Offices	[7920m²]
GFA Atrium	[360m²]
GFA Ground floor	[1350m²]
GFA / floor	[990m²]
Total Volume	[45360m³]

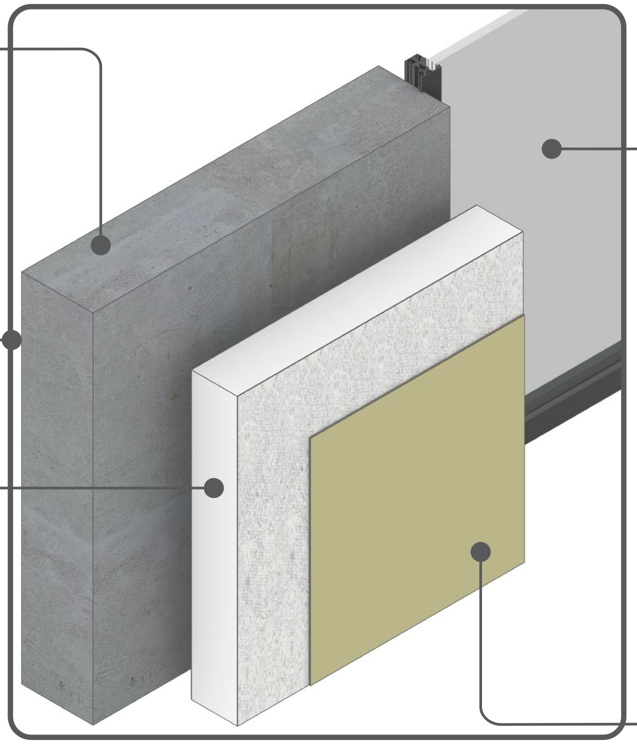
Uncertain Parameters

Occupancy	
Occupants	[0.037 - 0.0435 ppl/m²]
Building Envelope	
Wall-window ratio	[20 - 95 %]
Airtightness	[0.001 - 0.003 m³/s/m²]
Exhaust Ventilation	
Air flow to exterior	[0.01 - 5.00 60q/V]
Cooling Ventilation	
Air Change/hour	[0.01 - 5.00 60q/V]
Flow/person	[0.0024 - 0.0235 m³/s]

Building set up

Case study set-up





Concrete [lightweight]

Thickness	[0.15-0.35 m]
Conductivity	[1.20-2.0 W/mK]
Density	[800-2100 kg/m³]
SpecHeat	[840-1170 J/kgK]
Thermal absorbance	[0.75-0.95]
Solar Absortivity	[0.50-0.80]
Visible Absortivity	[0.10-0.70]

Glass [double-tripple]

U-value	[0.70-2.40 W/m²]
SHGC	[0.30-0.90]
Visible Transmittance	[0.20-0.80]

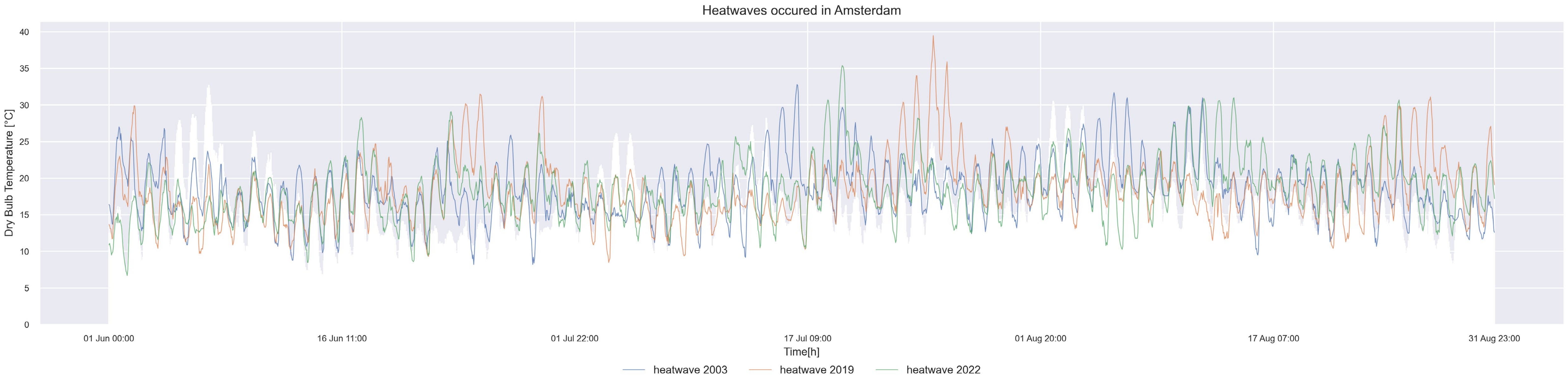
Thermal Insulation [EPS-XPS]

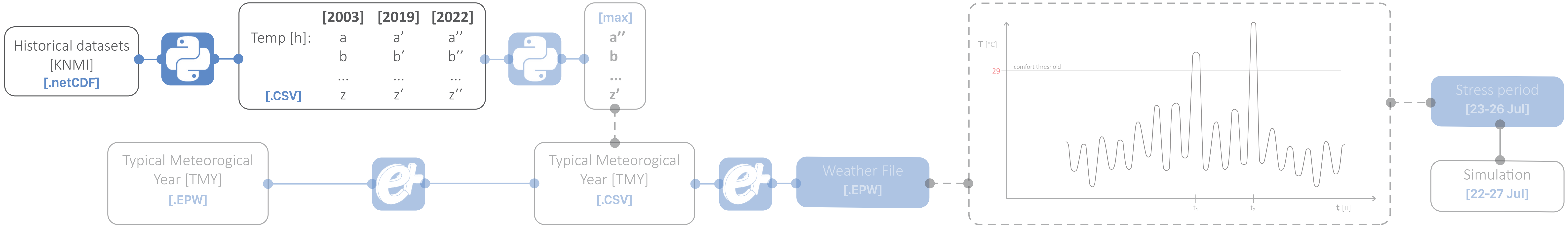
Thickness	[0.035-0.15 m]
Conductivity	[0.024-0.038 W/mK]
Density	[28-45 kg/m³]
SpecHeat	[1300-1700 J/kgK]
Thermal absorbance	[0.85-0.95]
Solar Absortivity	[0.80-0.90]
Visible Absortivity	[0.80-0.90]

Aluminium Cladding [-]

Thickness	[0.001-0.0085 m]
Conductivity	[120-240 W/mK]
Density	[2700-2800 kg/m³]
SpecHeat	[1215-900 J/kgK]
Thermal absorbance	[0.05-0.20]
Solar Absortivity	[0.20-0.40]
Visible Absortivity	[0.20-0.40]

Case study set-up

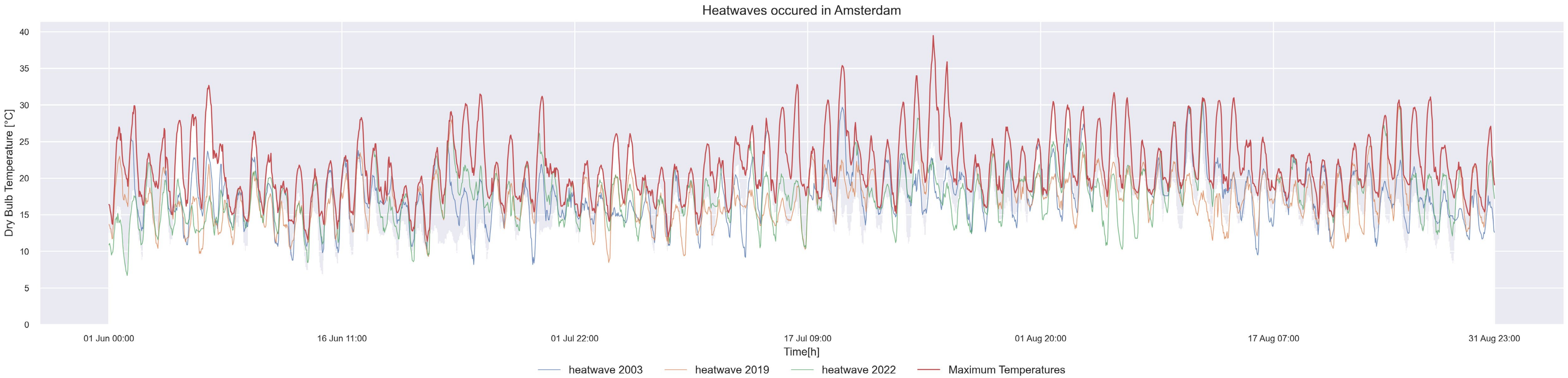


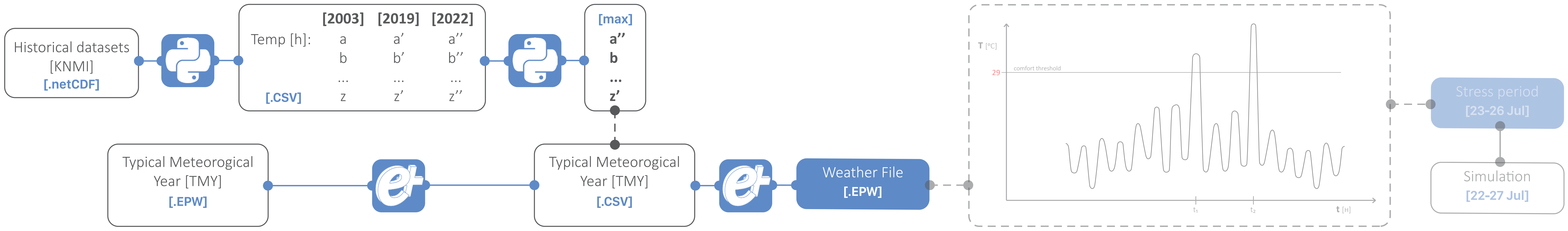


Case Study

Weather file generation

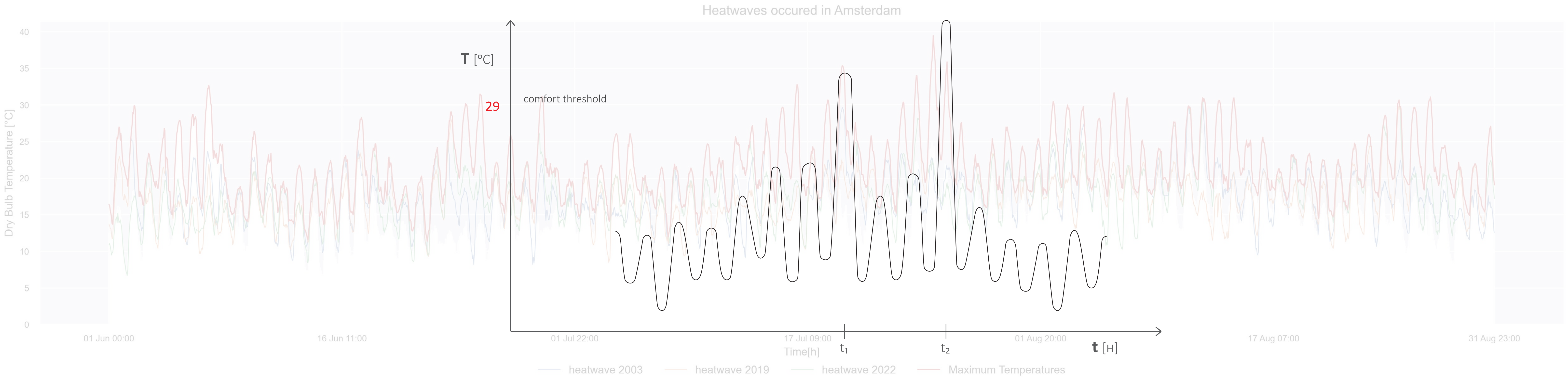
Case study set-up

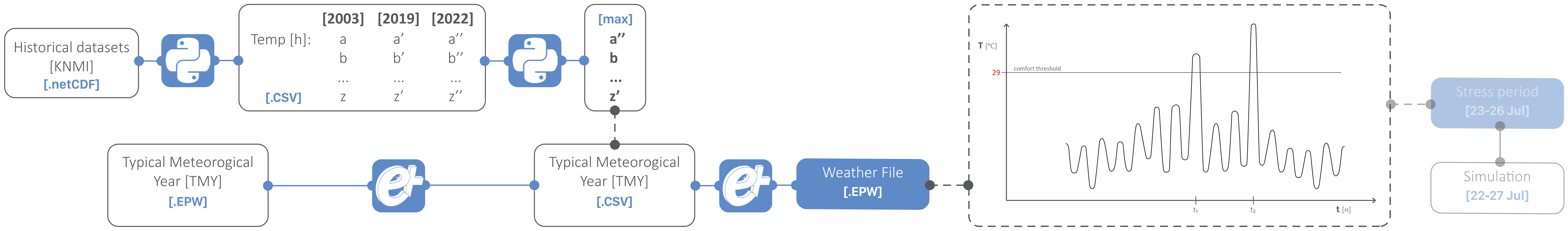




Extreme Temperatures

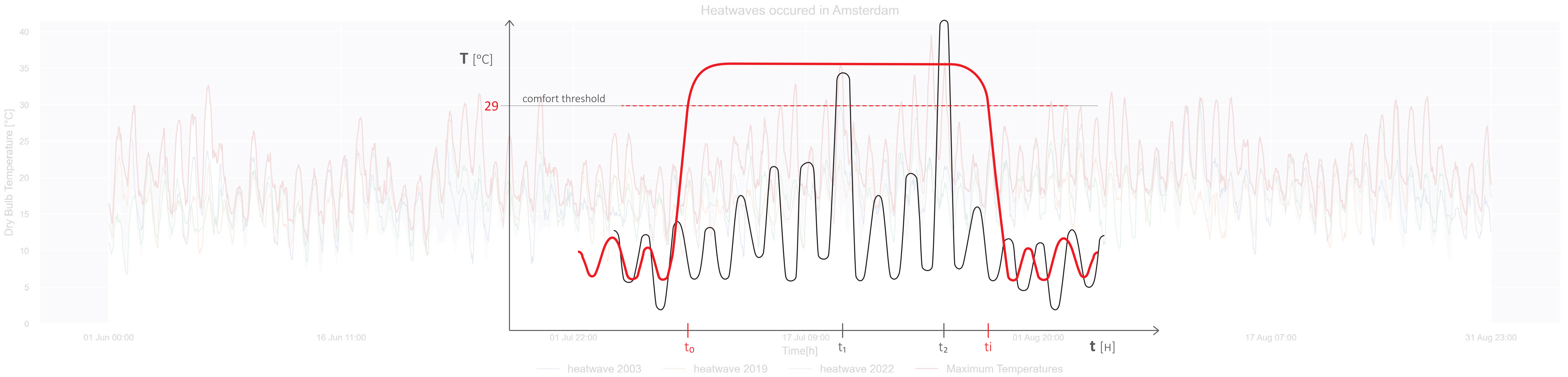
Case study set-up

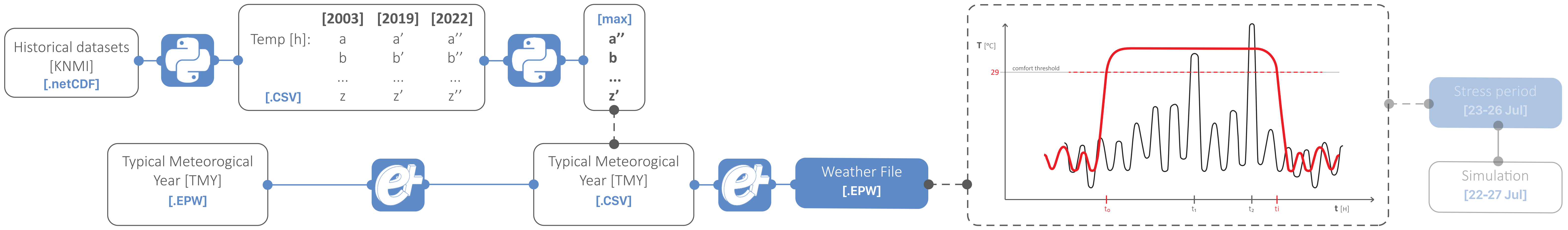




Heat stress concept

Case study set-up





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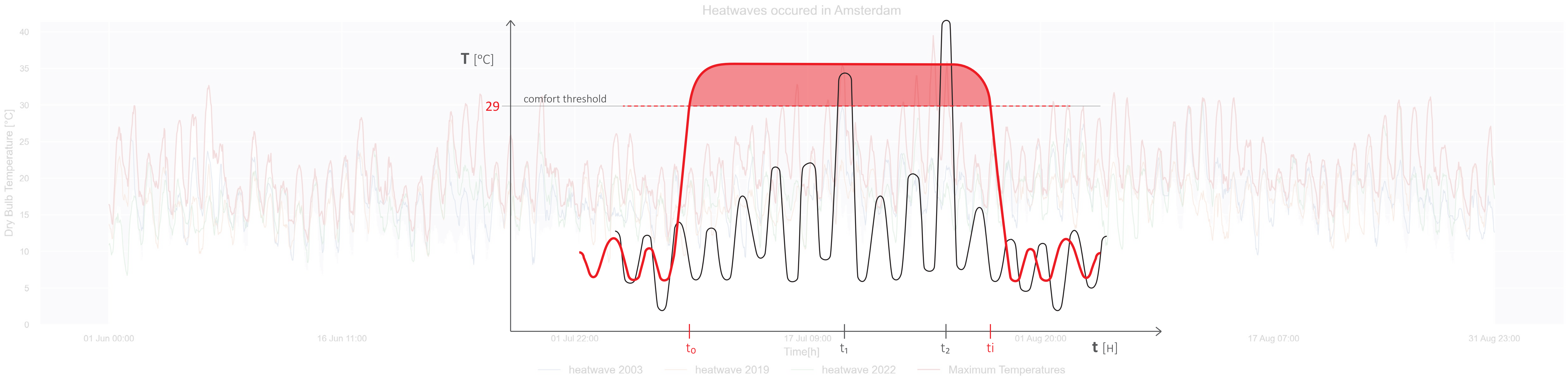

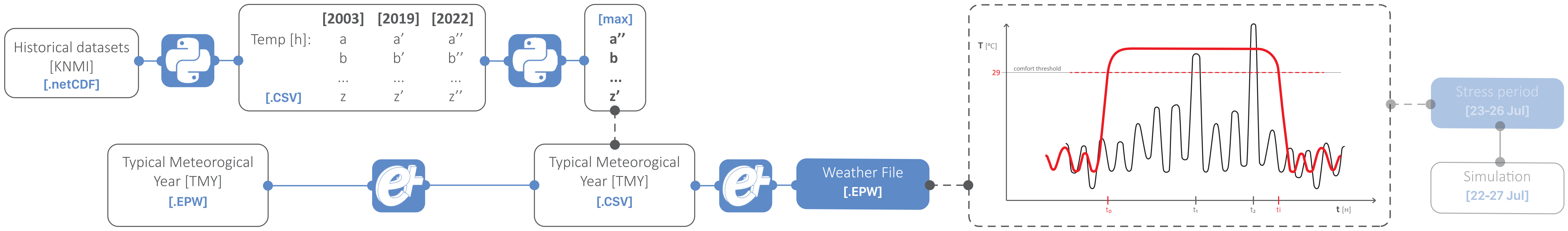

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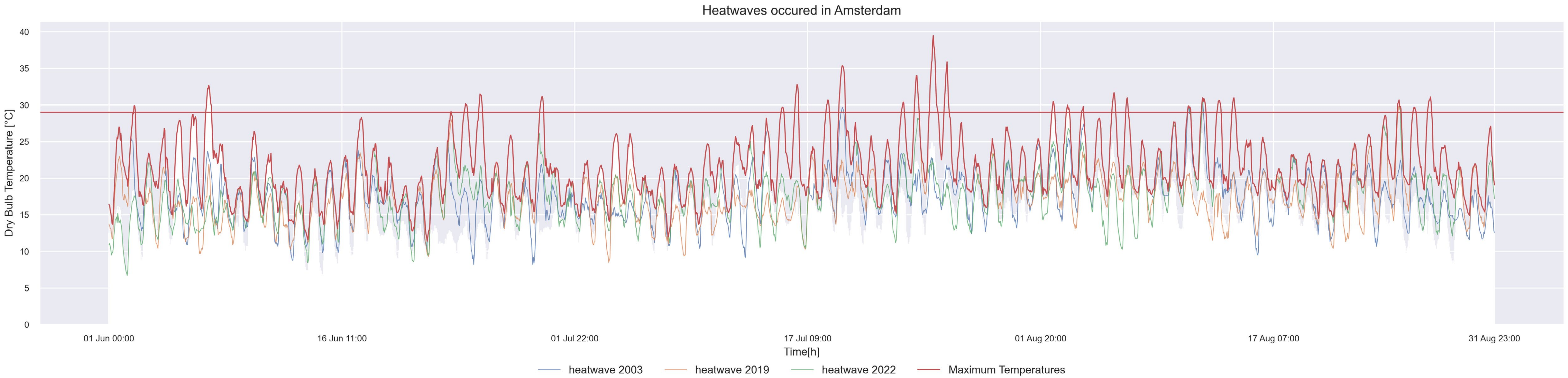
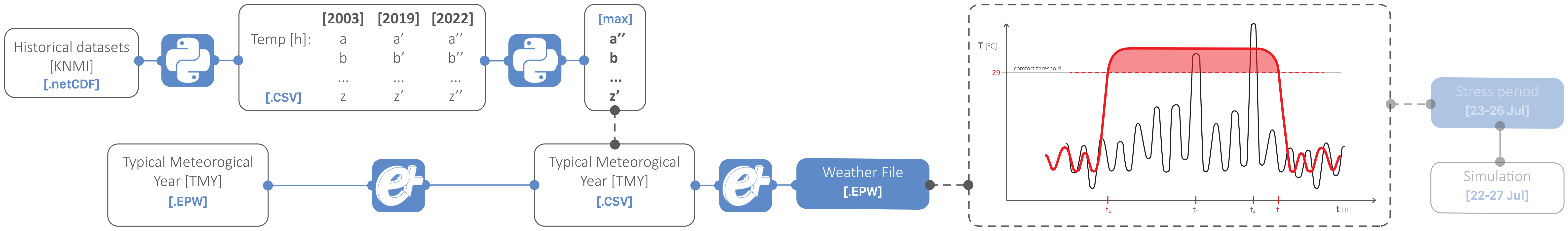
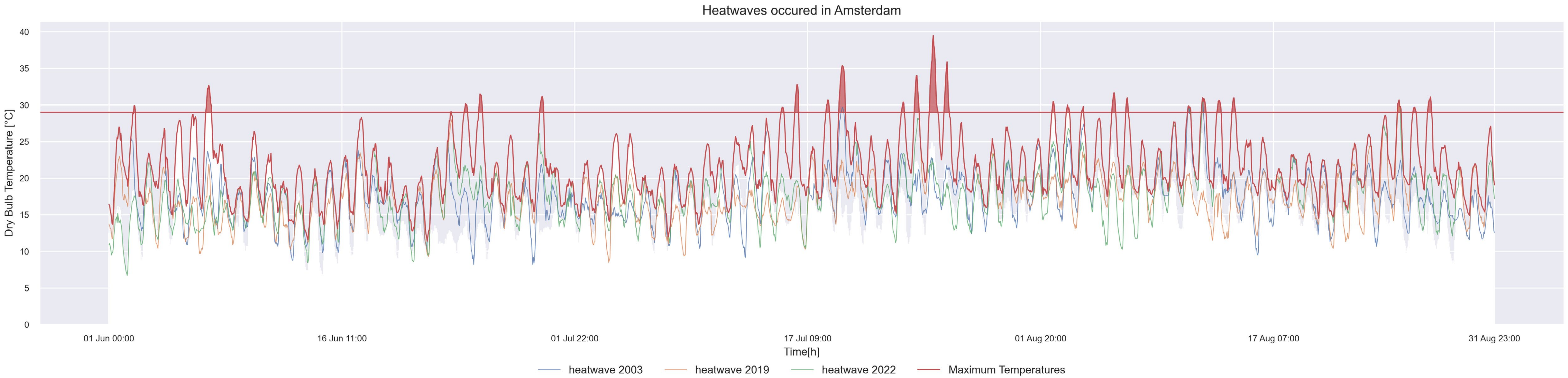
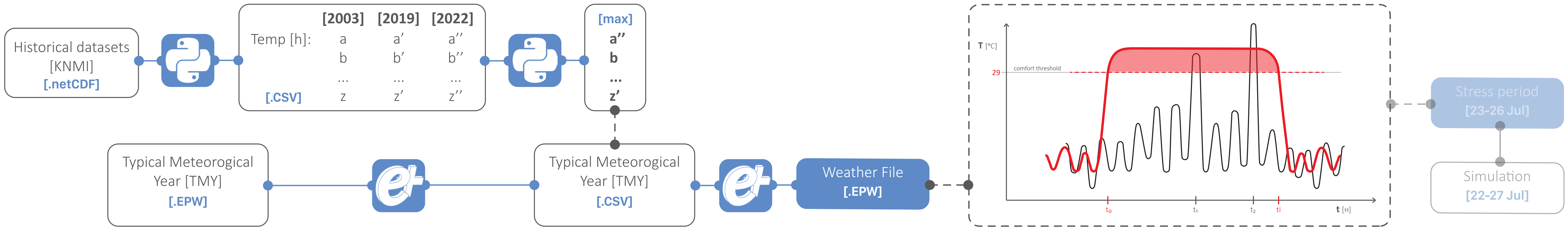




Heat stress threshold

Case study set-up





Heat stress threshold

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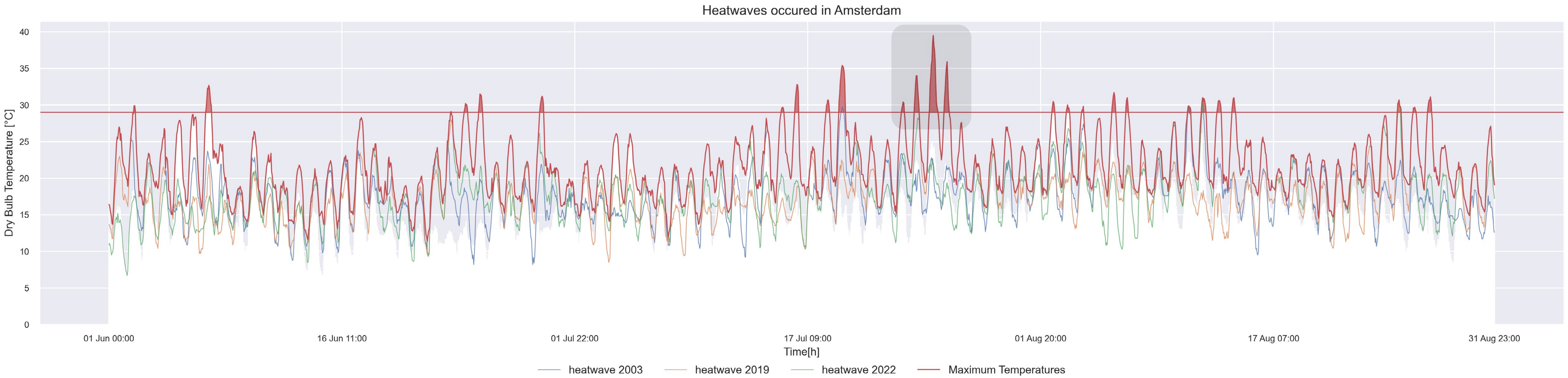
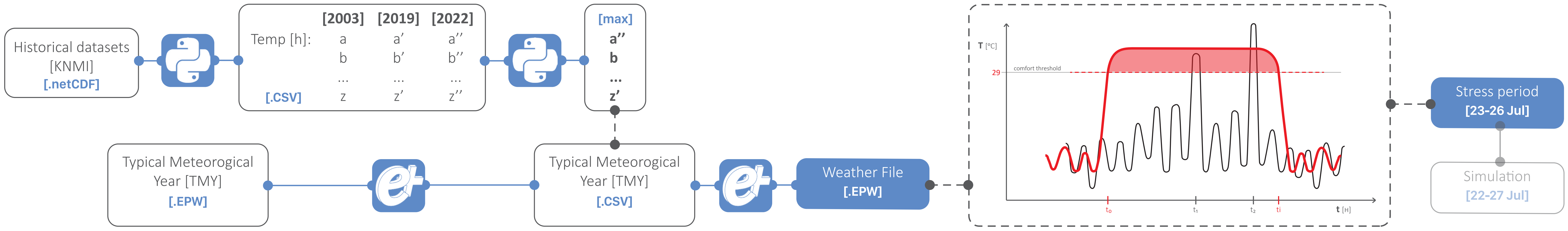
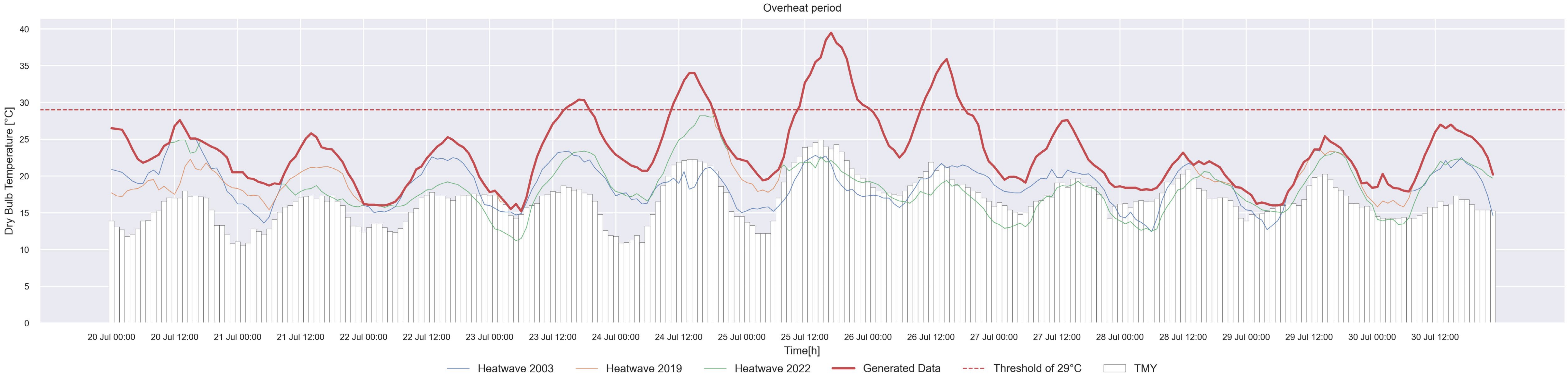


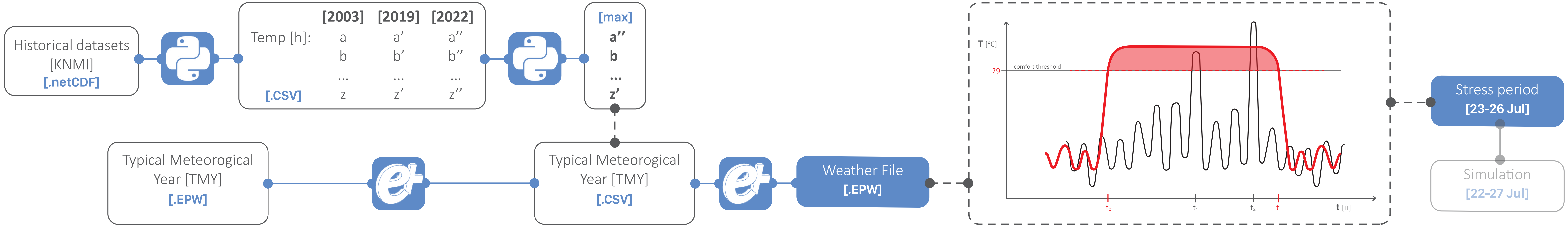


Case Study

Heat stress period

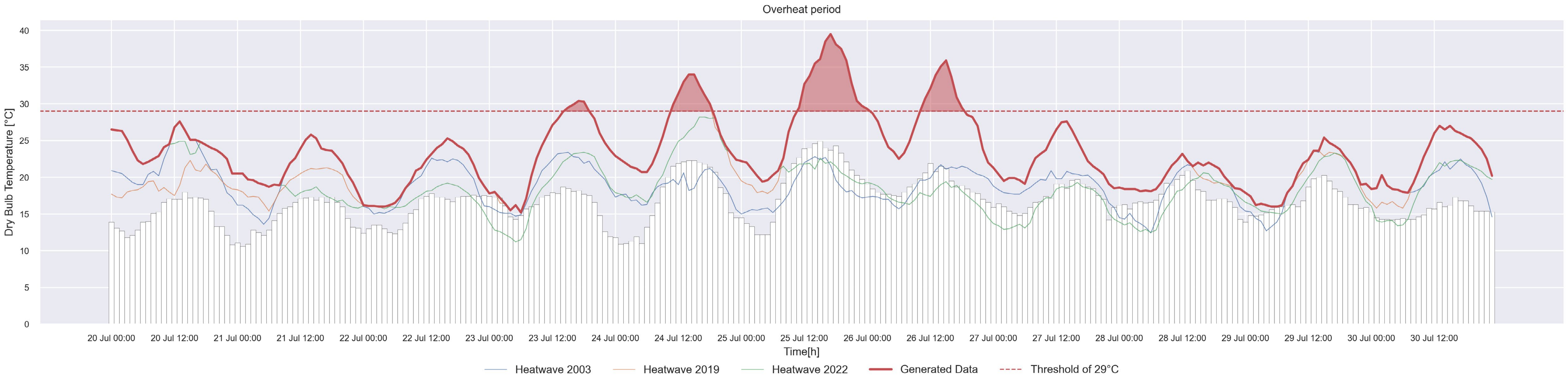
Case study set-up

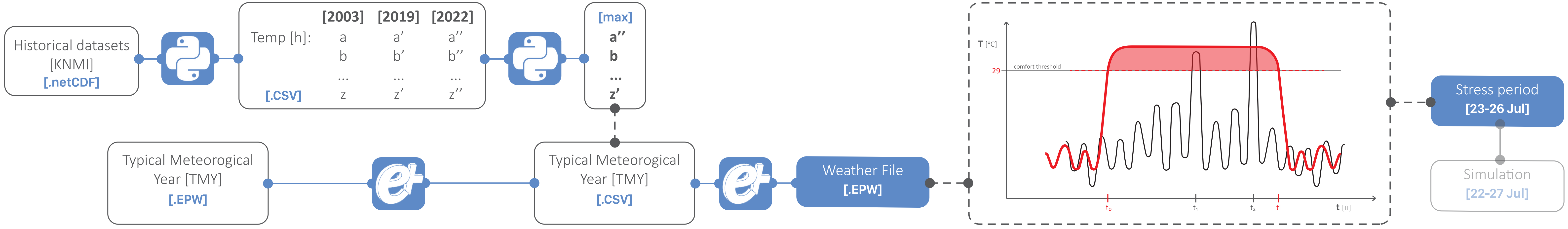




Heat stress period zoom-in

Case study set-up

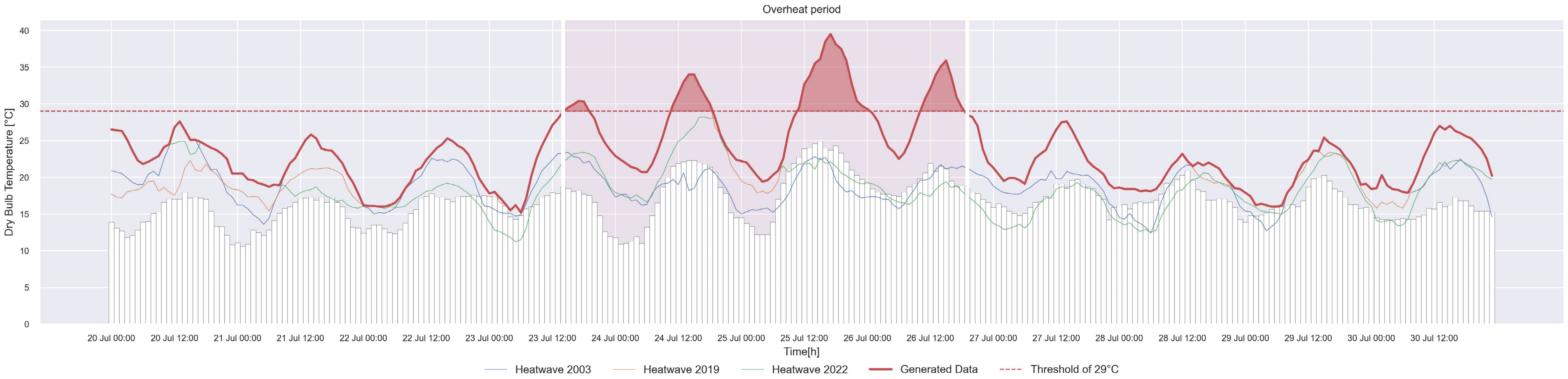


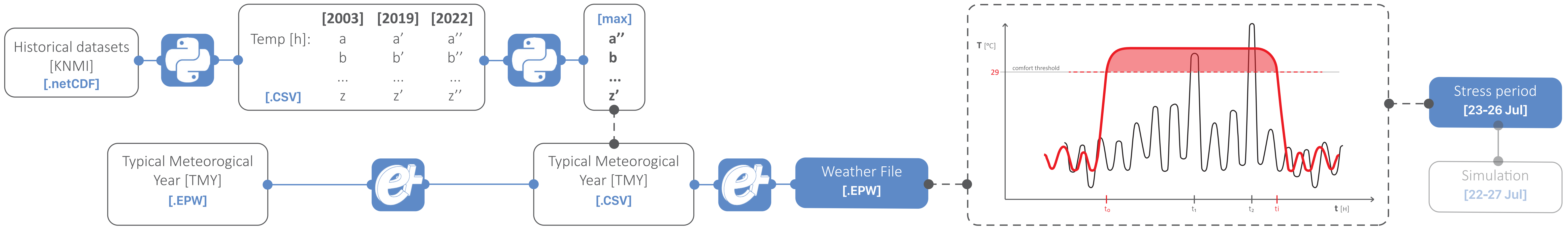


Case Study

Heat stress period zoom-in

Case study set-up

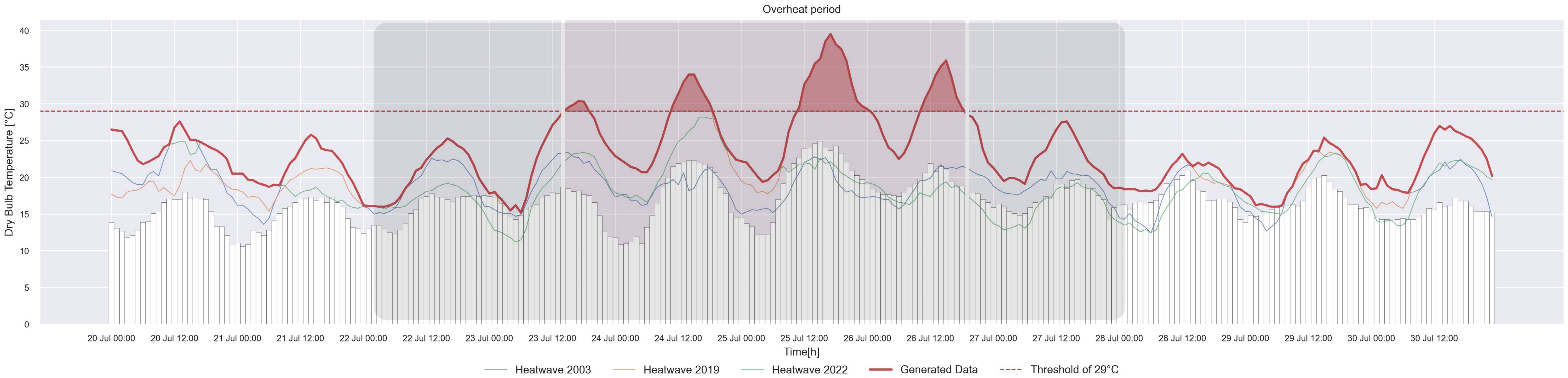


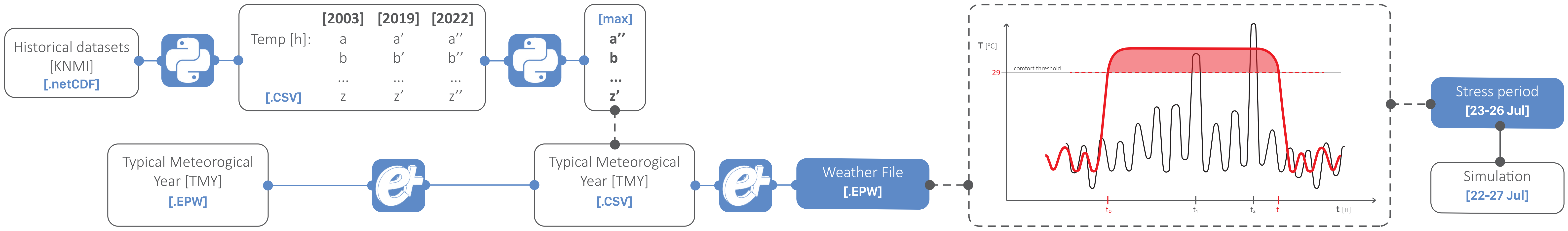


Case Study

Heat stress period zoom-in

Case study set-up

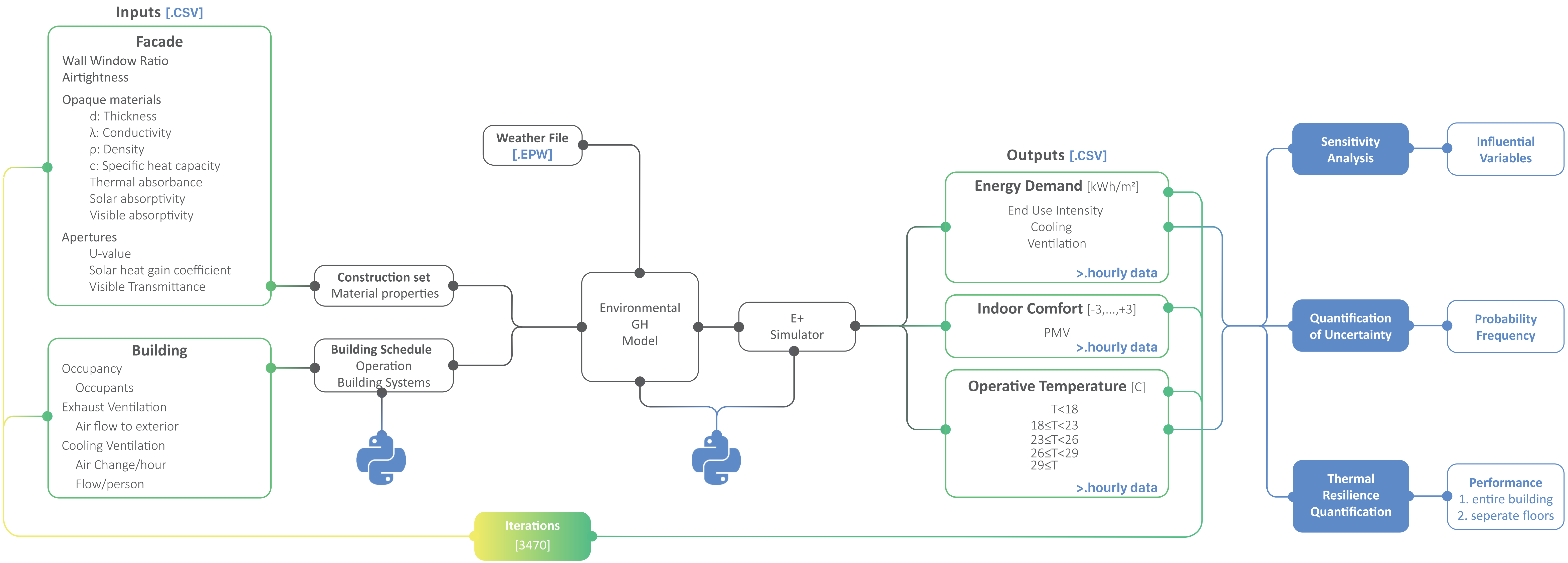




Simulation period

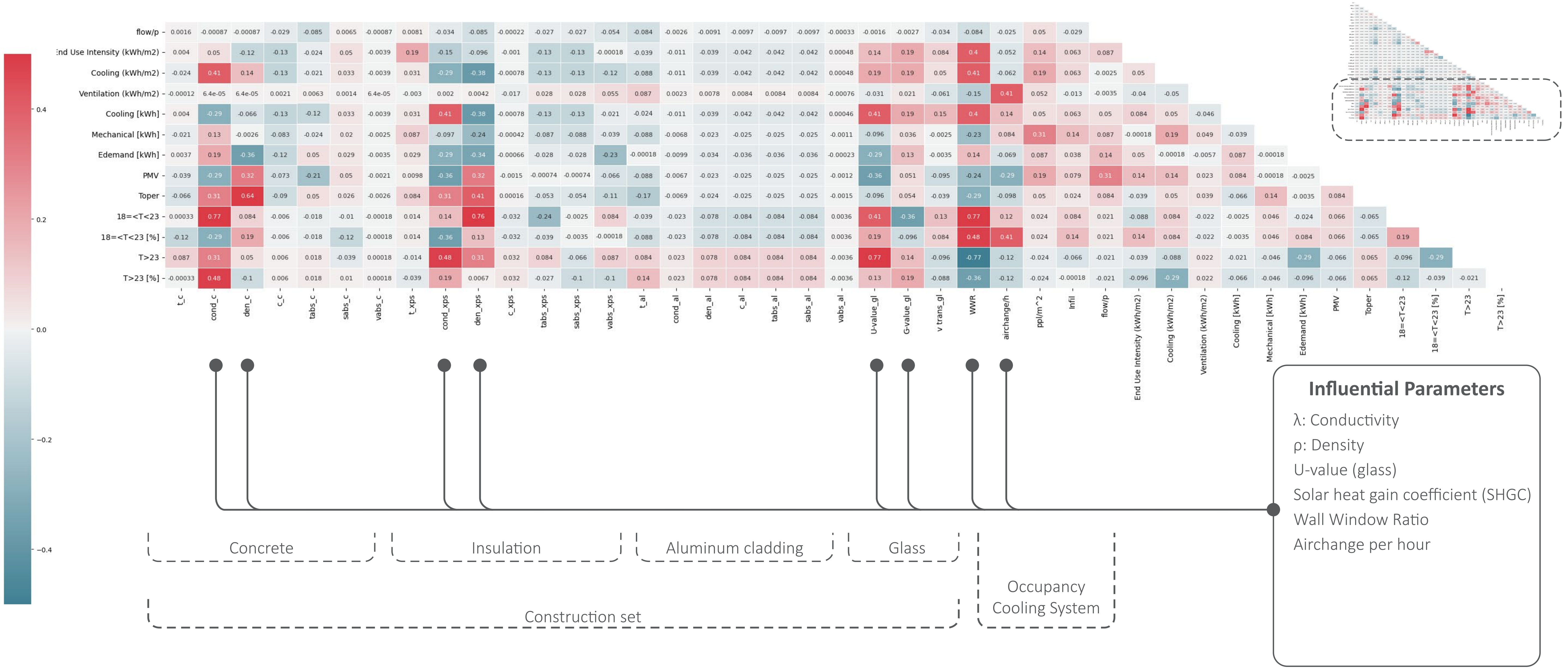
Workflow

Overview of the simulation model



Core of the GH model

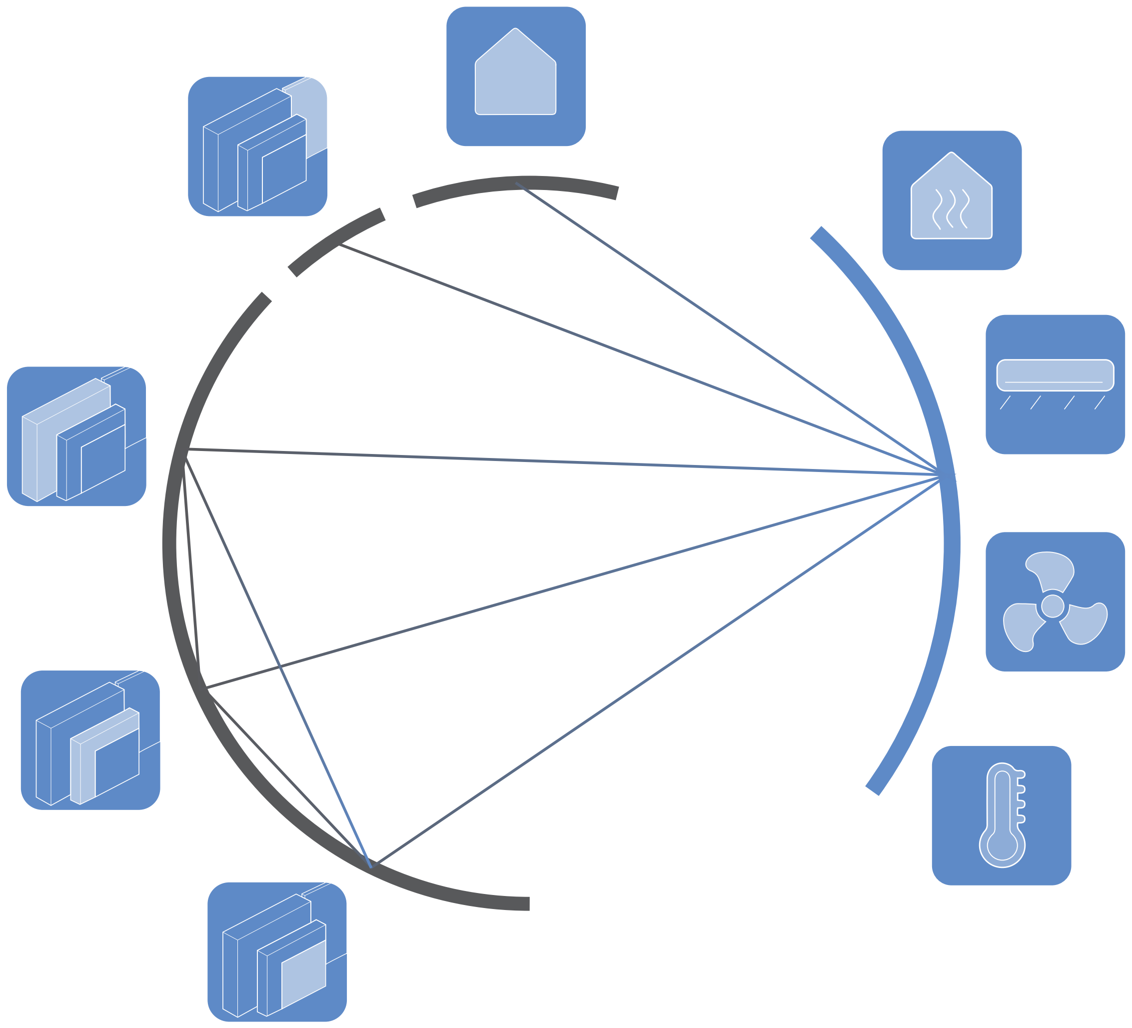
Simulation Results

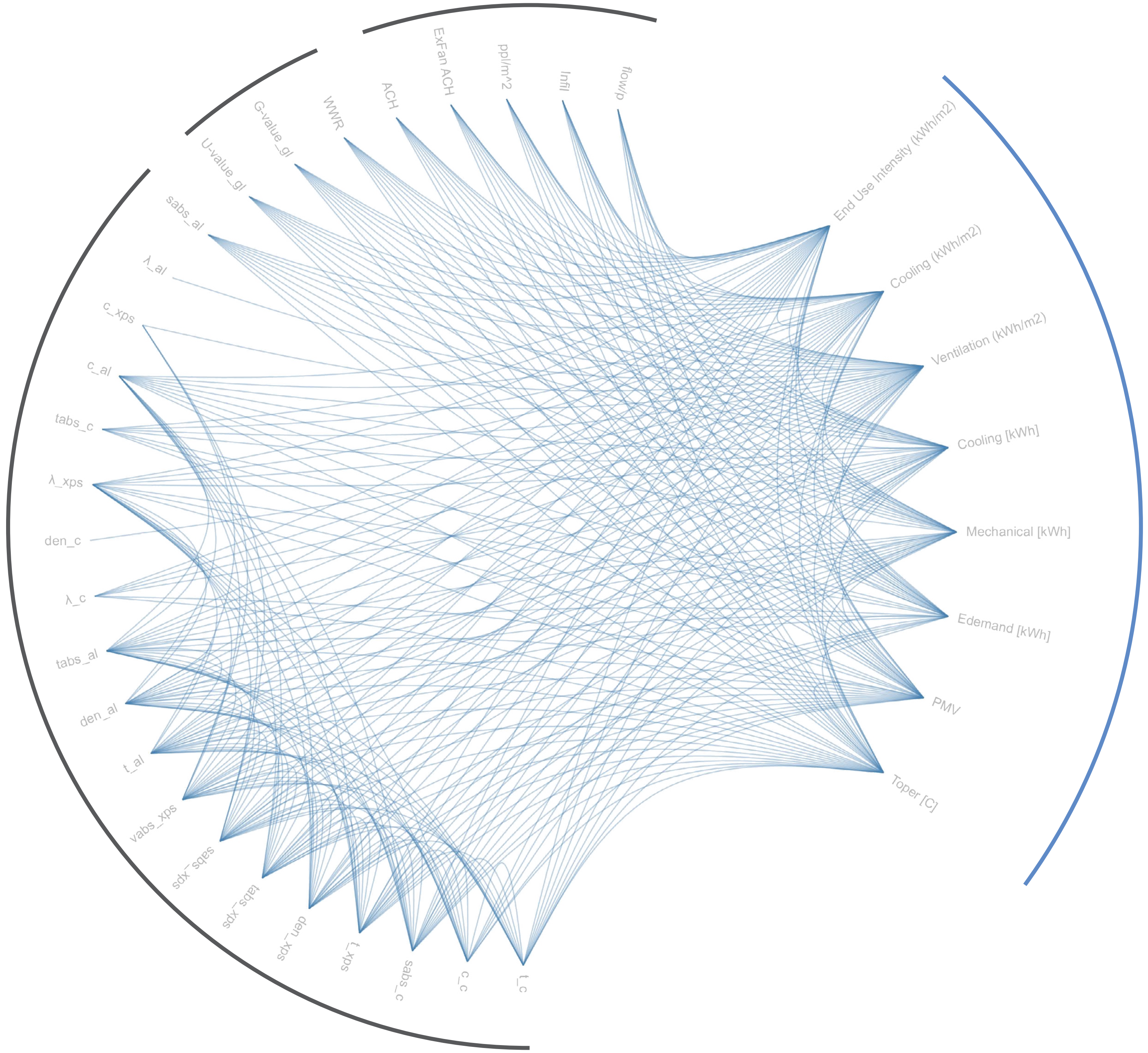


Workflow

Correlation matrix

Simulation Results





Inter-relationships among problem variables

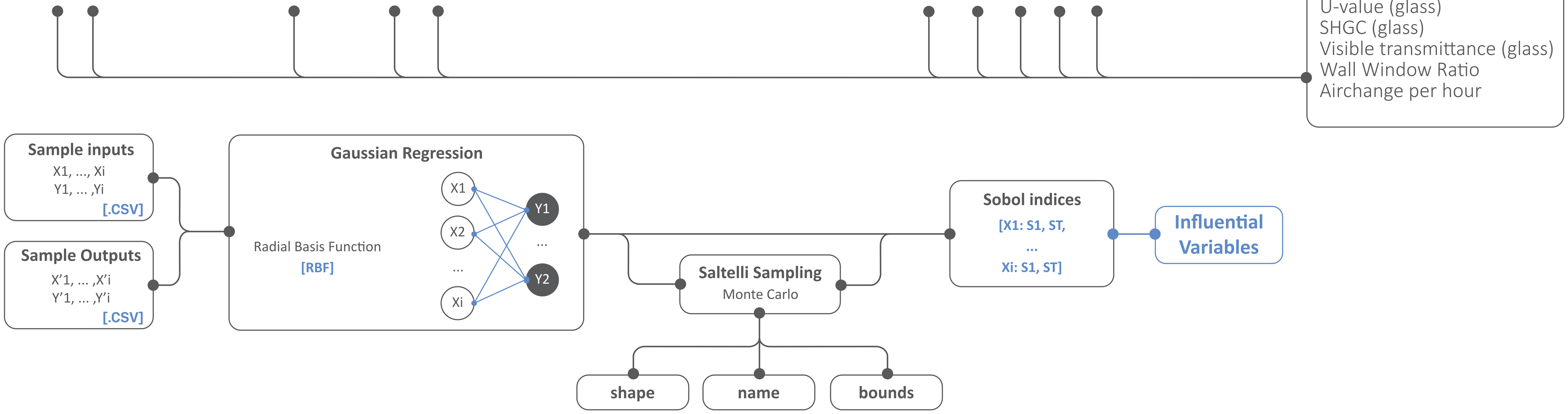
Workflow

Sensitivity Analysis workflow

Output variables

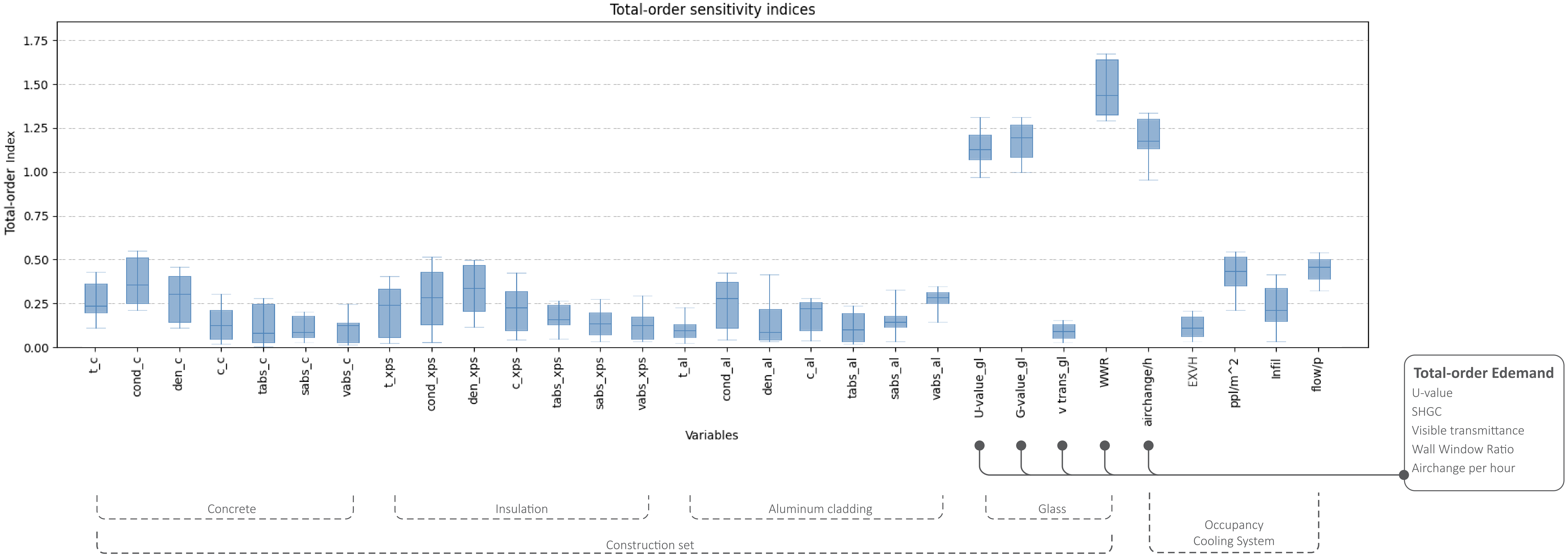
Output variable	Unit	t_c	cond_c	den_c	c_c	tabs_c	sabs_c	vabs_c	t_xps	cond_xps	den_xps	c_xps	tabs_xps	sabs_xps	vabs_xps
EUI	[kWh/m²]	-0.05	0.22	0.24	0.15	0.03	0.09	-0.01	-0.17	0.02	-0.24	-0.14	0.02	0.01	0.01
Cooling	[kWh/m²]	-0.01	-0.17	0.19	0.05	-0.02	0.02	0.02	0.22	0.13	0.22	-0.16	0.01	0.01	0.01
Mech Vent	[kWh/m²]	0.03	0.12	-0.23	0.02	-0.03	-0.04	0.06	0.15	-0.14	-0.26	0.18	-0.03	-0.01	-0.05
Cooling	[kWh]	0.15	-0.21	-0.17	-0.03	0.02	-0.02	-0.04	-0.16	0.06	0.25	-0.12	0.01	0.03	-0.01
Mech Vent	[kWh]	-0.05	0.16	-0.28	-0.01	0.01	0.04	0.03	0.19	-0.07	0.14	0.24	0.01	0.04	-0.04
Edemand	[kWh]	0.12	-0.19	-0.16	0.05	0.01	-0.03	-0.01	0.10	-0.05	-0.17	0.11	0.03	-0.06	0.01
PMV	[-3,…,+3]	0.22	0.41	0.32	0.15	0.00	0.03	0.01	0.33	0.08	-0.39	-0.41	-0.04	0.01	0.01
$\mathbf{T_{oper}}$	[°C]	-0.13	-0.57	0.45	0.02	0.06	-0.01	0.06	-0.58	0.01	-0.43	-0.46	-0.04	-0.03	0.03

Output variable	t_al	cond_al	den_al	c_al	tabs_al	sabs_al	vabs_al	U-value	g-value	Vtrans	WWR	ACH	EXVH	ppl/m²	Infil	flow/p
EUI	0.03	0.01	0.01	0.01	0.01	0.01	0.00	0.65	0.73	0.54	0.84	0.72	0.12	0.18	0.11	0.14
Cooling	0.01	-0.02	-0.04	0.03	0.00	0.01	0.00	0.52	0.89	0.71	-0.78	-0.86	-0.09	-0.16	0.06	0.16
Mech Vent	0.01	-0.01	-0.03	0.00	-0.01	-0.01	0.01	-0.25	0.35	-0.43	-0.57	0.14	0.25	-0.23	0.08	-0.31
Cooling	-0.01	0.03	0.02	-0.02	-0.02	-0.01	0.01	-0.58	-0.91	0.77	0.72	0.82	-0.05	-0.26	-0.07	0.13
Mech Vent	-0.03	0.03	-0.01	-0.01	0.03	-0.01	-0.01	0.27	-0.32	-0.38	0.51	-0.20	-0.34	0.15	0.12	-0.41
Edemand	0.01	-0.02	0.01	-0.03	0.00	0.01	0.00	-0.68	0.72	0.58	-0.87	-0.71	0.06	0.24	-0.10	0.25
PMV	0.02	0.01	0.06	0.03	0.01	0.02	0.01	0.49	0.64	0.43	0.52	0.48	-0.05	0.28	0.05	0.02
$\mathbf{T_{oper}}$	-0.01	-0.02	0.04	0.00	-0.01	0.00	-0.02	-0.78	-0.89	-0.64	-0.95	0.82	0.03	-0.16	0.03	-0.14



Post-proccesing

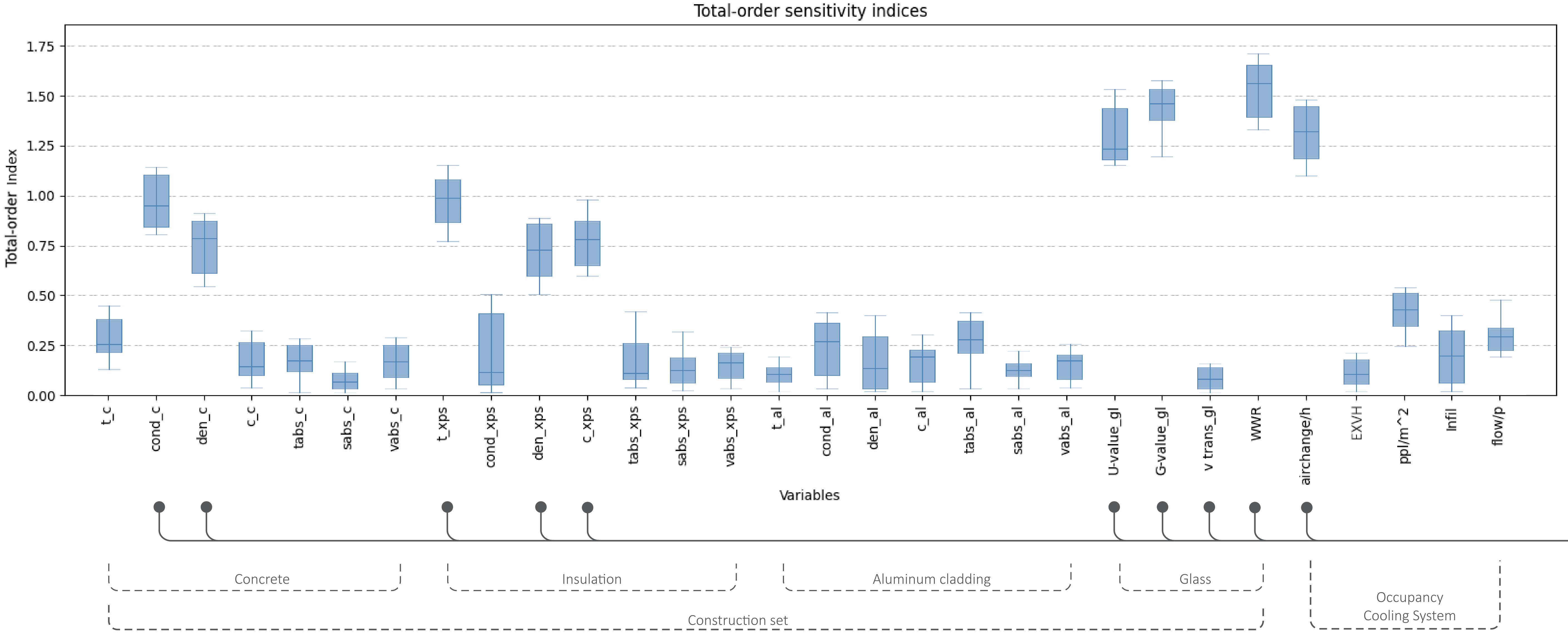
Sensitivity Analysis – Energy demand



Sensitivity Analysis

Post-proccesing

Sensitivity Analysis – Operative temperature



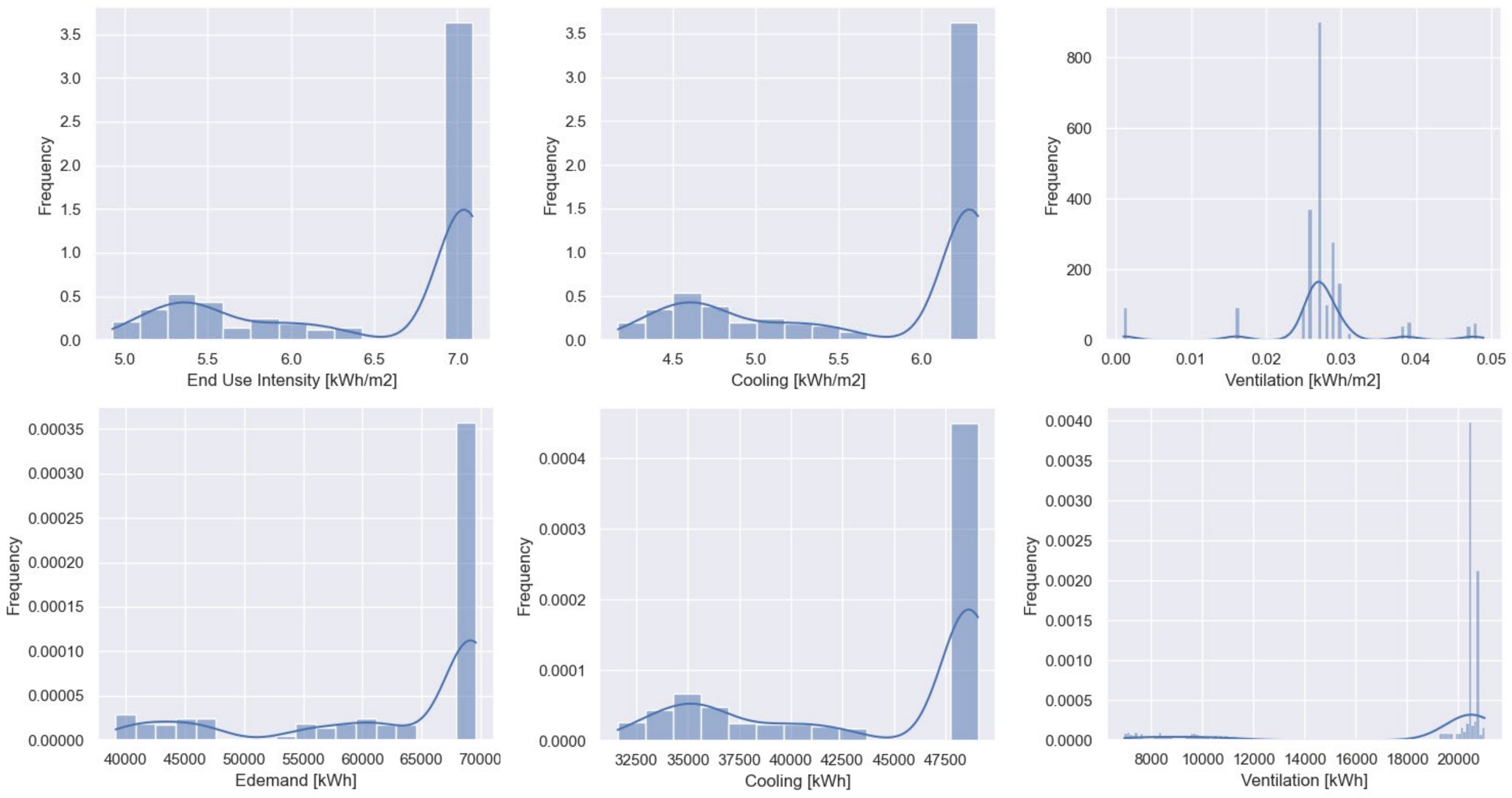
Total-order Toper

λ: Conductivity
ρ: Density
t: Thickness
Specific Heat Capacity
U-value
SHGC
Visible transmittance
Wall Window Ratio
Airchange per hour

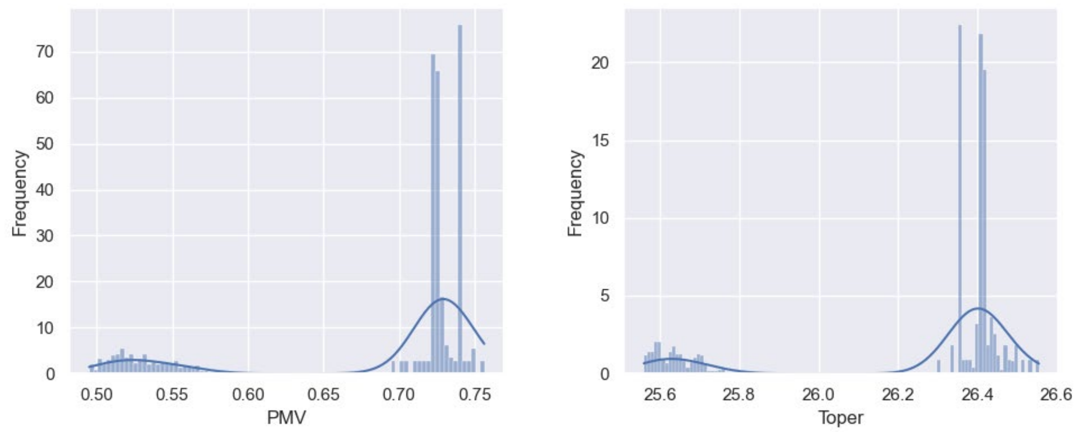
Post-proccesing

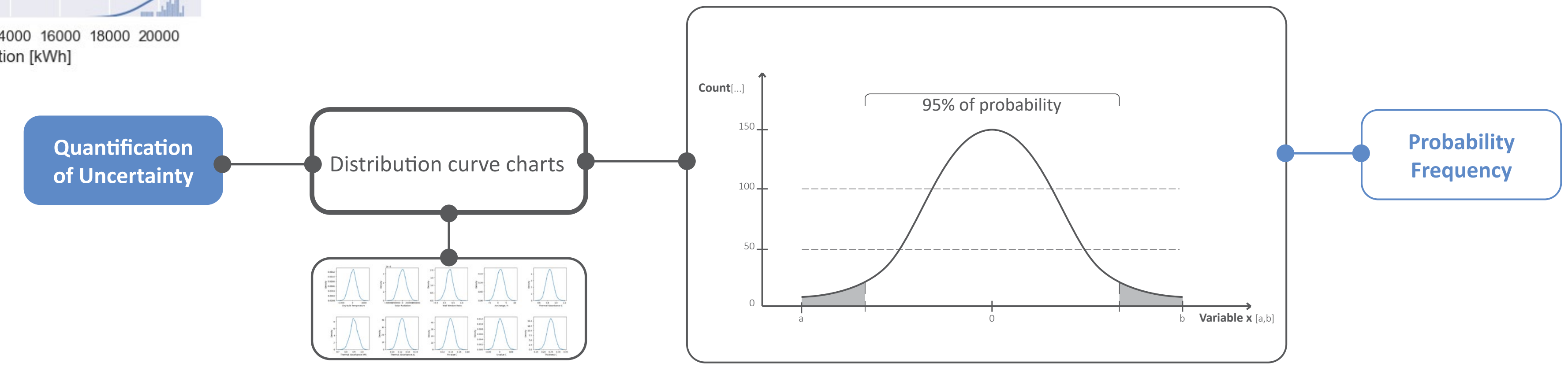
Probability of the results

Energy demand



Thermal Comfort

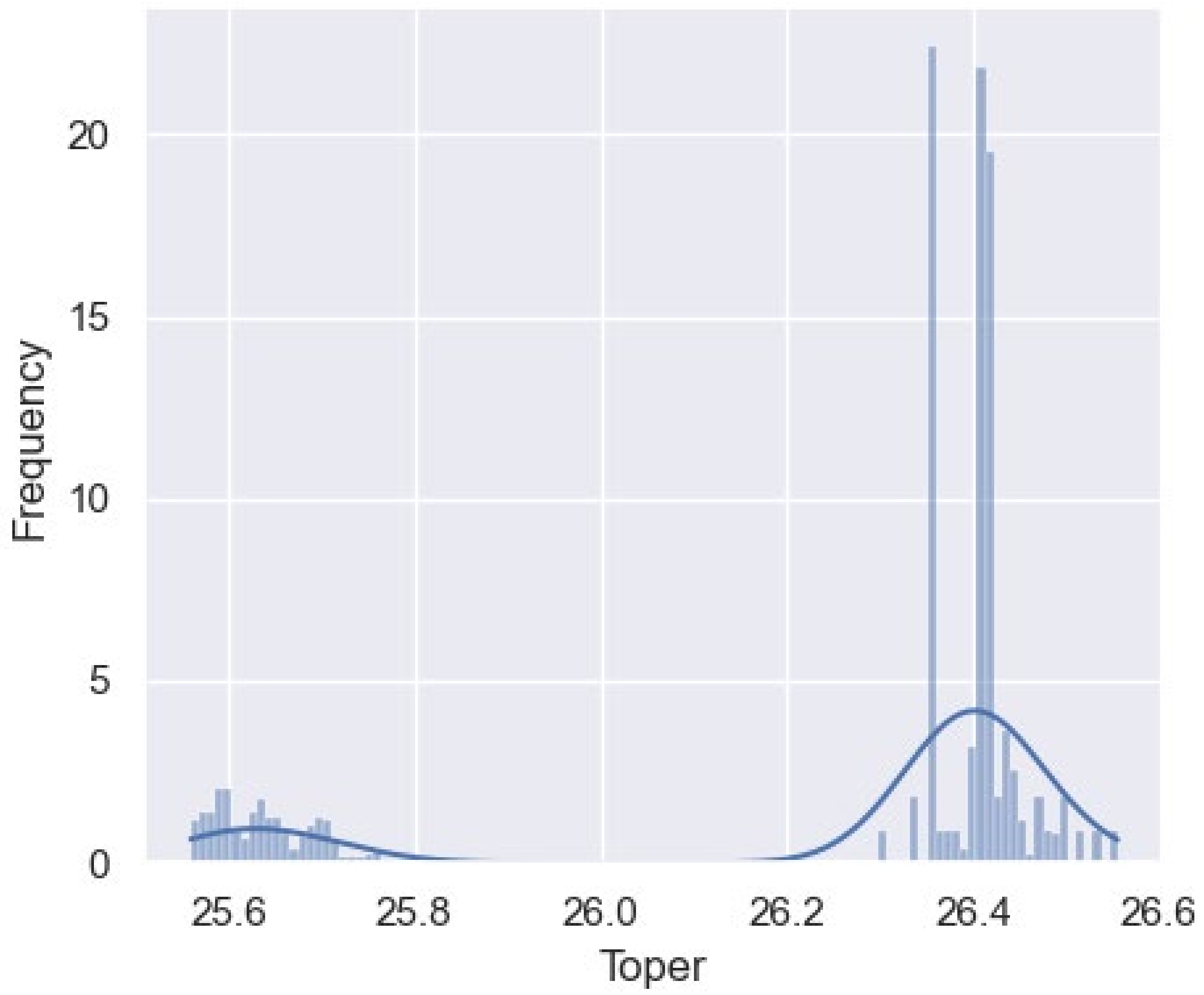


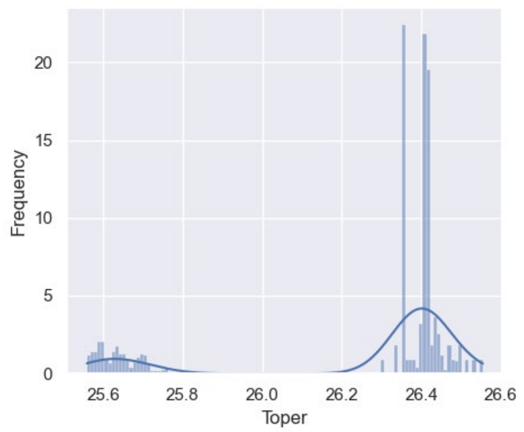


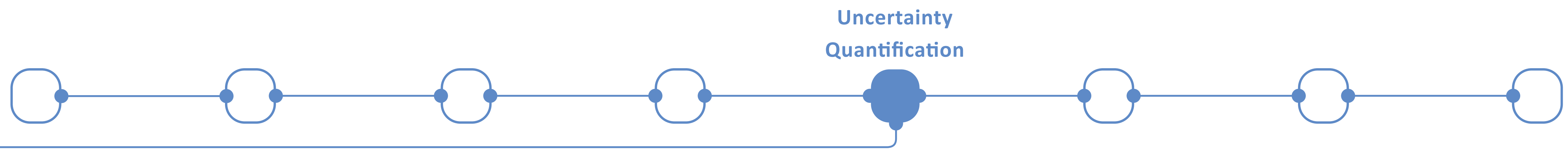
Uncertainty Quantification

Post-proccesing

Probability of the Temperature results

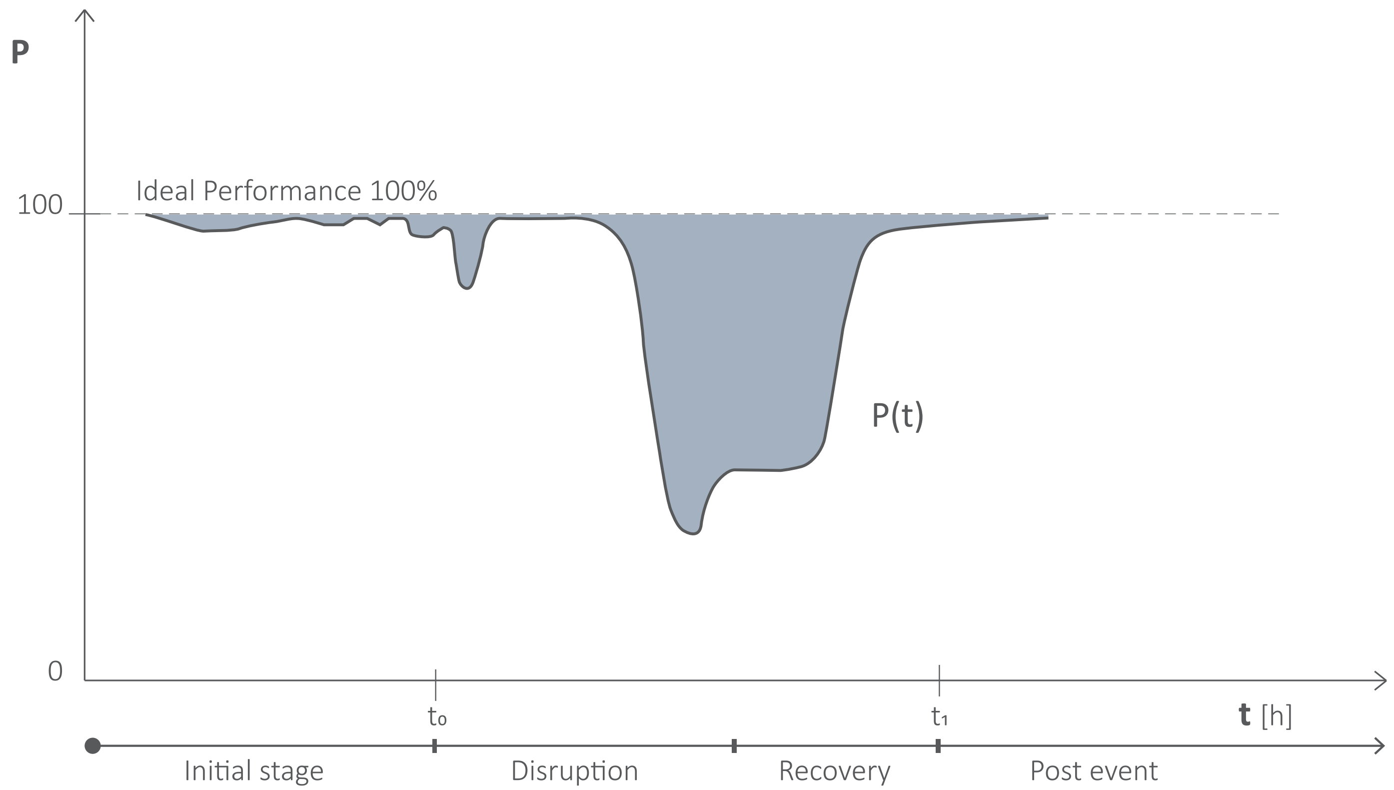


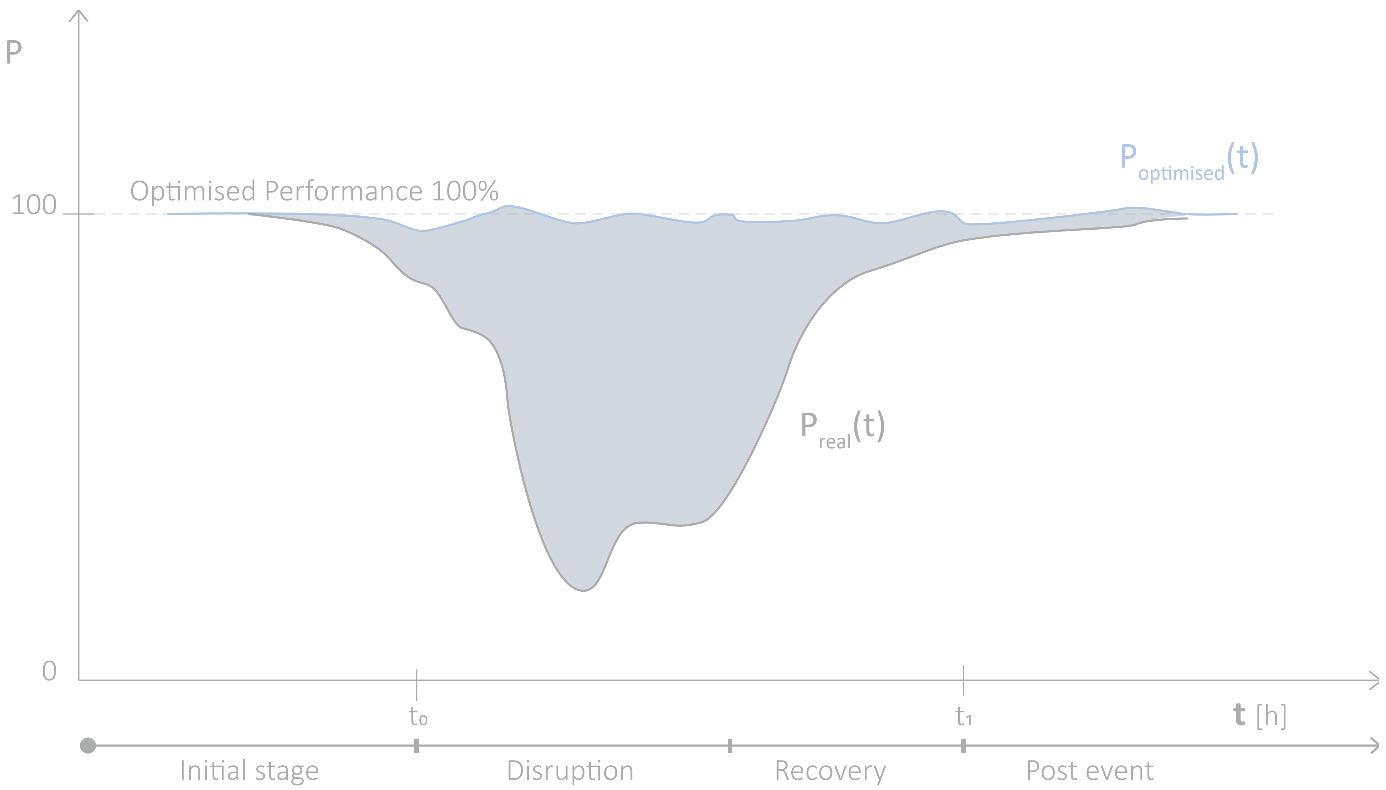




Post-proccesing

Thermal resilience quantification



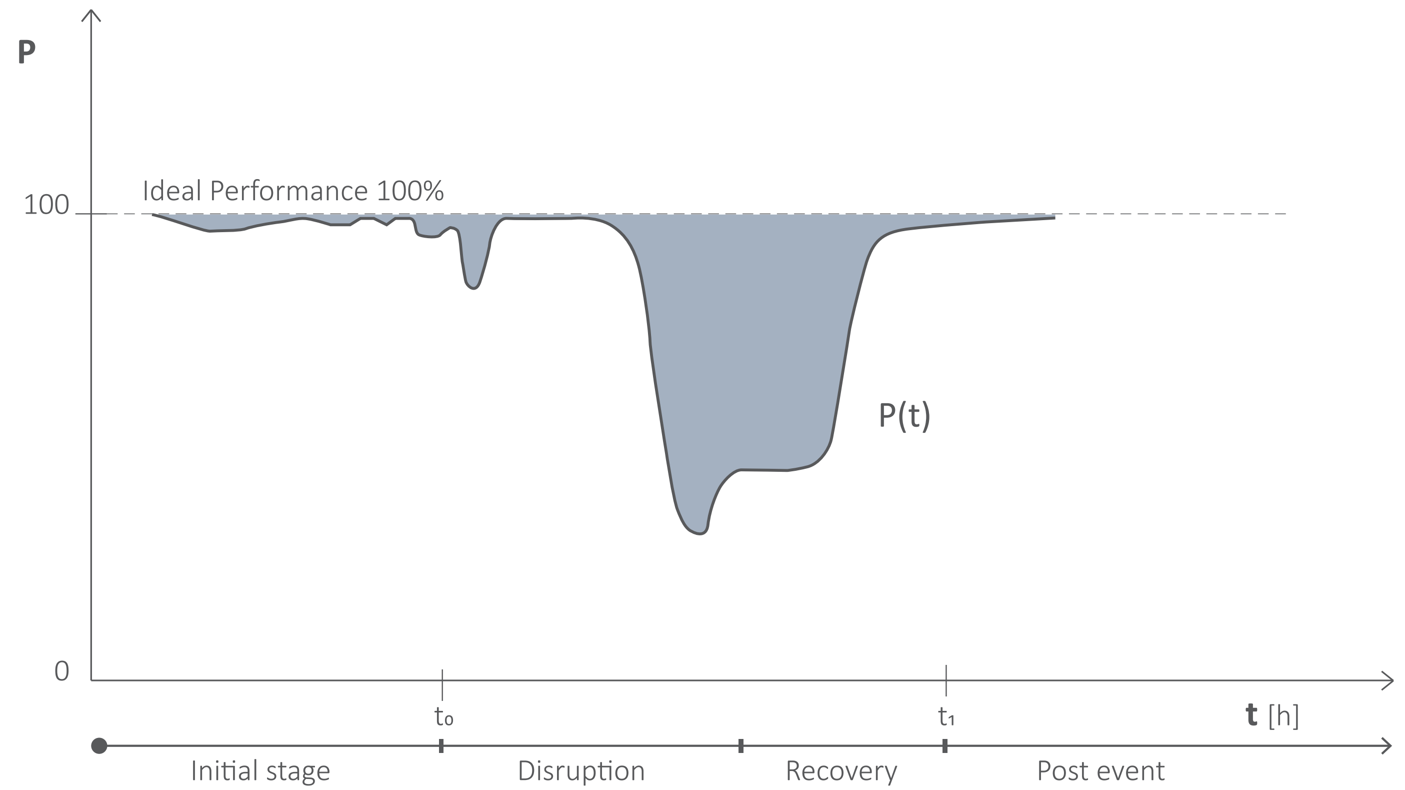


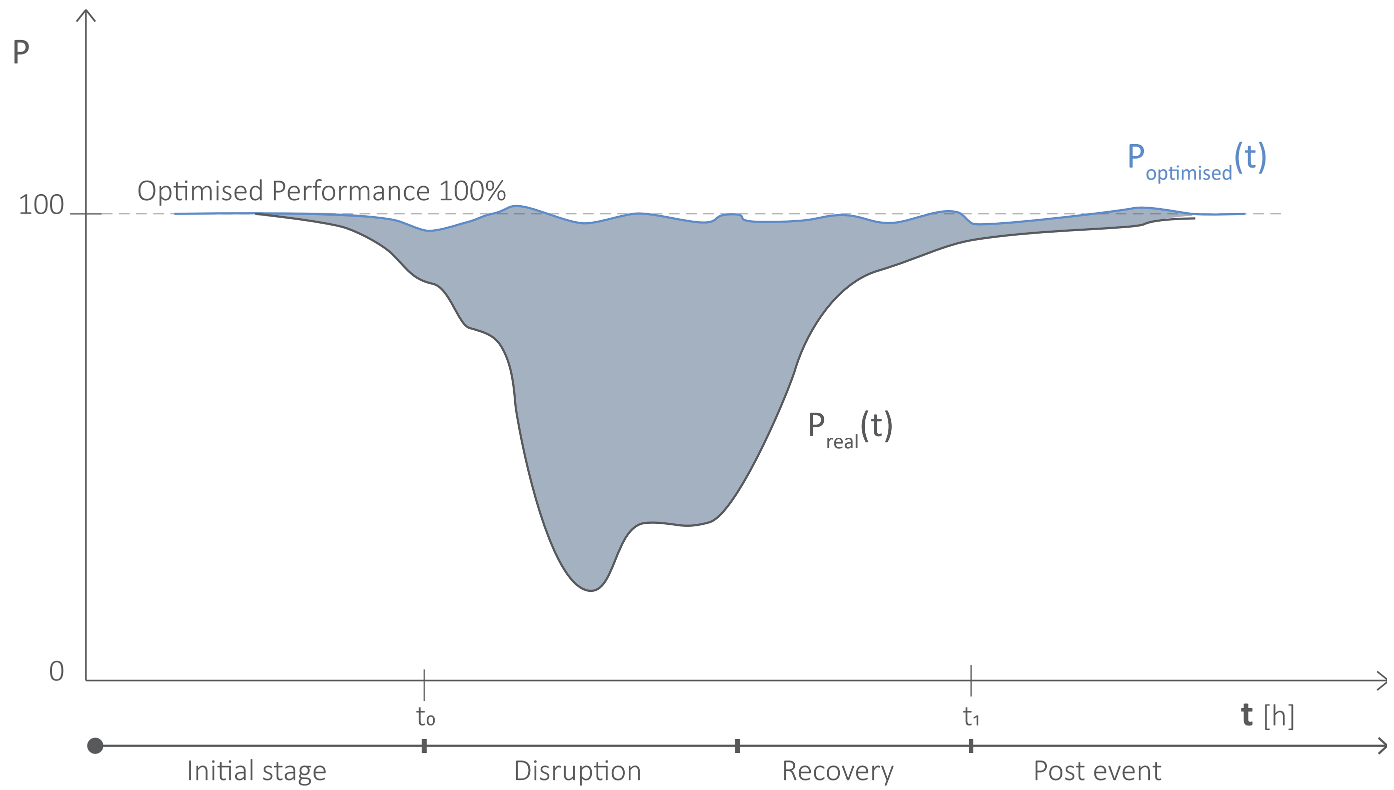
$$R_{Loss} = \int_{t_0}^{t_1} [100 - P(t)]\, dt$$

$$R_{Loss} = \int_{t_0}^{t_1} [p_{(t)}^{optimised} - p_{(t)}^{real}]\, dt$$

Quantification concept

Thermal resilience quantification

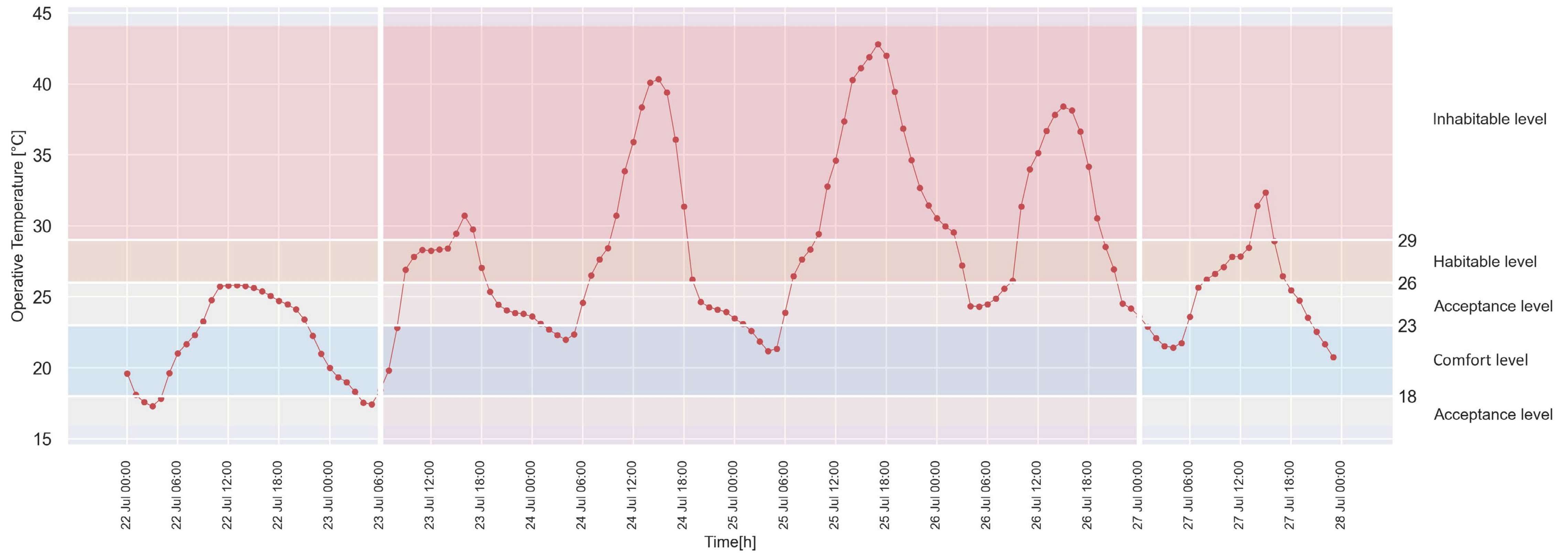




$$R_{Loss} = \int_{t_0}^{t_1} [100 - P(t)]\, dt$$

$$R_{Loss} = \int_{t_0}^{t_1} [p_{(t)}^{optimised} - p_{(t)}^{real}]\, dt$$

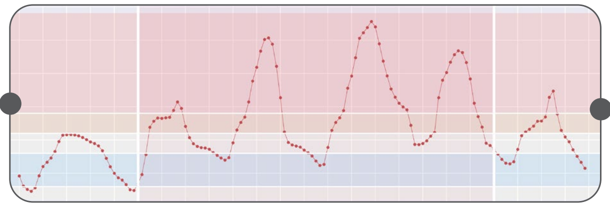
Thermal resilience quantification



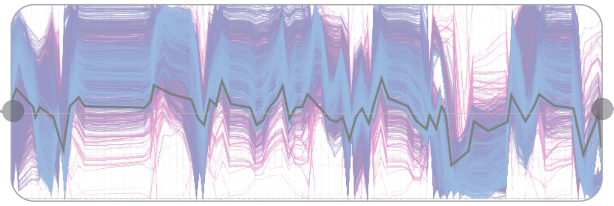
Hazard penalty
0.7
0.5
0.2
0.1

Energy Demand [kWh]
Cooling
Ventilation
>.hourly data

Operative Temperature [C]
T<18
18≤T<23
23≤T<26
26≤T<29
29≤T
>.hourly data



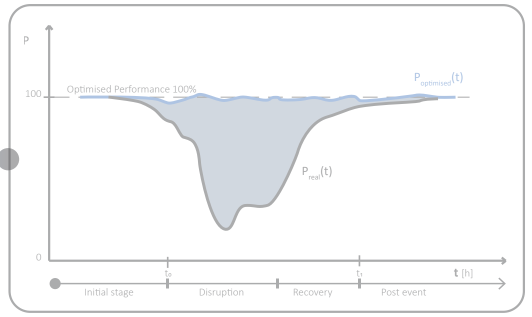
Opitmised Performance
Edemand x Toper



[T≈21ºC]

Building Performance
Edemand x W x Toper

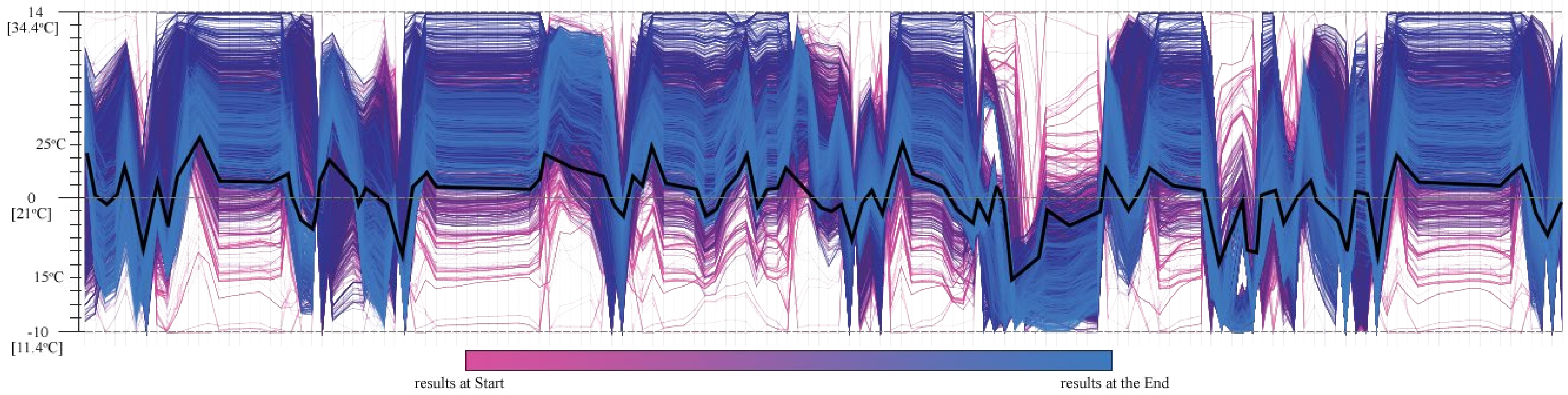
Poptimised - Preal

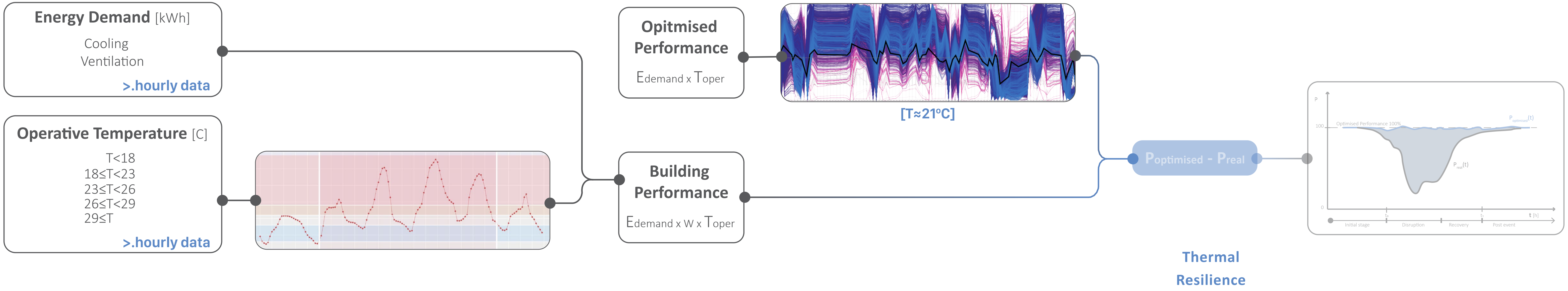


Thermal Resilience

Classification of the temperature values

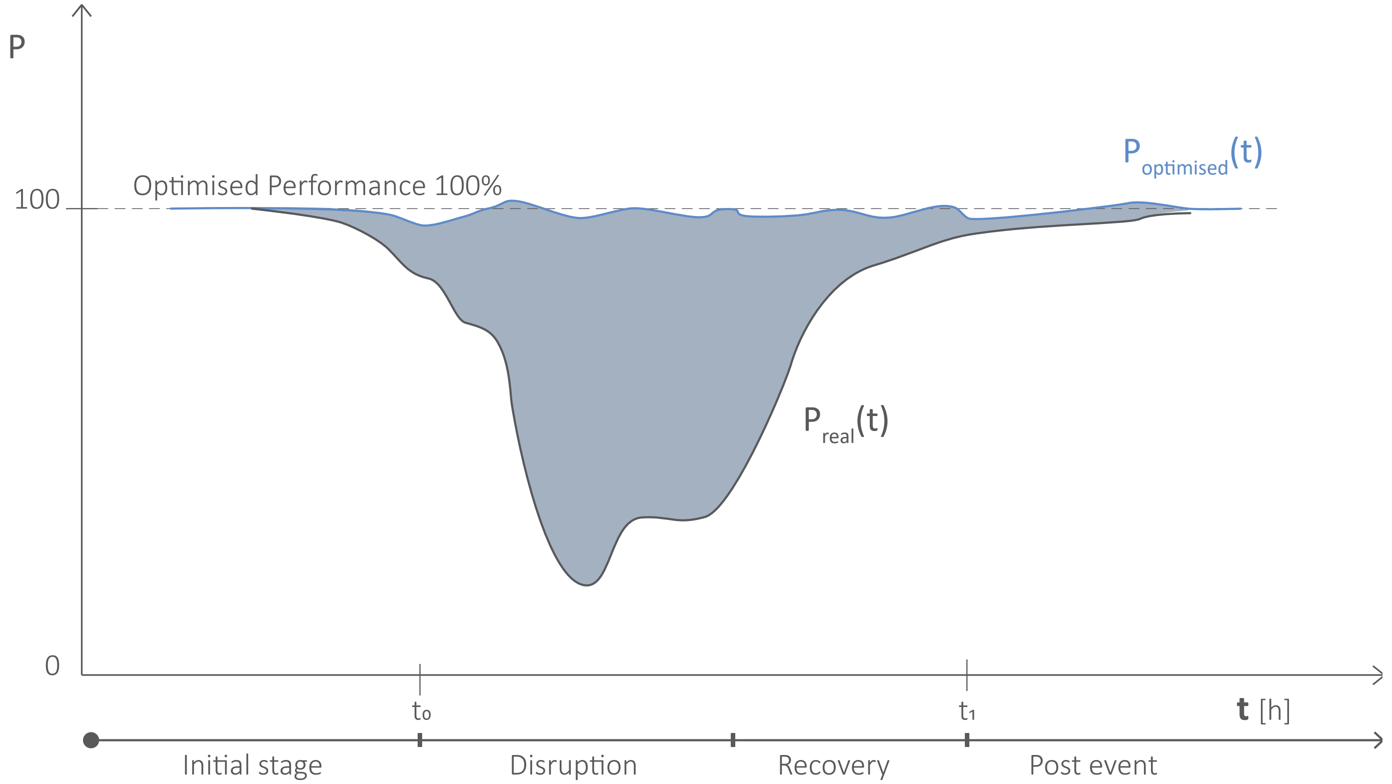
Thermal resilience quantification





Optimisation

Thermal resilience quantification



$$R_{Loss} = \int_{t_0}^{t_1} [p_{(t)}^{optimised} - p_{(t)}^{real}]\, dt$$

Energy Demand [kWh]

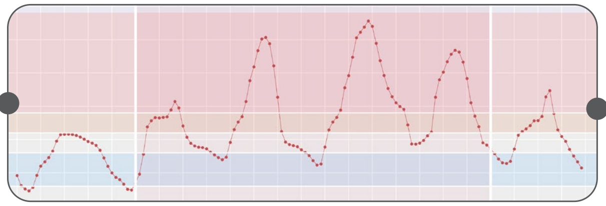
Cooling
Ventilation

>.hourly data

Operative Temperature [C]

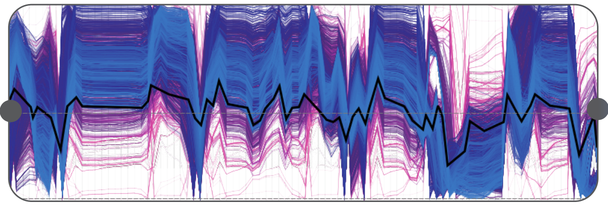
T<18
18≤T<23
23≤T<26
26≤T<29
29≤T

>.hourly data



Opitmised Performance

Edemand x Toper

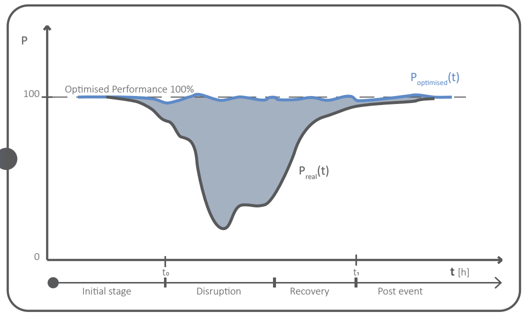


[T≈21ºC]

Building Performance

Edemand x W x Toper

Poptimised - Preal

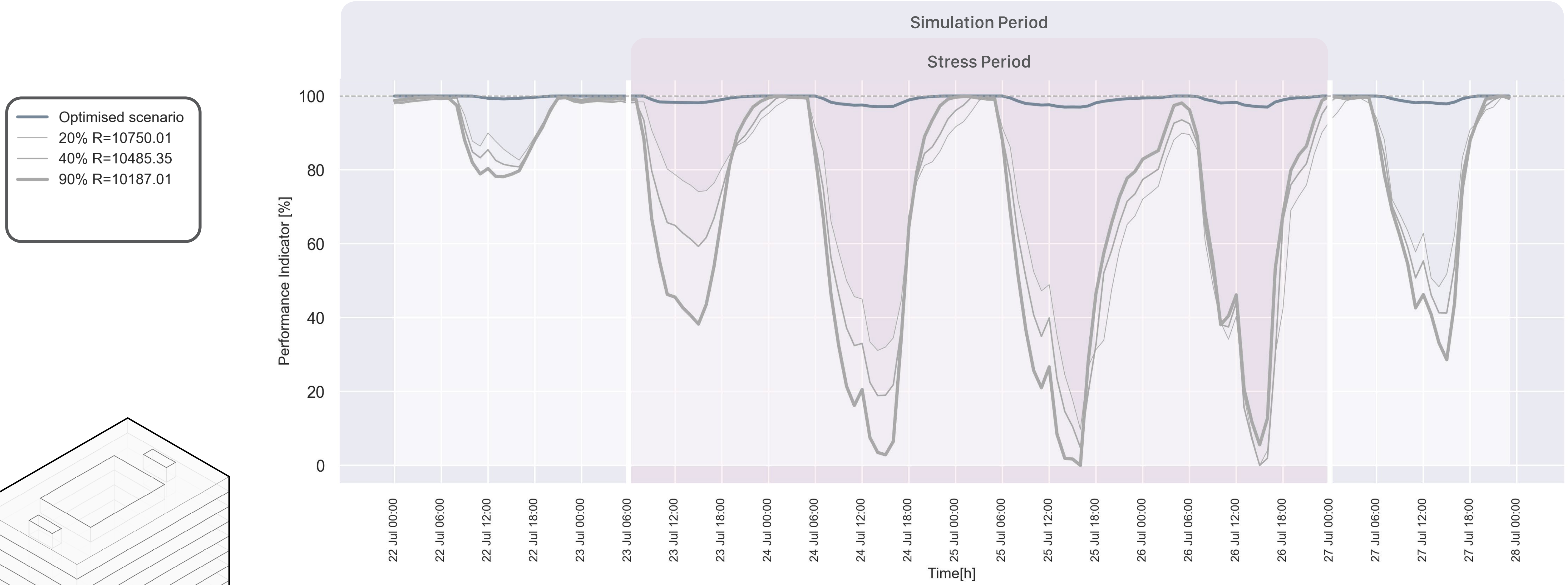


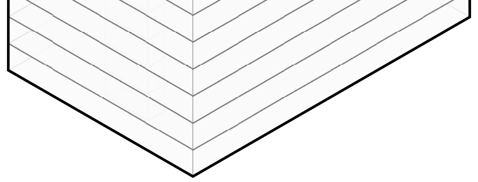
Thermal Resilience

Performance curve

Thermal Resilience Performance

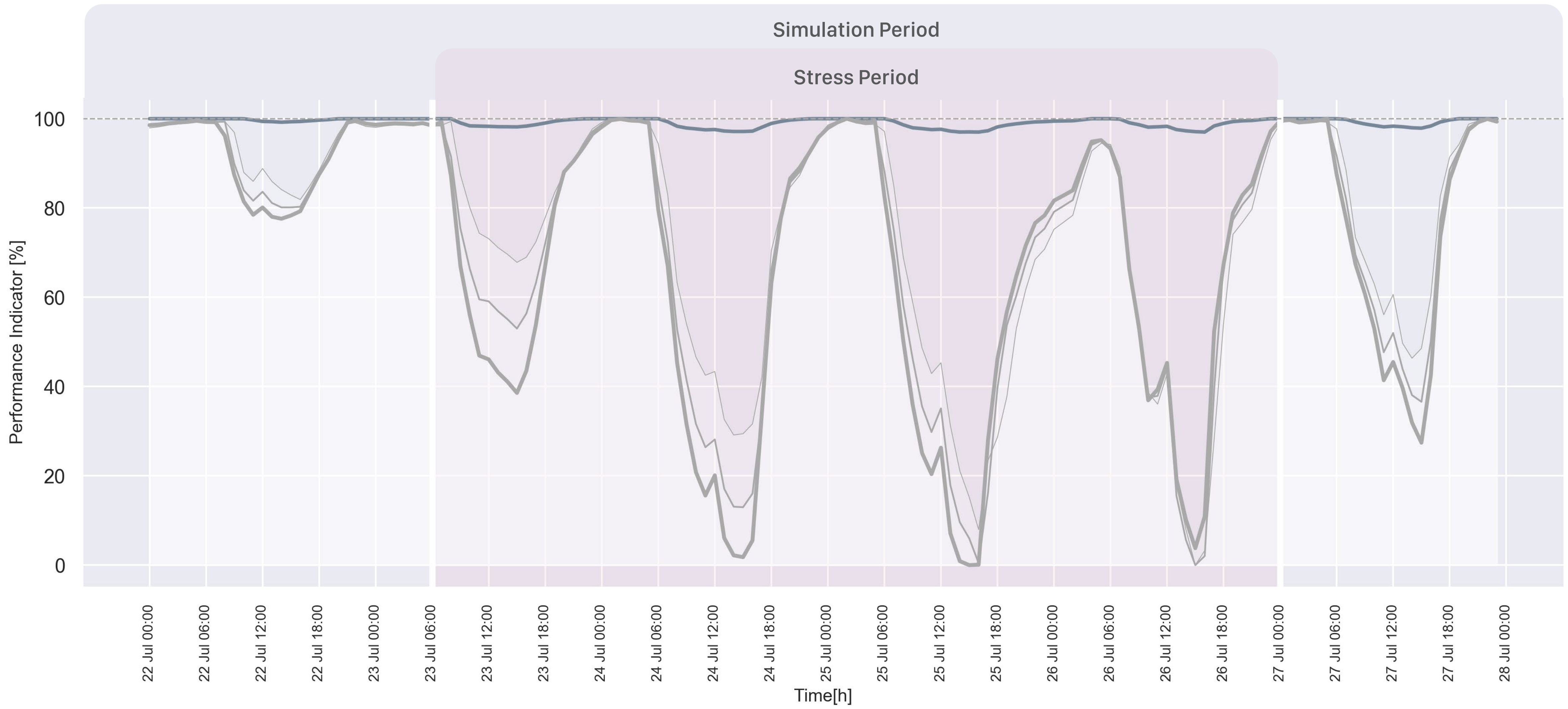
Thermal resilience performance:
different **wall-window ratio**

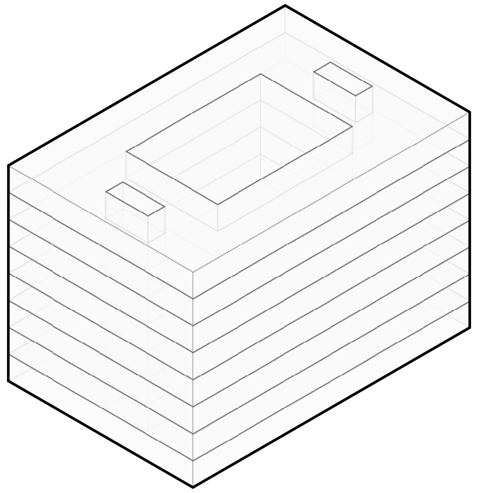




Entire building

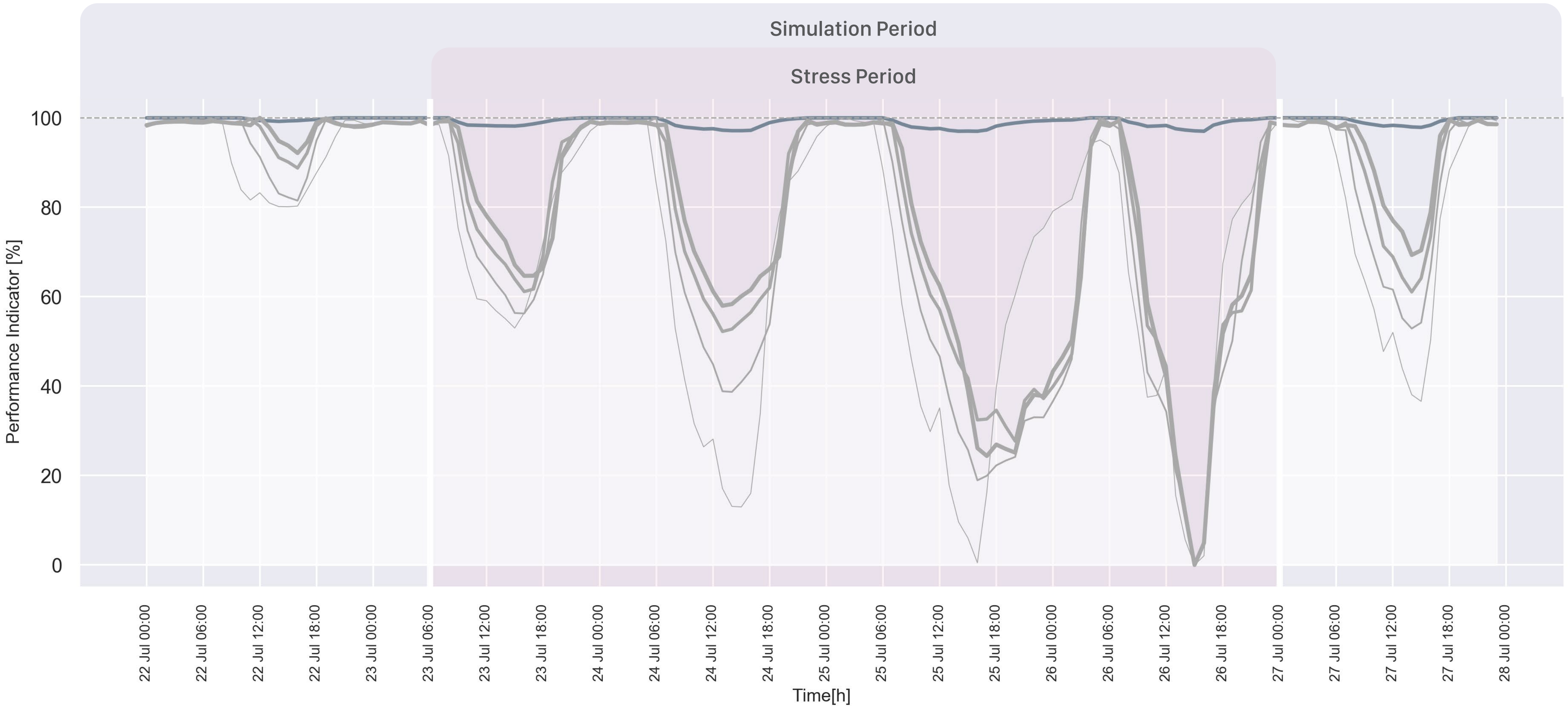
Thermal resilience performance:
different **solar-heat gain coefficient** (G-value)

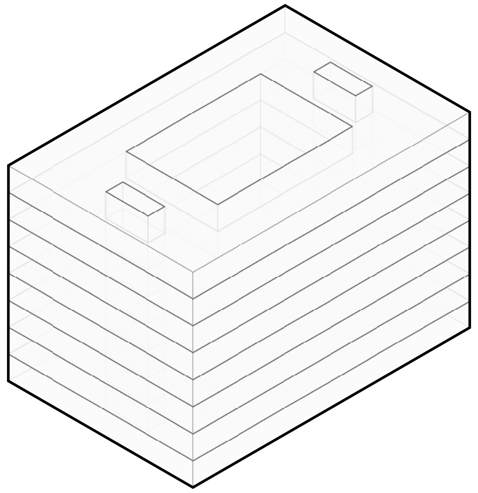




Entire building

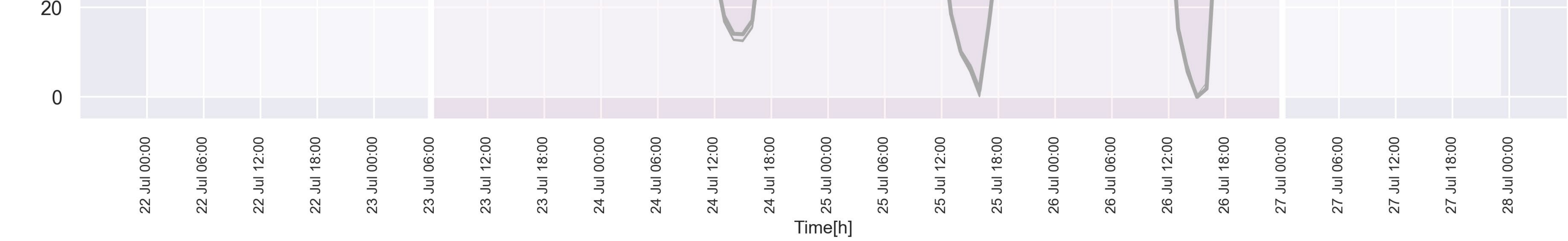
Thermal resilience performance:
different **air change/h** (ACH)

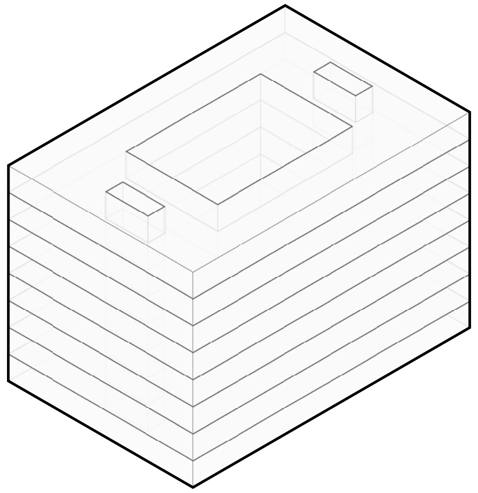




Entire building

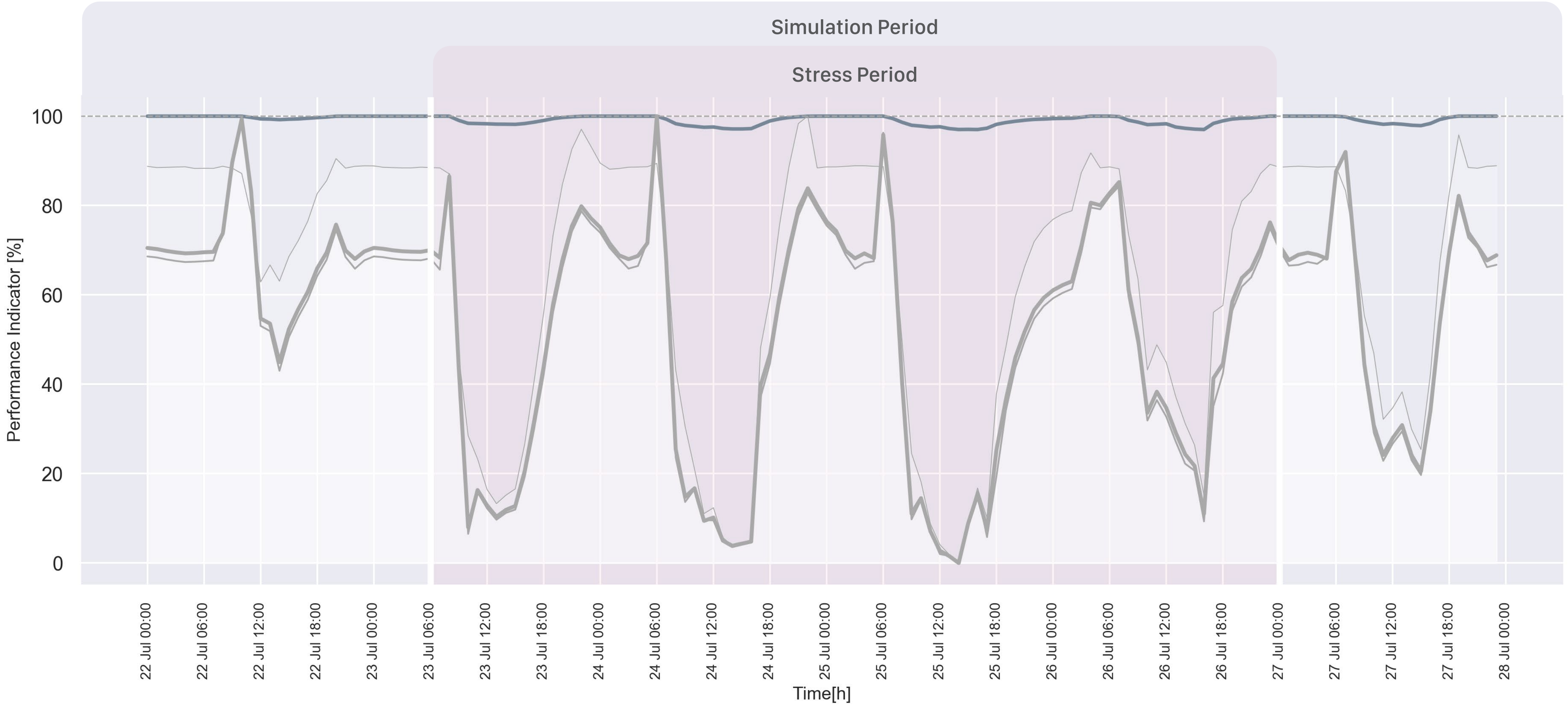
Thermal resilience performance:
different glazzing **thermal transmittance** (U-value)

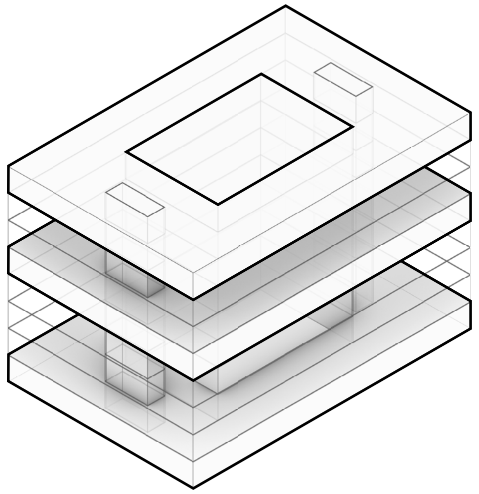




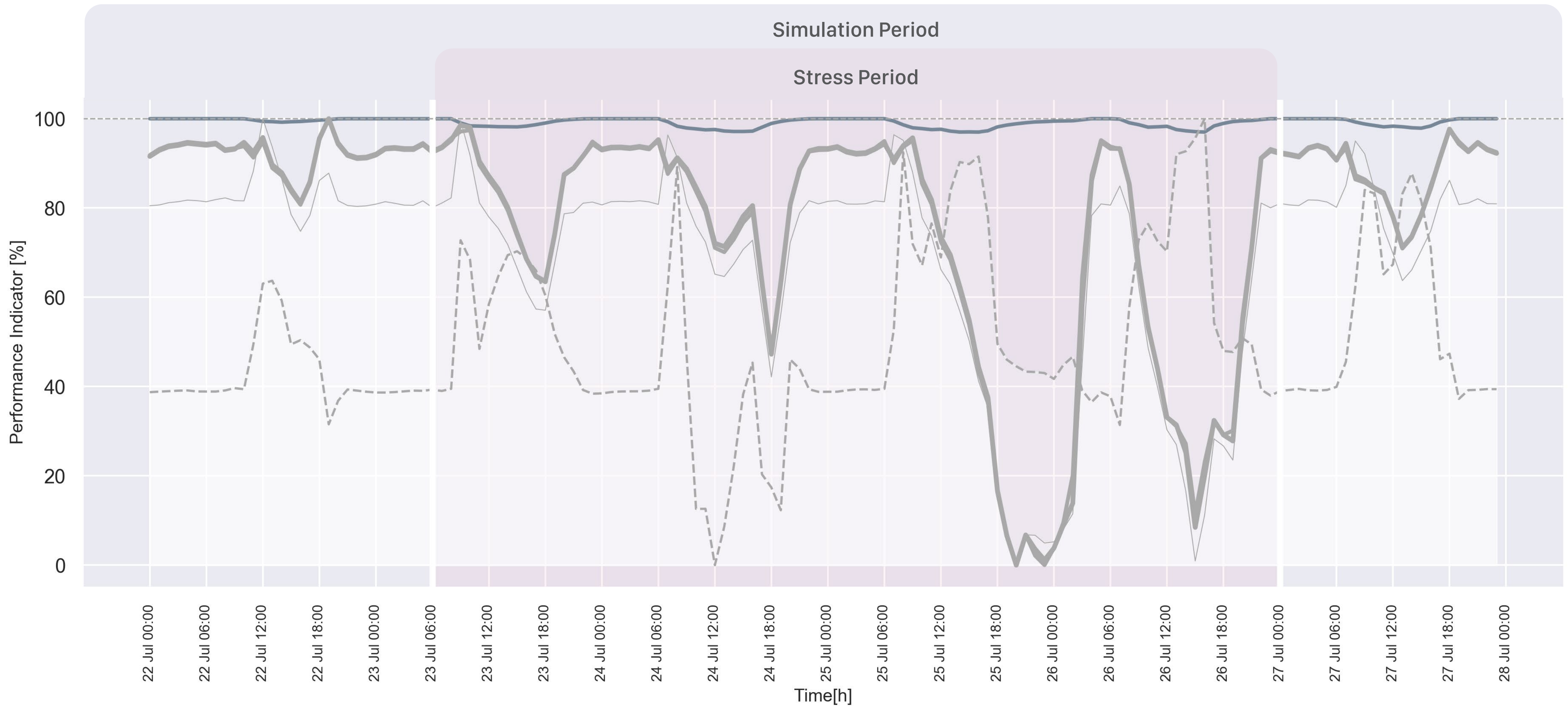
Entire building

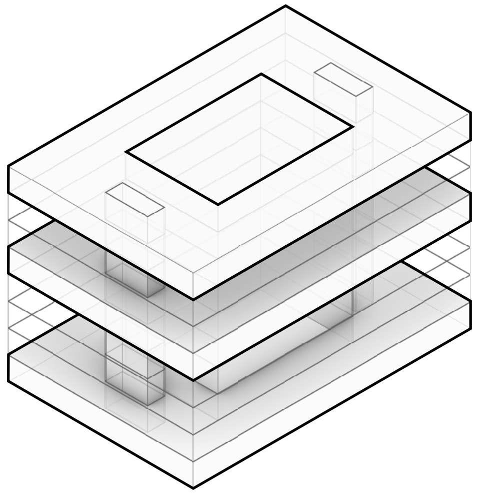
Thermal resilience performance:
floor comparison



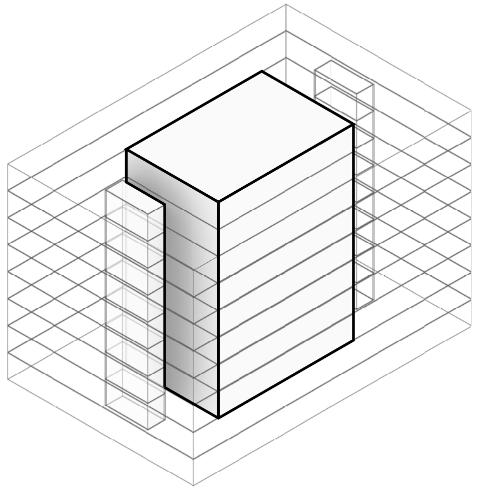


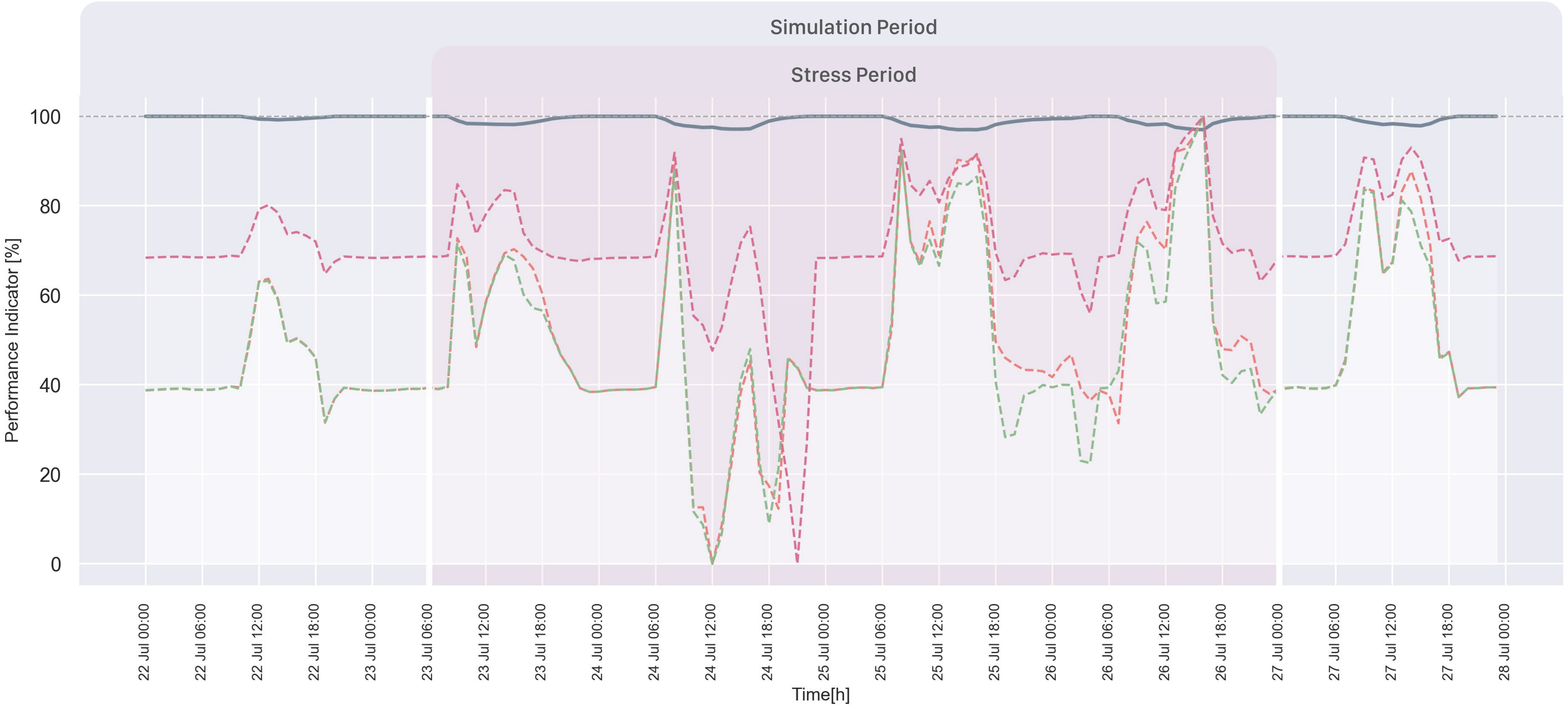
Thermal resilience performance:
floor - atrium comparison





Thermal resilience performance:
different **ACH in atrium**





Conclusion & Discussion

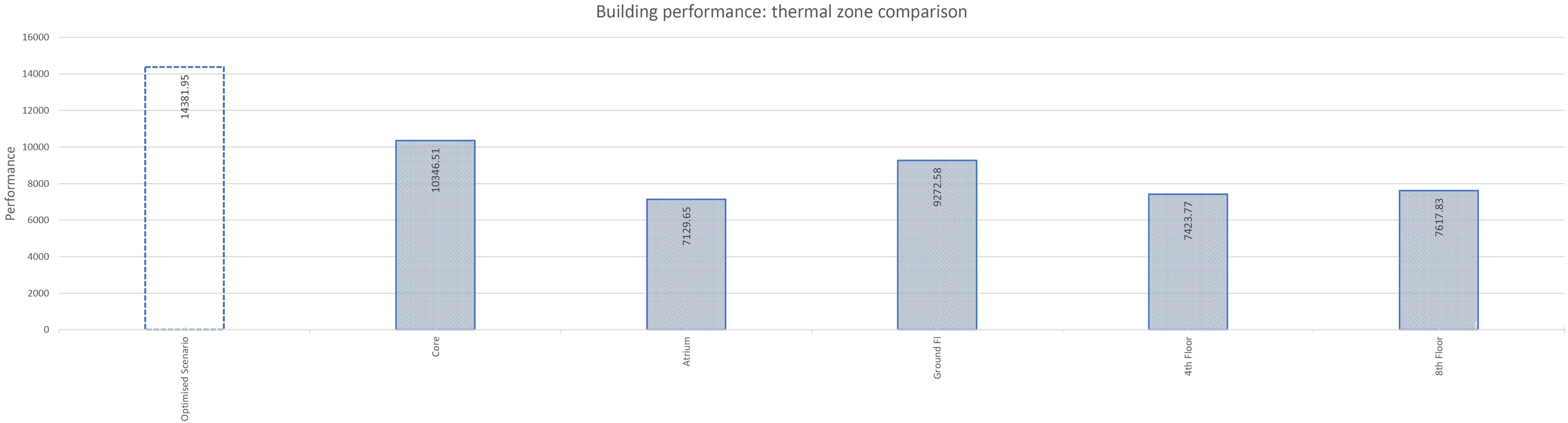
Conclusion
Discussion

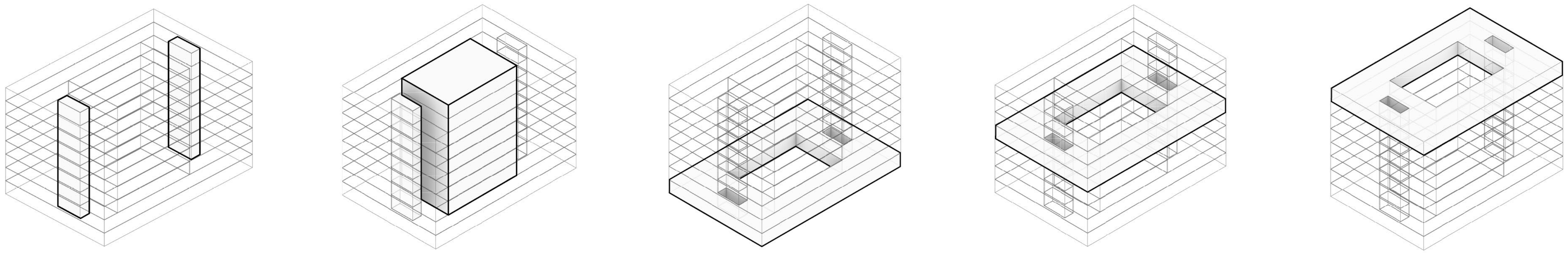
Influential parameters

Conclusion
Discussion

Case study outcomes

Thermal Zone Comparison





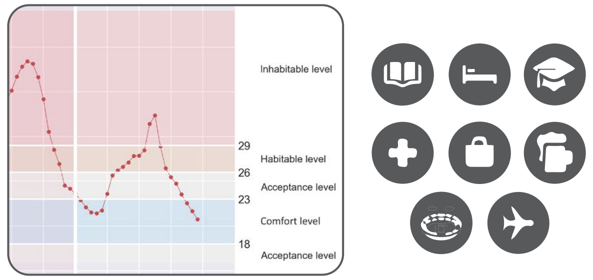
Conclusion
Discussion

Discussion

Large data handling and deep knowledge of **climate modeling**

Time-consuming and high computational **cost** process

Levels of comfort can vary for different **building types**



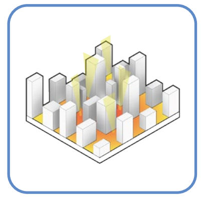
Multidisciplinary research that engages the fields of building, climate, computer sciences

Further Development

Suggestions for Further development

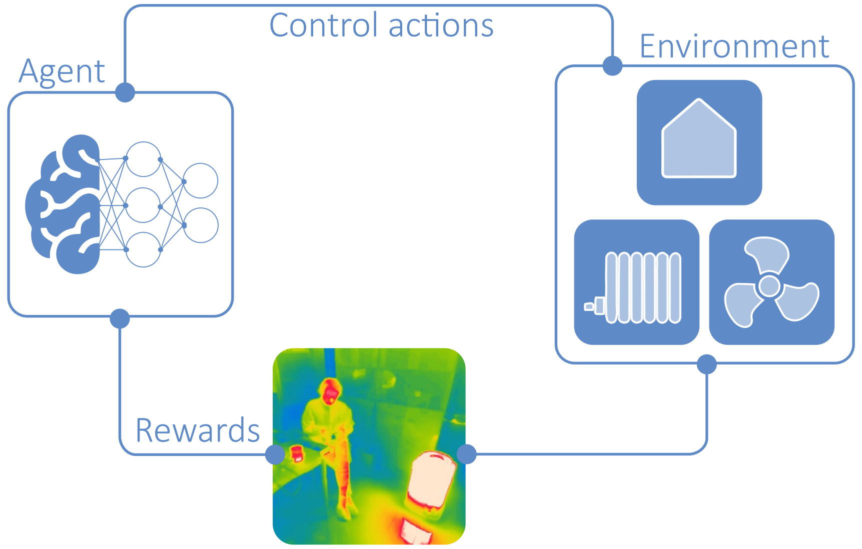
Labelling buildings according to their Resilience Class

Entire building simulation with **eppy** library



Expand to the **urban scale** Urban Heat Islands

Implementation of **RL** and CNN in existing buildings



Thank you!

TU Delft ARUP

June 2023