MSc Graduation Presentation on:

Resilience-based Facade Design Framework

Kyujin Kim

TU Delft

date

Monday, 3rd July 2023

09:00 CEST (16:00 KST)

schedule

08:45-09:00 I Doors Open

09:00-09:30 I Presentation

09:30-10:00 I Q&A from Jury

10:00-10:15 I Ceremony

in person:

Hall F, TU Delft BK

online:

https://teams.microsoft.com/l/meetup-join/19%3ameeting_Y2UxMjMzZmMtZGZkMy00MzhjLWIxMDYtZWMxODZmNjU3ODU0%40thread.v2/0?context=%7b%22Tid%22%3a%22096e524d-6929-4030-8cd3-8ab42de0887b%22%2c%22Oid%22%3a%226568c6ec-fed2-4a07-a48a-44176b69a1ab%22%7d

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Resilience-based Facade Design Framework

Kyujin Kim

TU Delft

presenter

Kyujin Kim

Delft University of Technology

Building Technology Track

Class of 2023

supervisors

Simona Bianchi I Structural Design & Mechanics

Alessandra Luna Navarro I Façade & Product Design

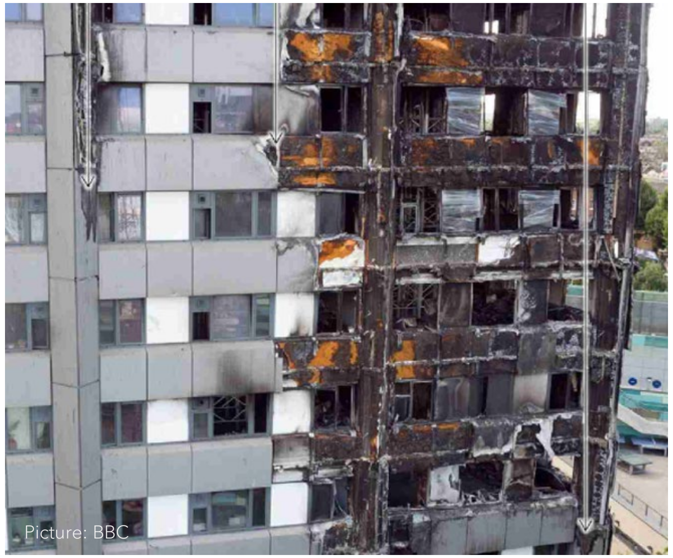
external supervisor

Jonathan Ciurlanti I Arup Amsterdam

delegate

Willem Korthals Altes I Urban Development Management


Picture: Wang Zhuangfei


Picture: BBC


Picture: Thornton Tomasetti


Picture: Eduardo Miranda


Picture: Sebastian Schula


Blast
Picture: Wang Zhuangfei

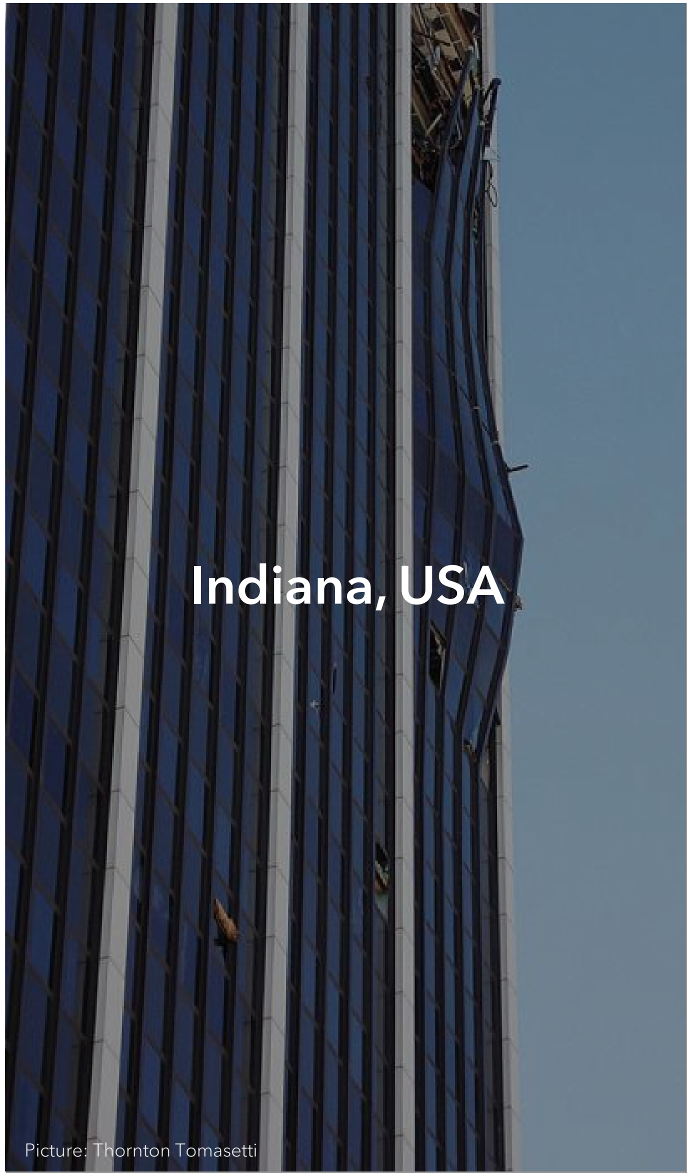

Wind
Picture: Thornton Tomasetti


Earthquake
Picture: Eduardo Miranda


Fire
Picture: BBC

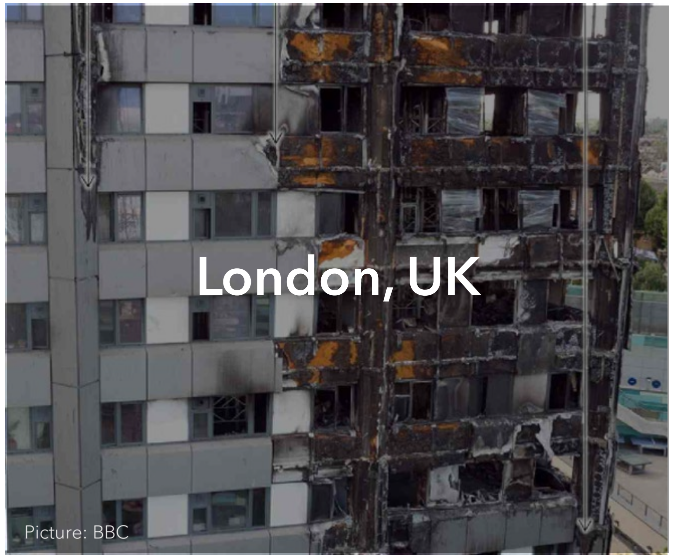

Temperature
Picture: Sebastian Schula

Picture: Wang Zhuangfei



Picture: Thornton Tomasetti

Picture: Eduardo Miranda

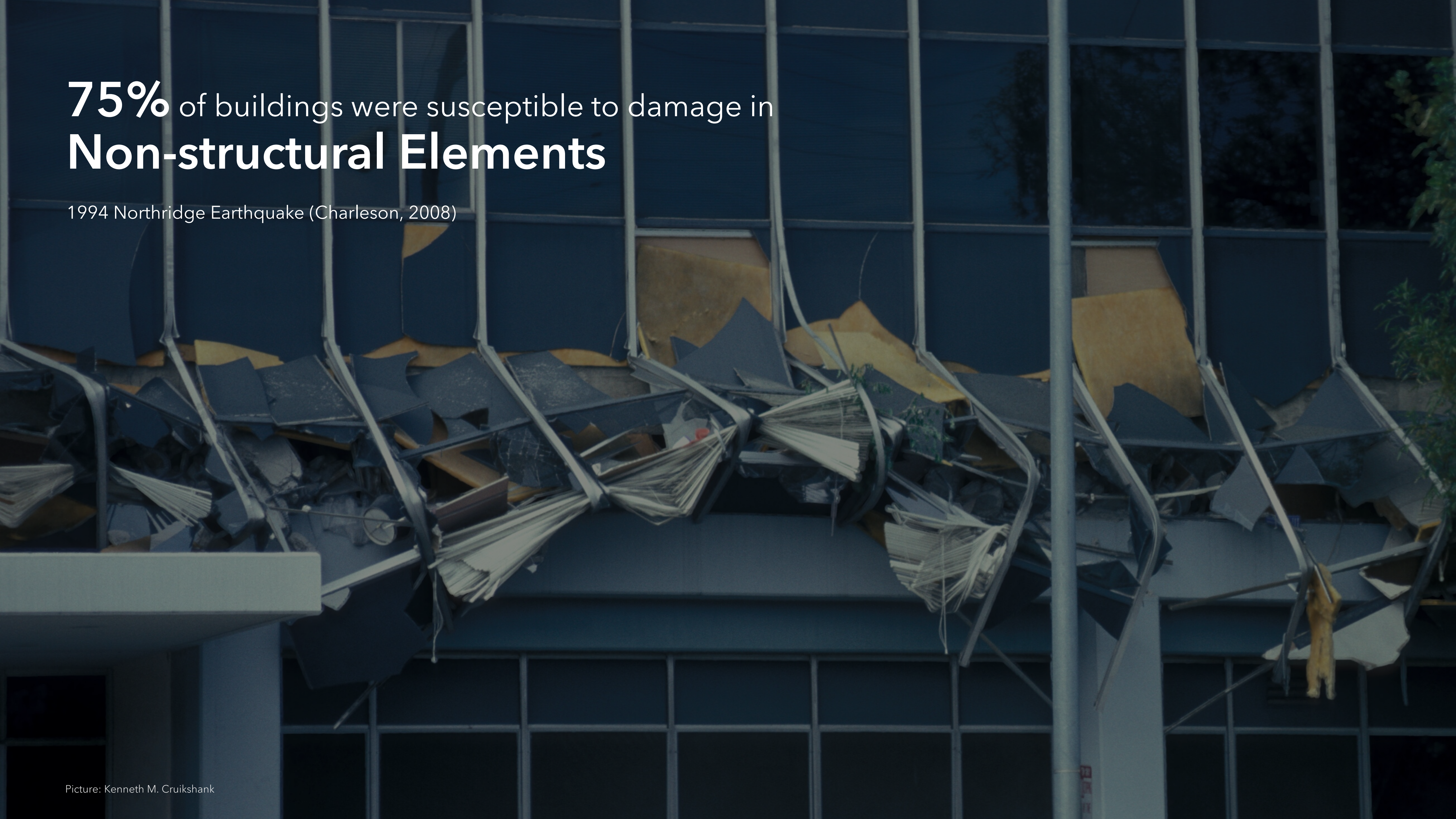


Picture: BBC

Picture: Sebastian Schula


hazard
Risk
vulnerability
exposure


hazard
vulnerability
Resilience
exposure
adaptability


75% of buildings were susceptible to damage in
Non-structural Elements
1994 Northridge Earthquake (Charleson, 2008)
Picture: Kenneth M. Cruikshank

Implement Policies for Inclusion,
Resource Efficiency, and
Disaster Risk Reduction

Sustainable Development Goals (Target 11B)

11

Picture: United Nations

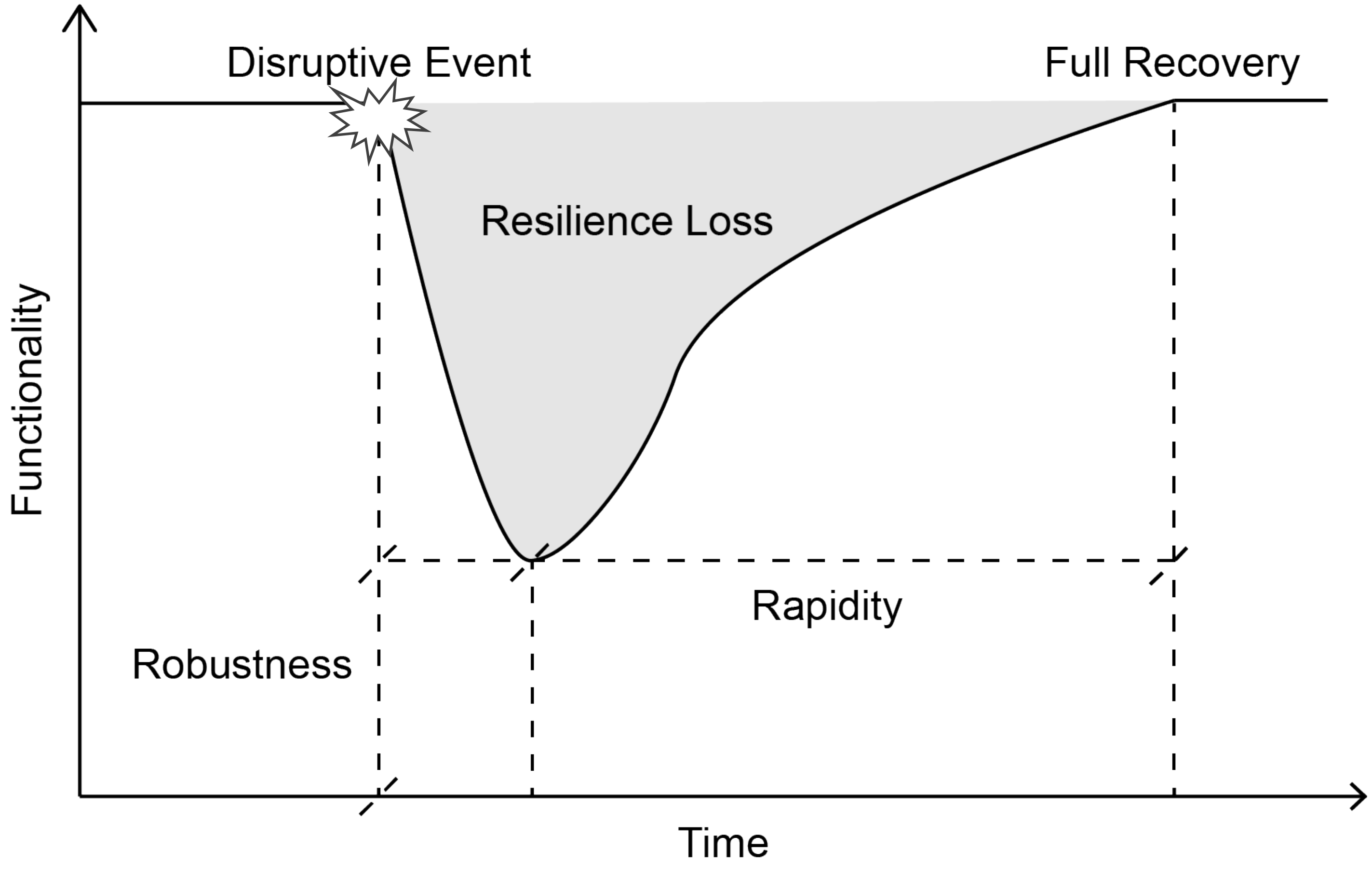
Resilience-based

Facade Design Framework

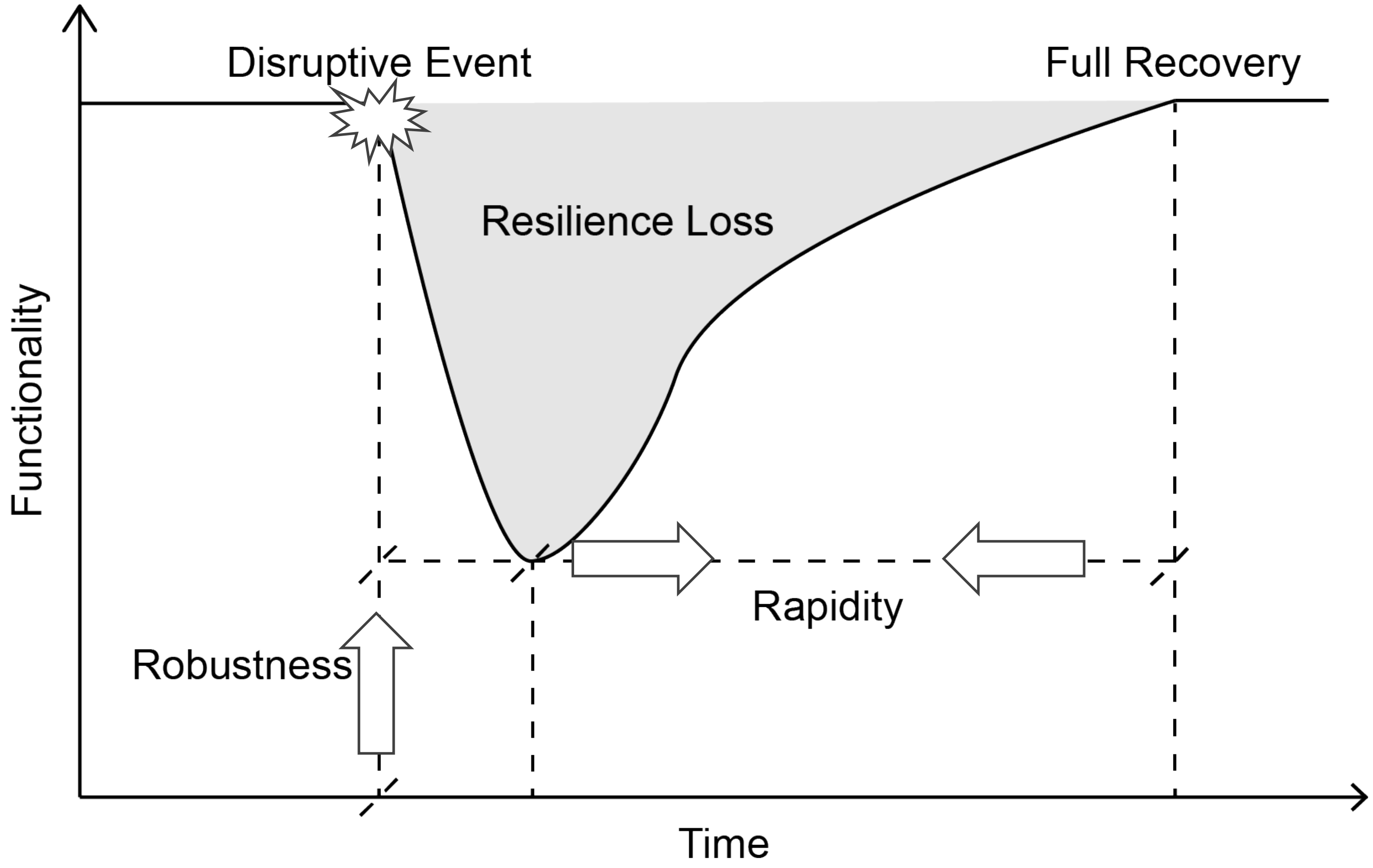
State of Art	**Framework**	**Case Study**	**Evaluation**
1	2	3	4

State of Art	Framework	Case Study	Evaluation
1	2	3	4

Engineering Resilience

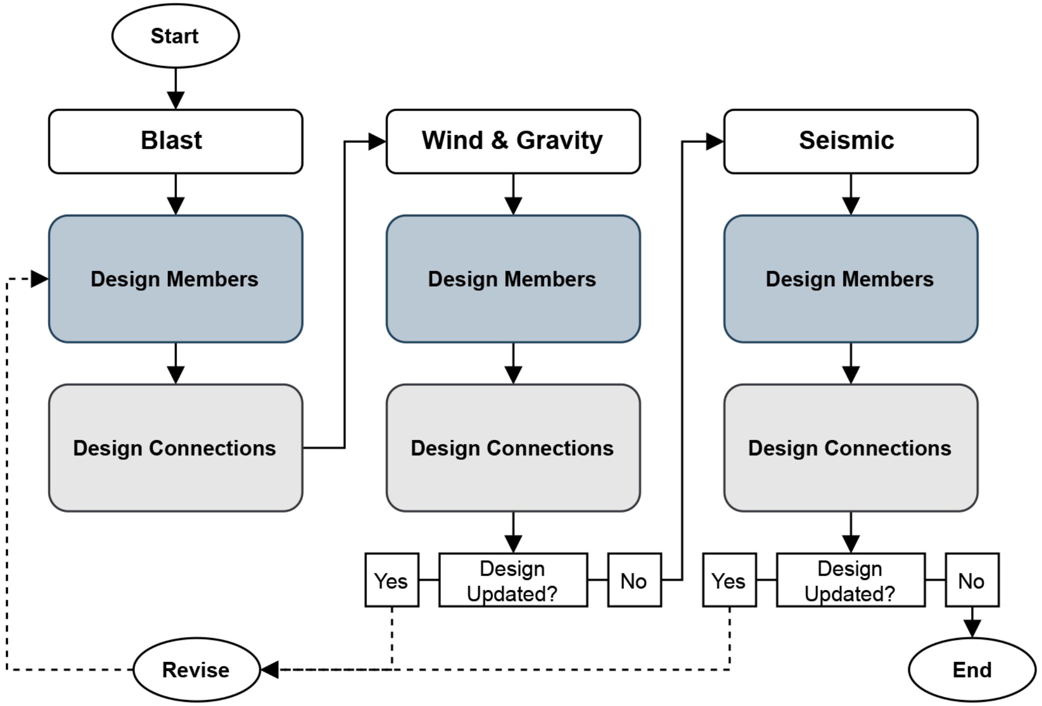


Engineering Resilience

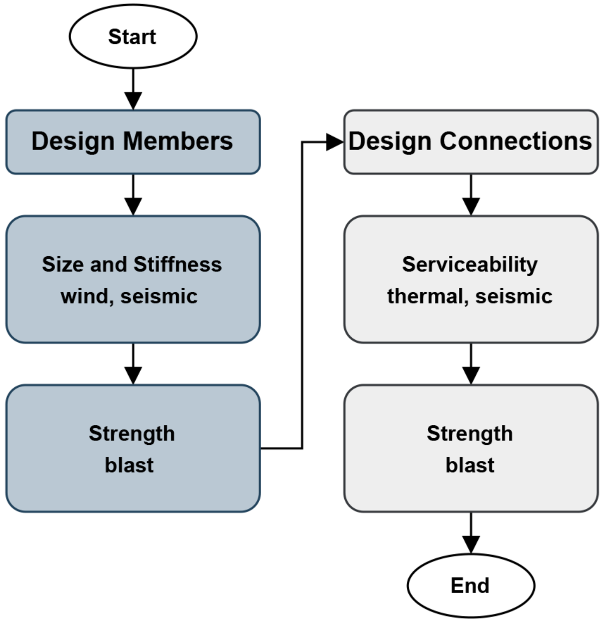


Resilience-based design approach aims for minimizing disruption impact and facilitating prompt recovery to operational status.

Design process for multiple hazards



Compartmentalized by discipline, adapted from Mckay et al. (2015)



Compartmentalized by task, adapted from Mckay et al. (2015)

Research Gap

1. The need for **resilience-based design** in facade engineering

2. The need to **integrate multi-hazards** into the design process

Research Question

What **methodology** can be developed to assess the resilience of facade systems under multiple hazards, and how can this methodology be integrated into the facade design process?

Research Objective

Framework Development

State of Art

1

Framework

2

Case Study

3

Evaluation

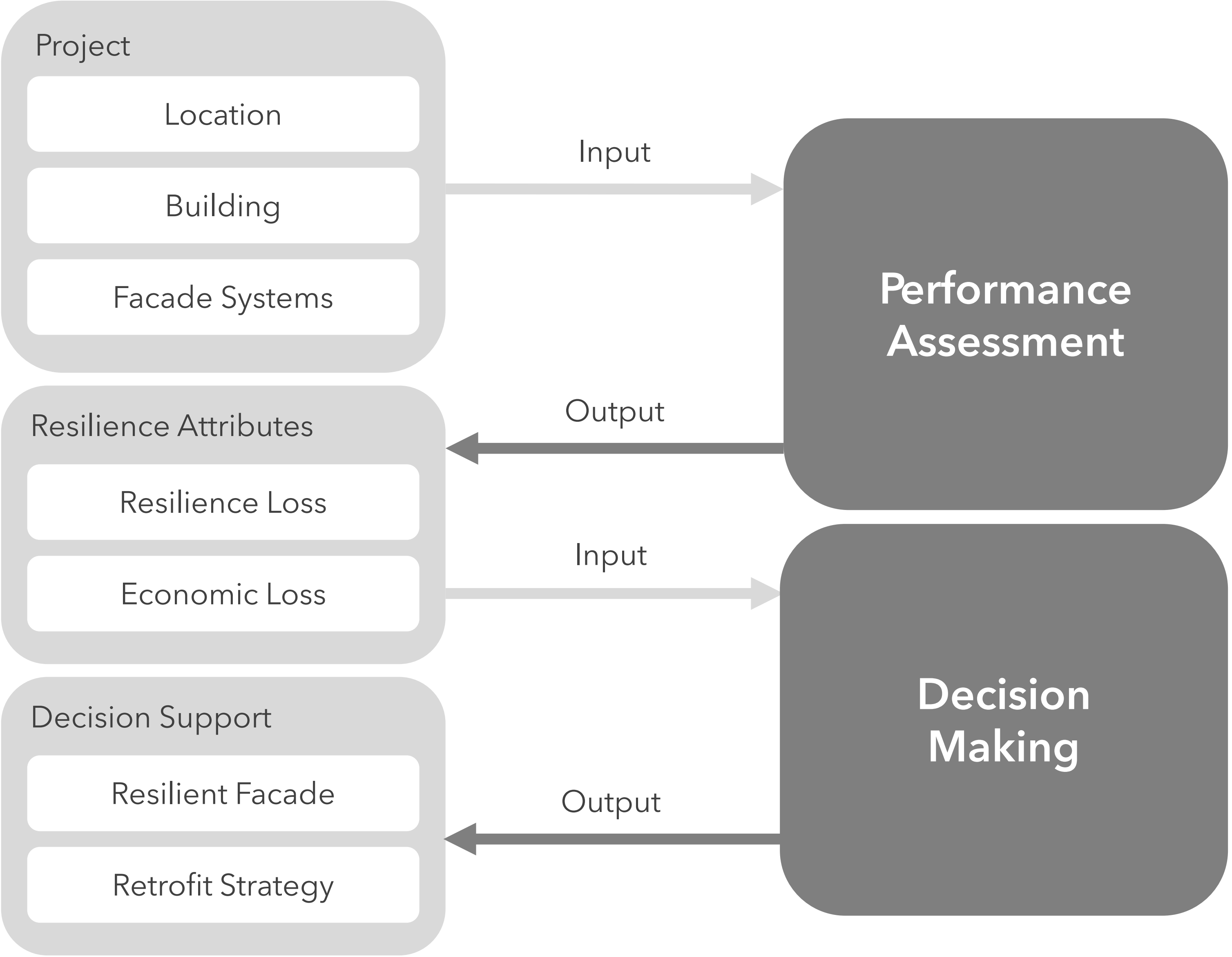
4

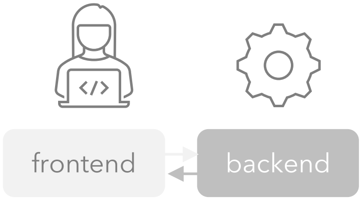
Resilience-based

Facade Design Framework

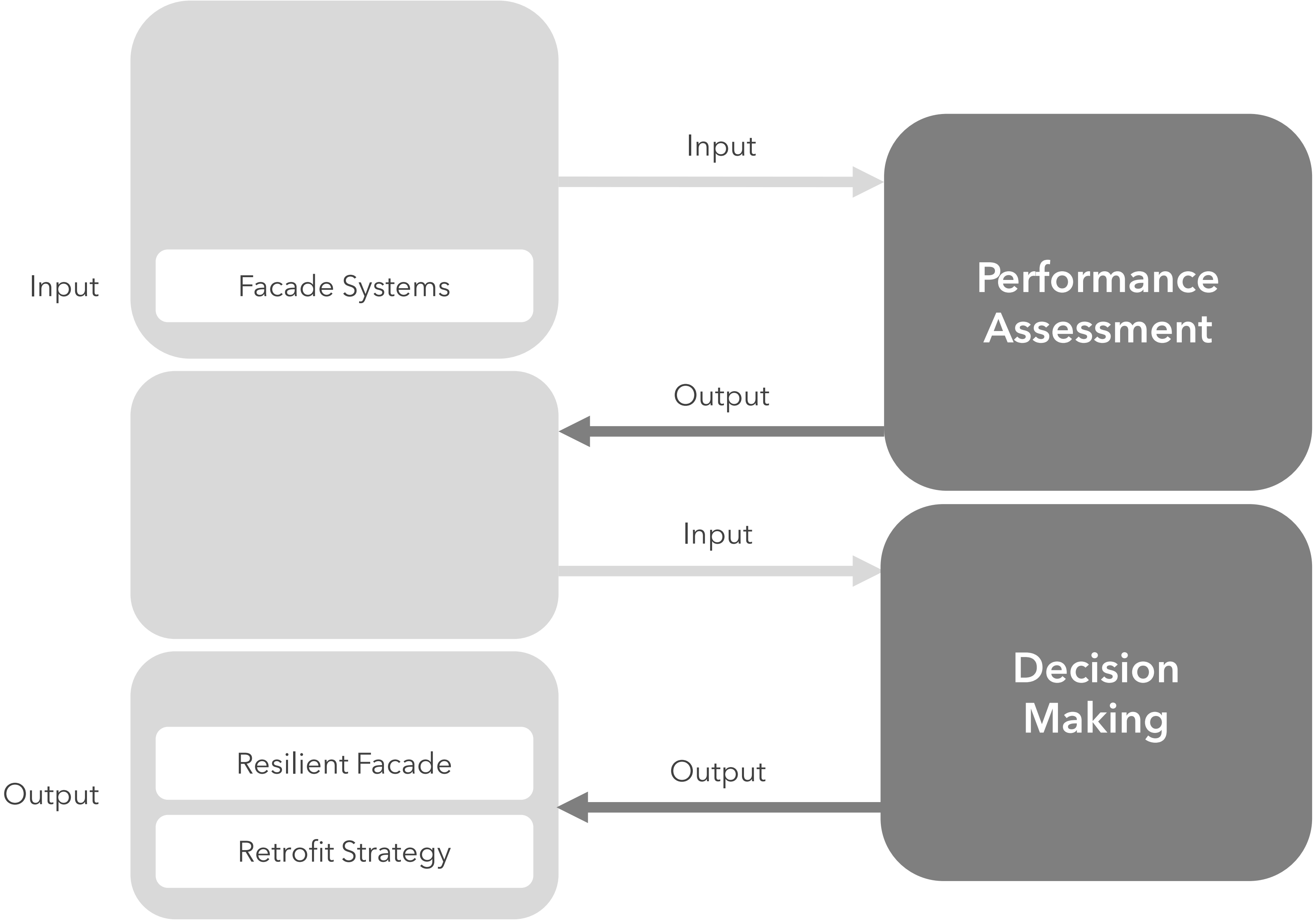
1. Digital Tool for Engineers
2. Multi-Hazard Approach
3. Quantitative Approach

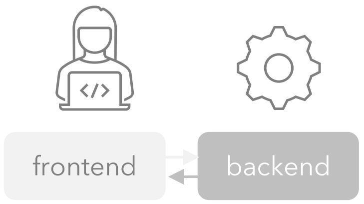
1. Digital Tool for Engineers



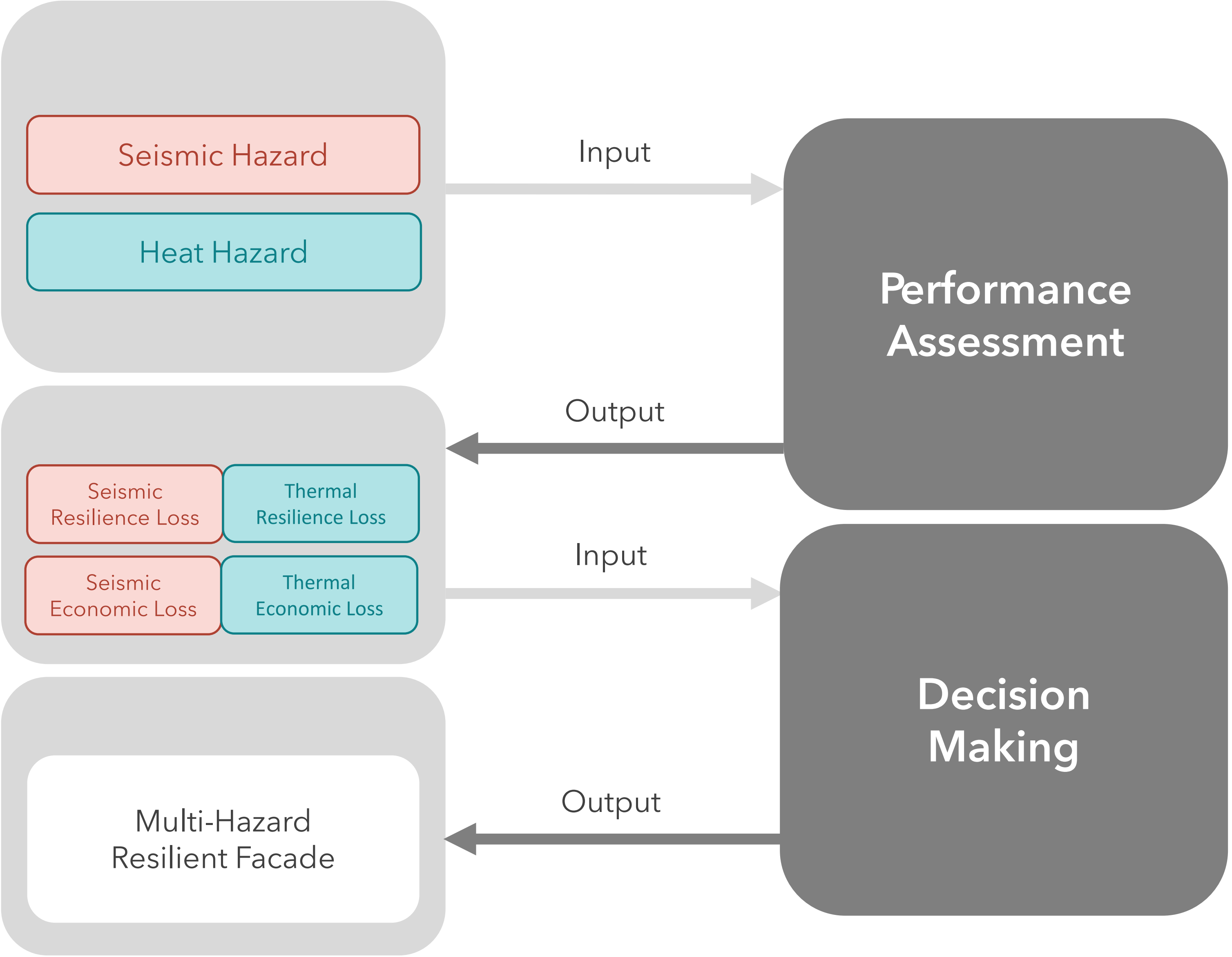


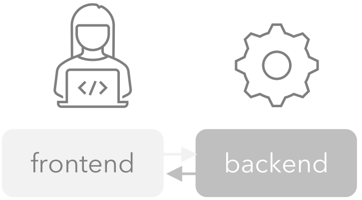
1. Digital Tool for Engineers



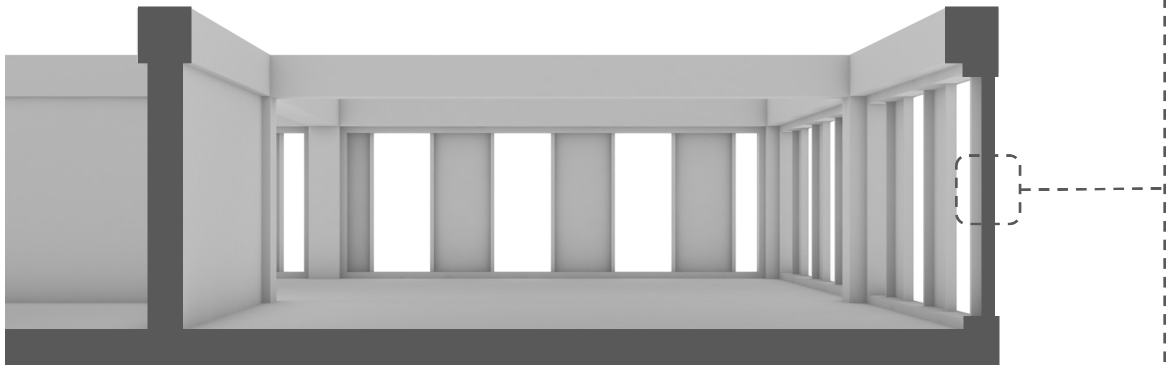


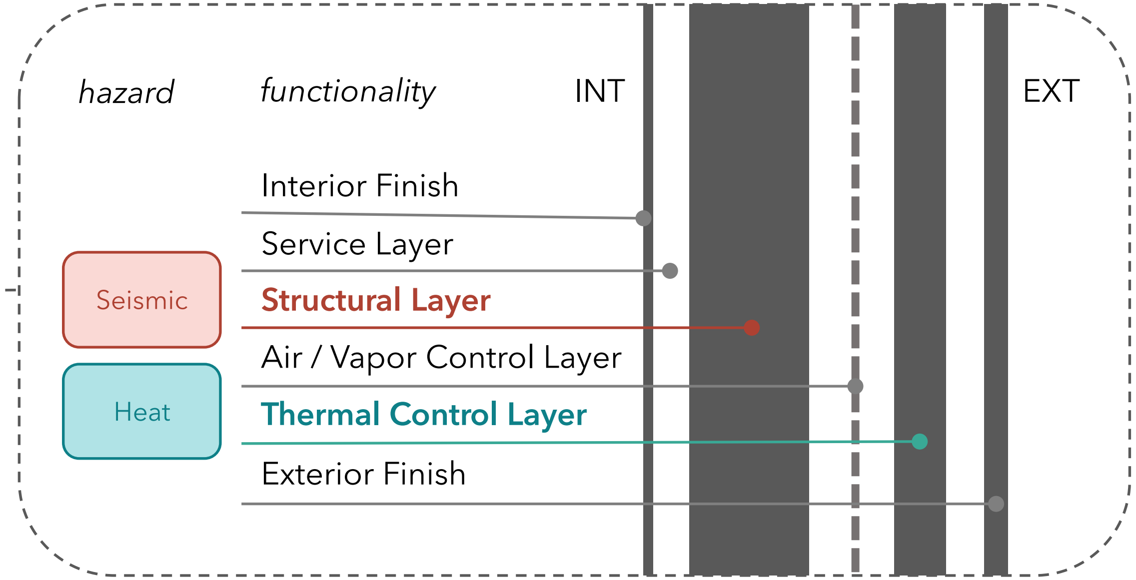
2. Multi-Hazard Approach



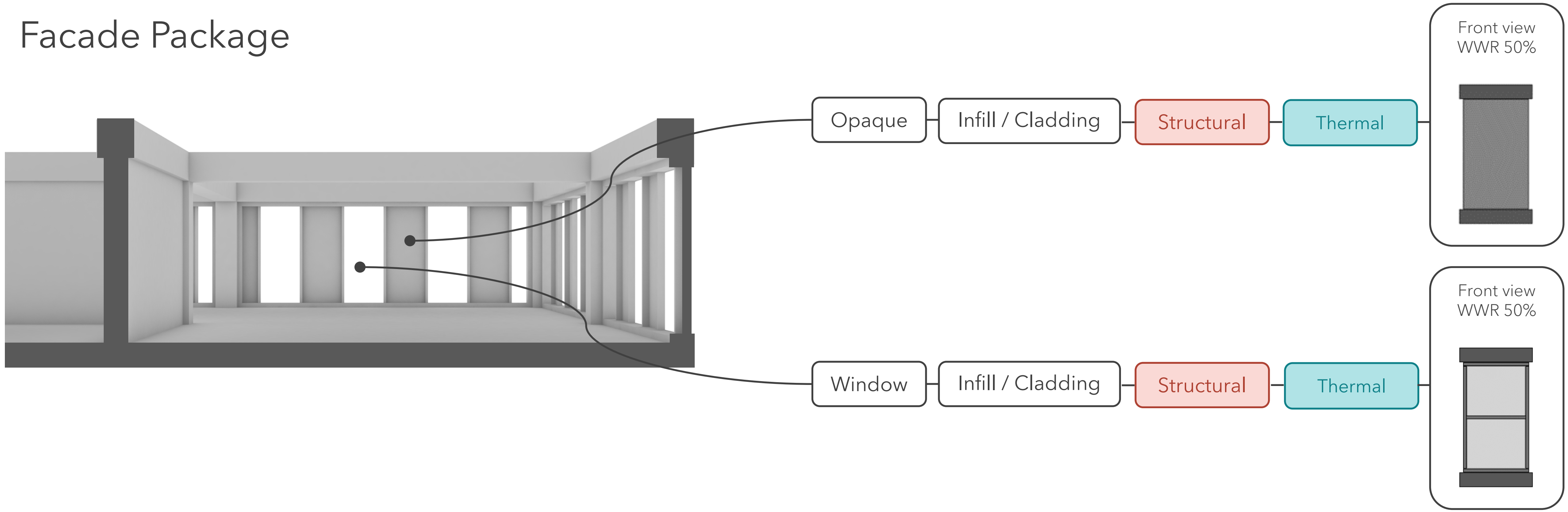


2. Multi-Hazard Approach



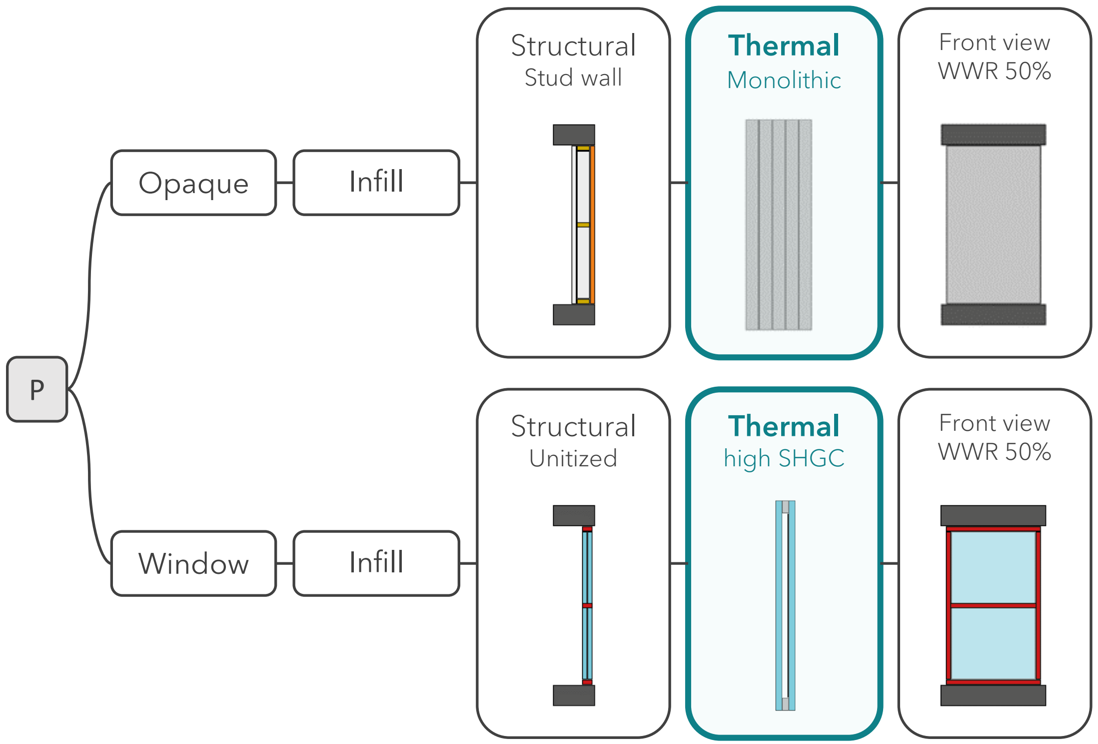


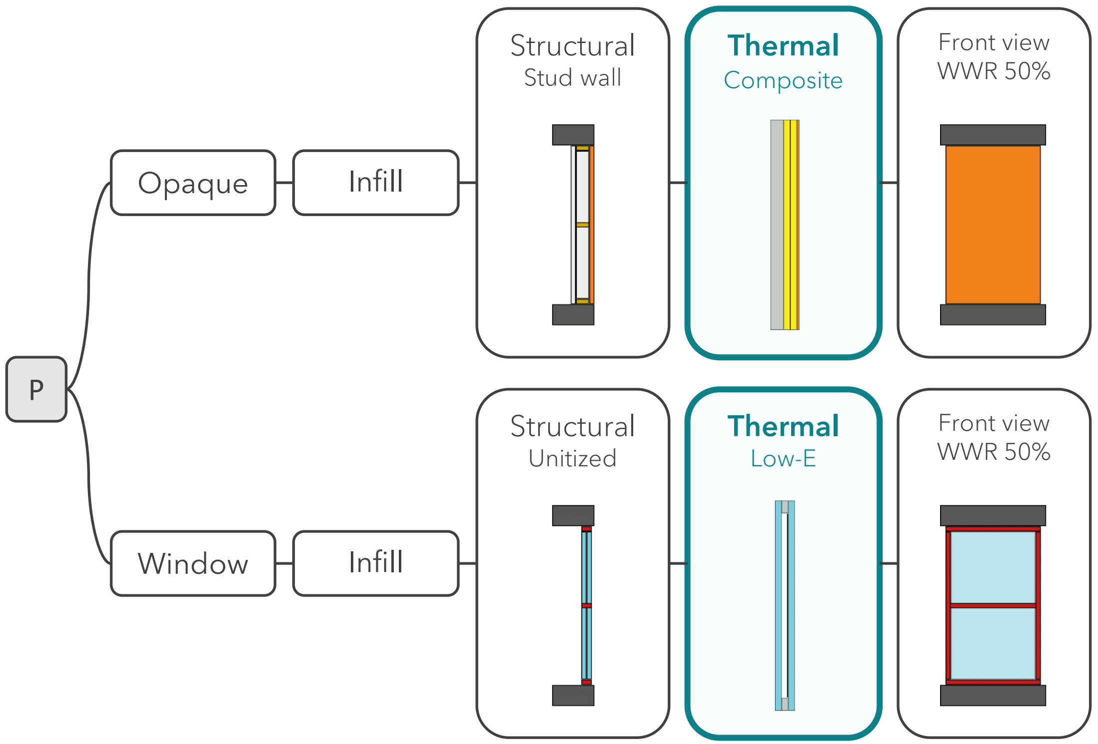
2. Multi-Hazard Approach



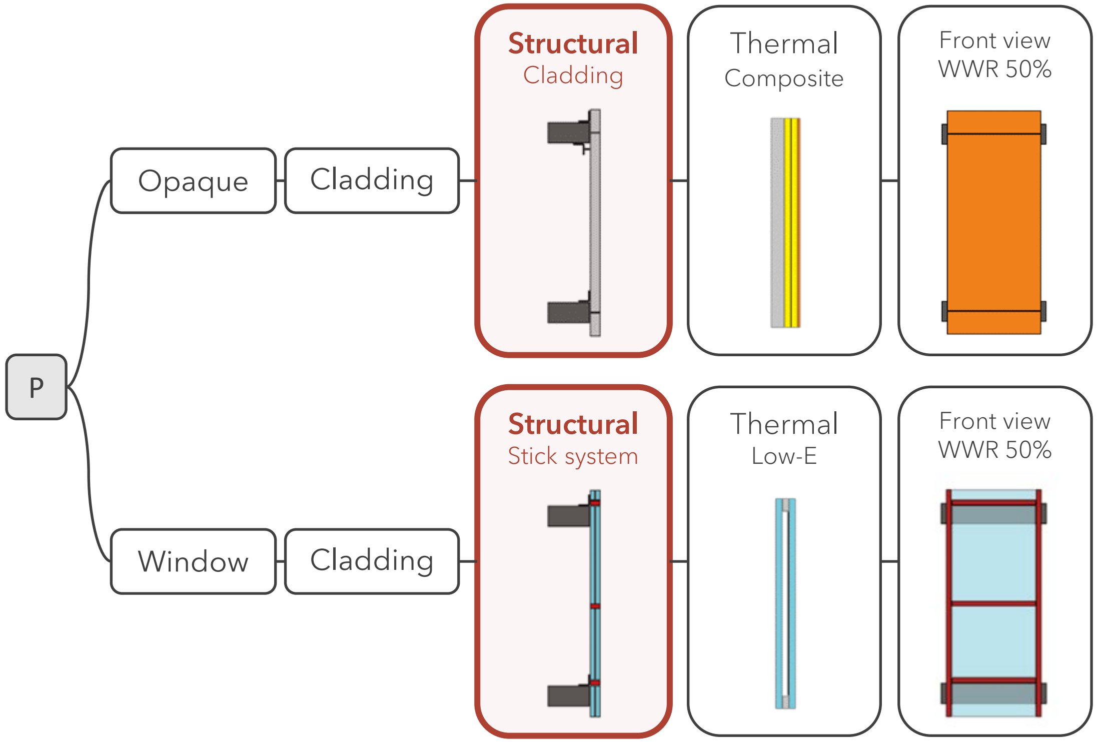
2. Multi-Hazard Approach

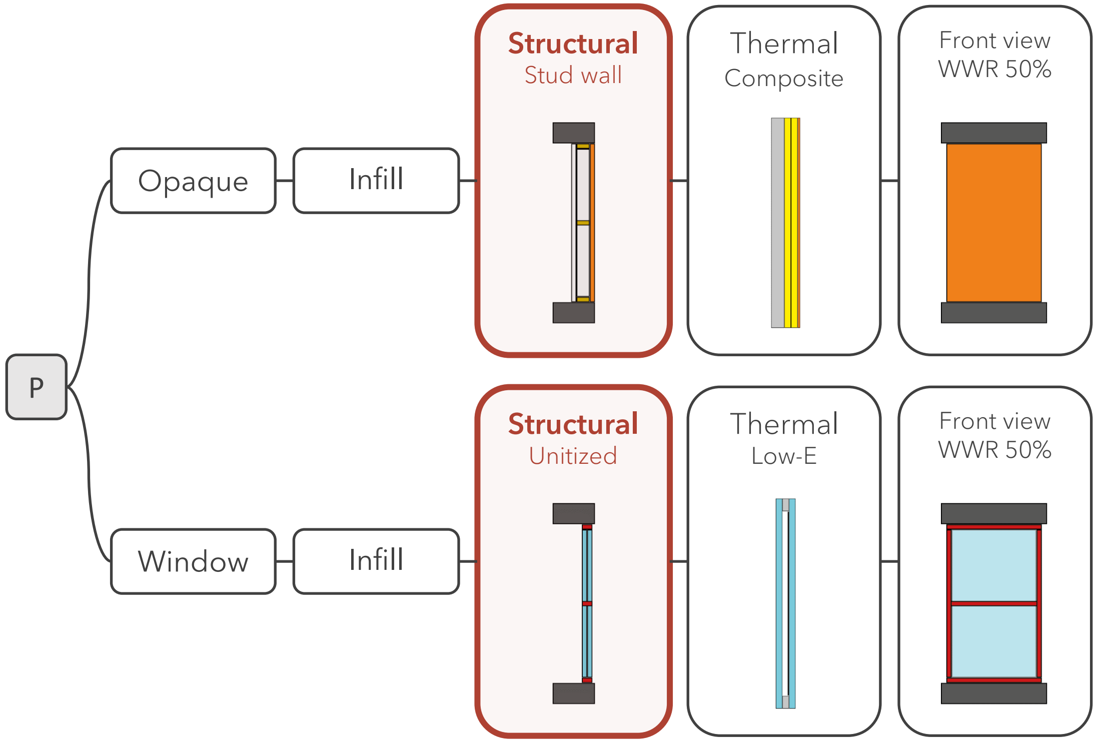
Facade Packages (structurally identical)



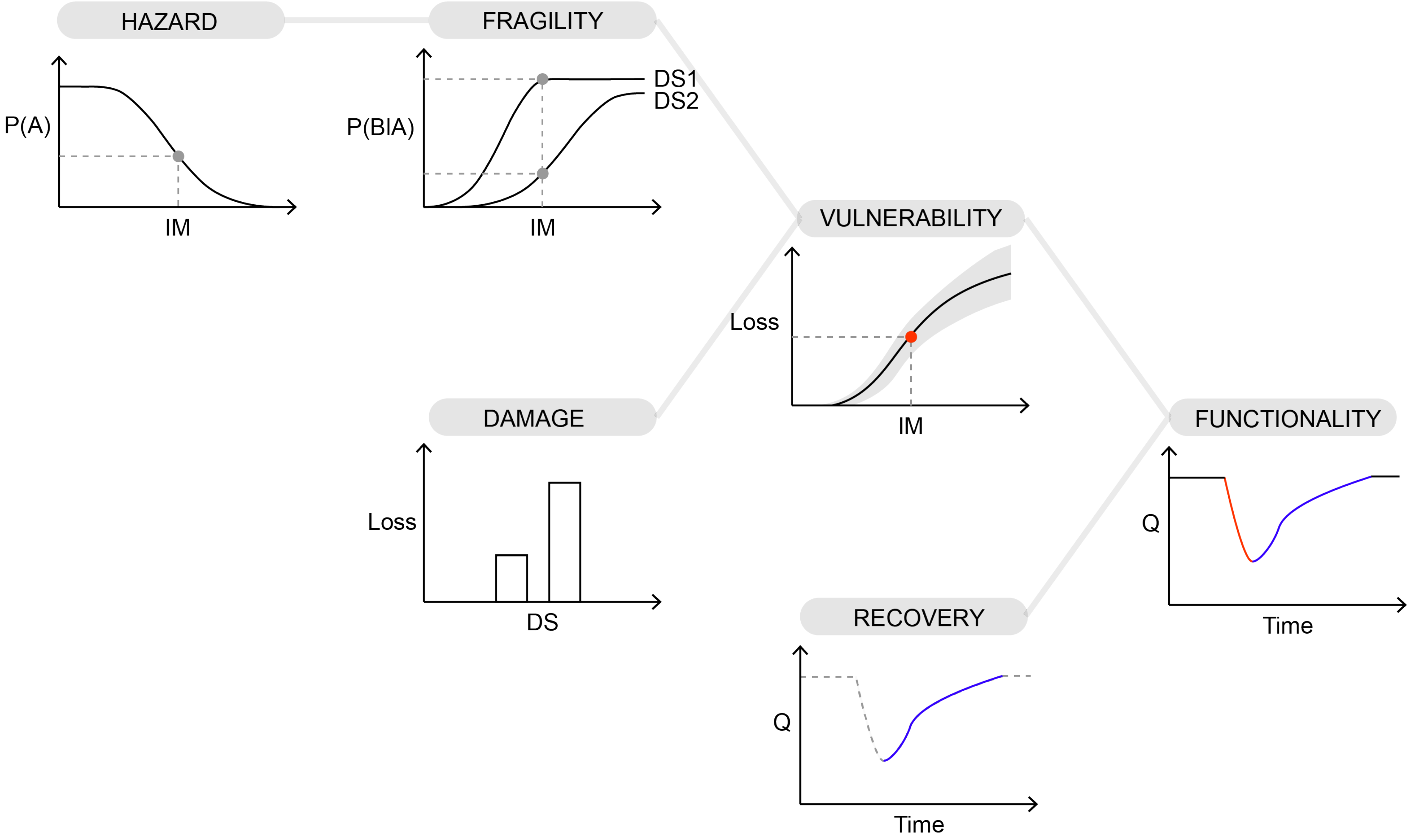


2. Multi-Hazard Approach
Facade Packages (thermally identical)





3. Quantitative Approach
Performance Assessment



3. Quantitative Approach
Decision Making

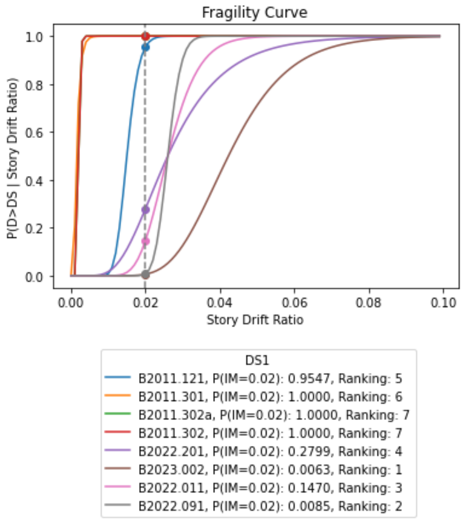
FRAGILITY DATABASE

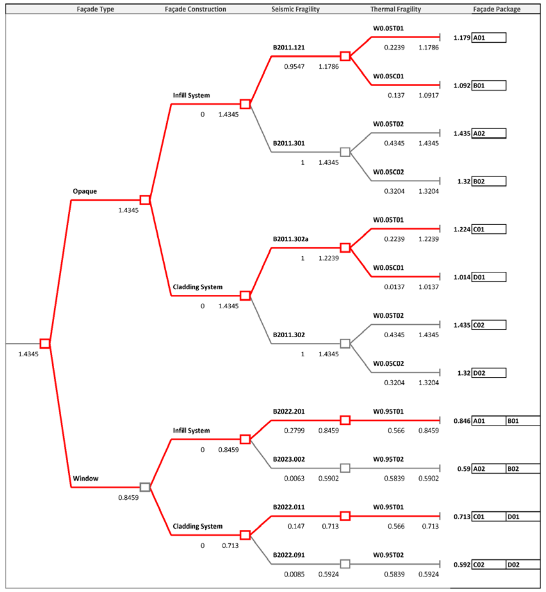
FRAGILITY COMPARISON

DECISION TREE

Fragility ID	Damage State	Description	Median Demand	Total Dispersion	Fragility Curve
B2022.201	Curtain Walls - Unitized curtain wall (also generic unitized curtain wall), Config: Symmetric insulating glass units (dual-pane, equal-thickness IGU), Lamination: Not laminated, Glass Type: Full tempered, Details: 1-1/4 in. (32 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], 4-sided SSG, VHBTM SGTTM;				
	DS1	Gasket seal failure.	0.026	0.45	
	DS2	Glass cracking.	0.05	0.25	
	DS3	Glass falls out.	0.1	0.25	
B2023.002	Generic Storefront, Config: IGU, Lamination: Unknown, Glass Type: Unknown, Details: Aspect ratio = 6:5, Other details Unknown				
	DS1	Gasket seal failure.	0.0423	0.3	
	DS2	Glass cracking.	0.059	0.25	
	DS3	Glass falls out.	0.0665	0.35	
B2022.011	Midrise stick-built curtain wall, Config: Asymmetric insulating glass units (dual-pane, unequal-thickness IGU), Lamination: Laminated, Glass Type: Annealed, Details: 1/4 in. (6 mm) inner AN / 1/2 in. (13 mm) outer AN LAM (0.030 PVB) IGU; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry				
	DS1	Gasket seal failure.	0.026	0.25	
	DS2	Glass cracking.	0.0268	0.25	
	DS3	Glass falls out.	0.0339	0.25	
B2022.091	Midrise stick-built curtain wall, Config: Symmetric insulating glass units (dual-pane, equal-thickness IGU), Lamination: Not laminated, Glass Type: Full tempered, Details: 1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes]; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry				
	DS1	Gasket seal failure.	0.026	0.11	
	DS2	Glass cracking.	0.031	0.25	
	DS3	Glass falls out.	0.032	0.25	

Fragility ID	Damage State	Description	Median Demand	Total Dispersion	Fragility Curve
B2011.121	Exterior Wall - Light framed wood walls with structural panel sheathing, gypsum wallboard and hold-downs				
	DS1	Slight separation of sheathing or nails which come loose.	0.015	0.26	
	DS2	Permanent rotation of sheathing, tear out of nails or sheathing.	0.0262	0.16	
	DS3	Fracture of studs, major sill plate cracking.	0.0226	0.17	
B2011.301	Exterior Wall - Masonry infills with French window and Partitions with door				
	DS1	Detachment of infill, Light diagonal cracking	0.0015	0.5	
	DS2	Extensive diagonal cracking	0.004	0.5	
	DS3	Corner crushing and sliding of mortar joints	0.01	0.4	
B2011.302a	Exterior Wall - Precast concrete cladding panel U-shaped Flexural Plate connection, 120x8mm steel plate				
	DS1	Pre-yielding	0.002	0.2	
	DS2	Post-yielding	0.027	0.2	
	DS3	N/A	N/A	N/A	
B2011.302	Exterior Wall - Precast concrete cladding panel Tie-back connection Threaded rod with 20mm diameter and 250 mm length				
	DS1	Pre-yielding	0.002	0.2	
	DS2	Post-yielding	0.005	0.2	
	DS3	Severe damage to connections	0.010	0.2	





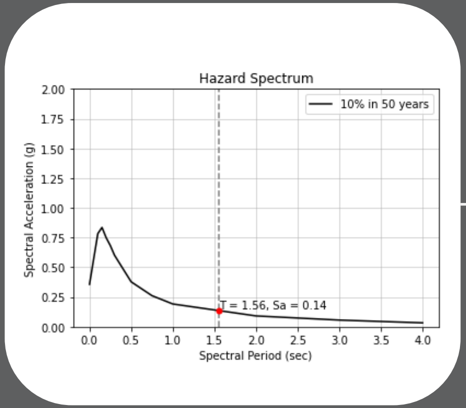
Resilience-based
Facade Design Framework

Assessment Process

Seismic Hazard

Hazard Spectrum

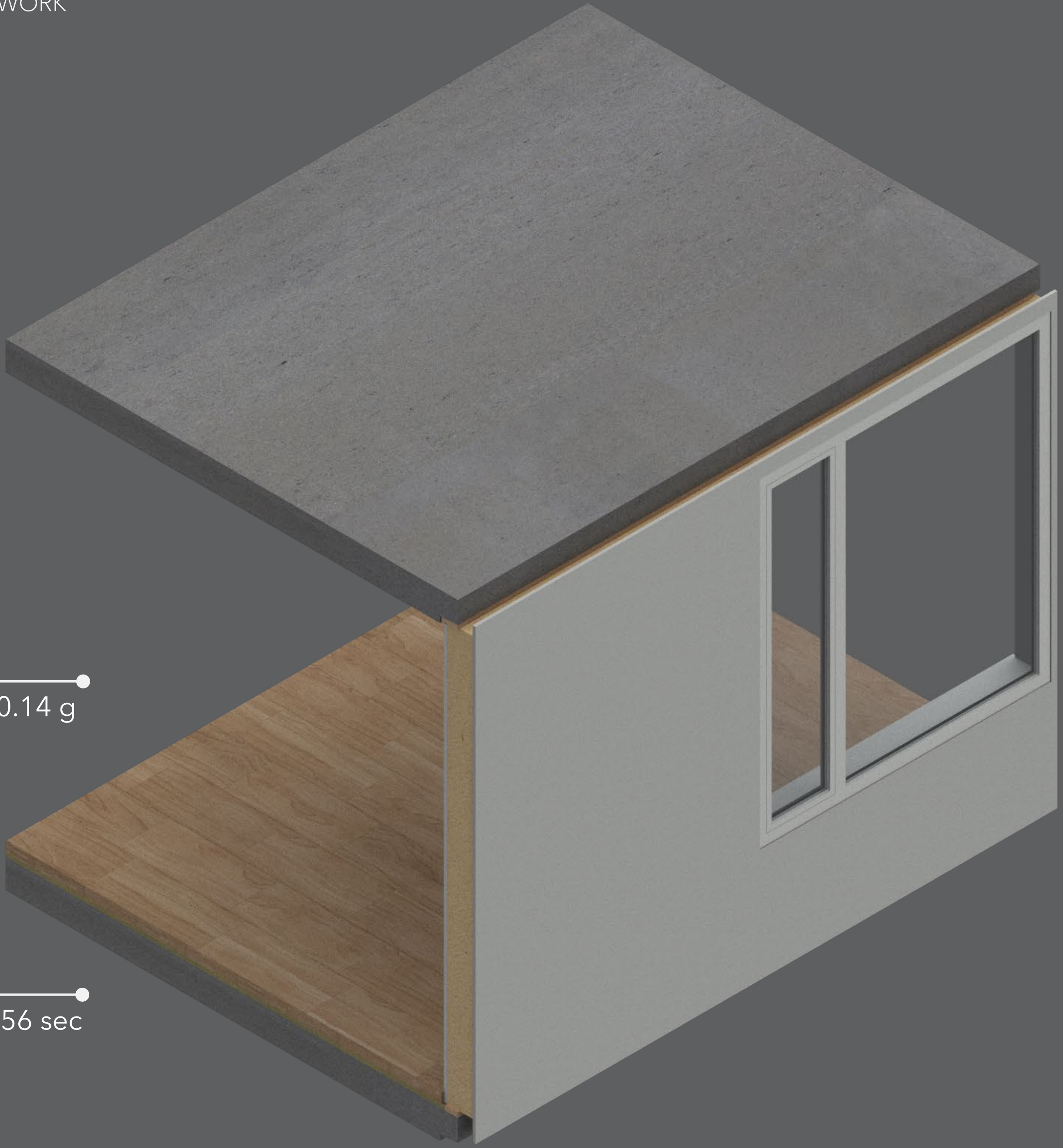
Peak ground acceleration with 10% probability of exceedance in 50 years (return period 475 years)



Sa = 0.14 g

Period of Vibration

Ts = 1.56 sec

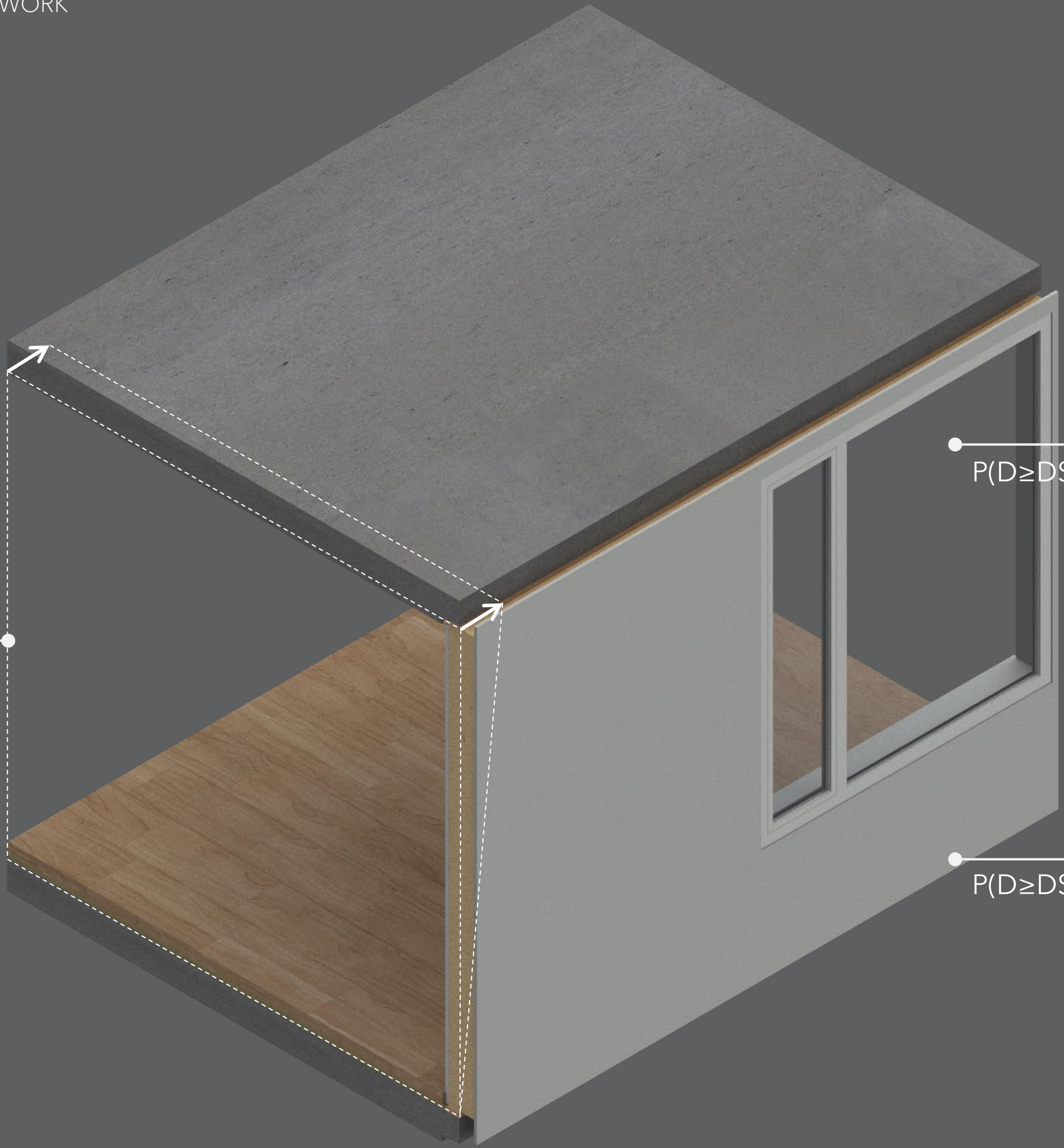


Seismic Fragility

Demand Parameter

Inter-story Drift

IDR = 0.02

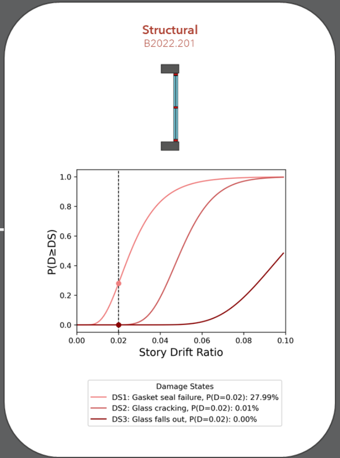


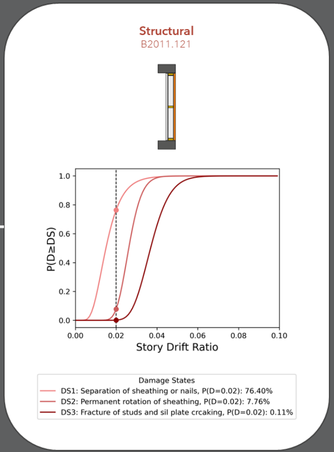
P(D≥DS1)=25%

P(D≥DS1)=70%

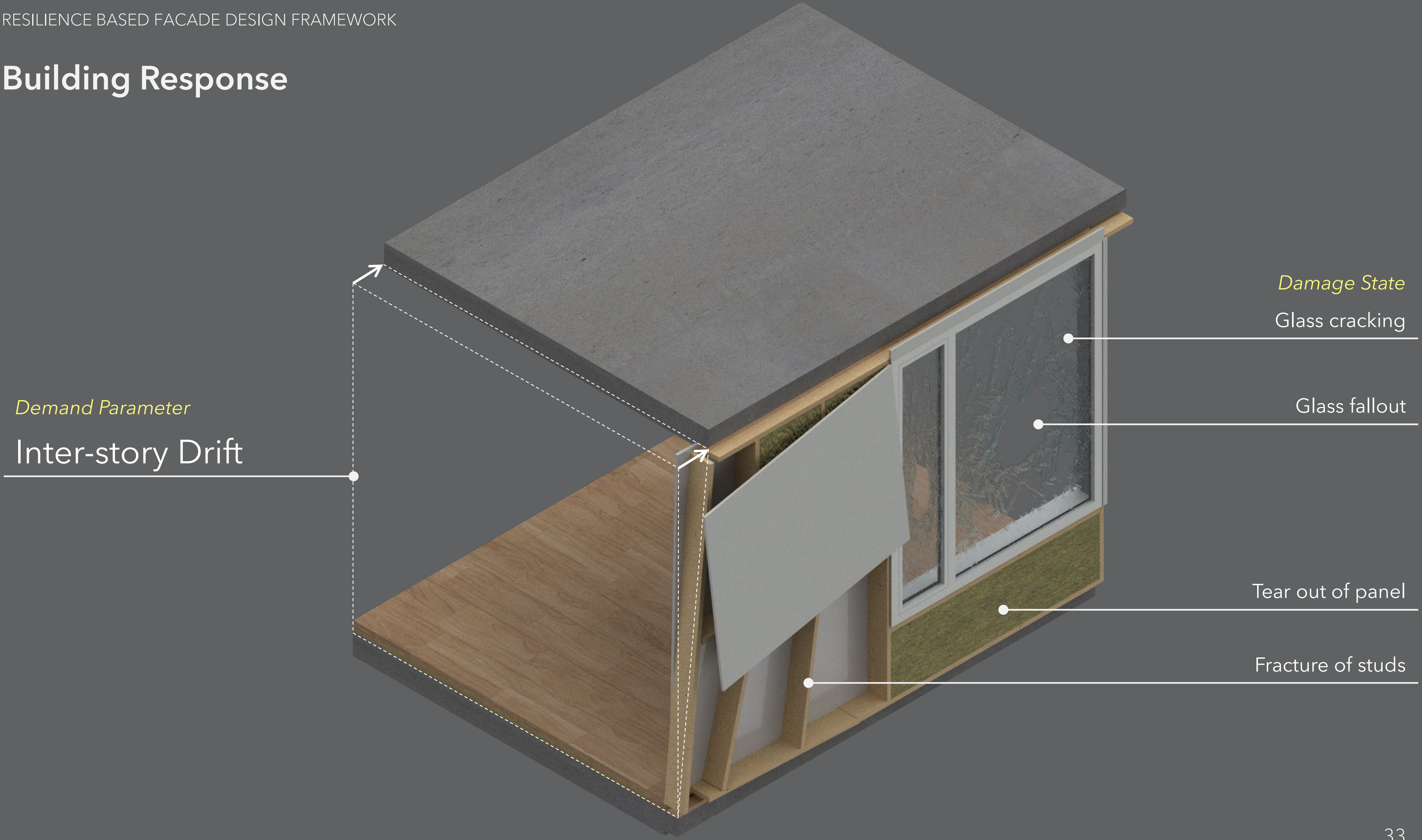
Fragility Curve

Probability of exceeding damage state, given demand parameter

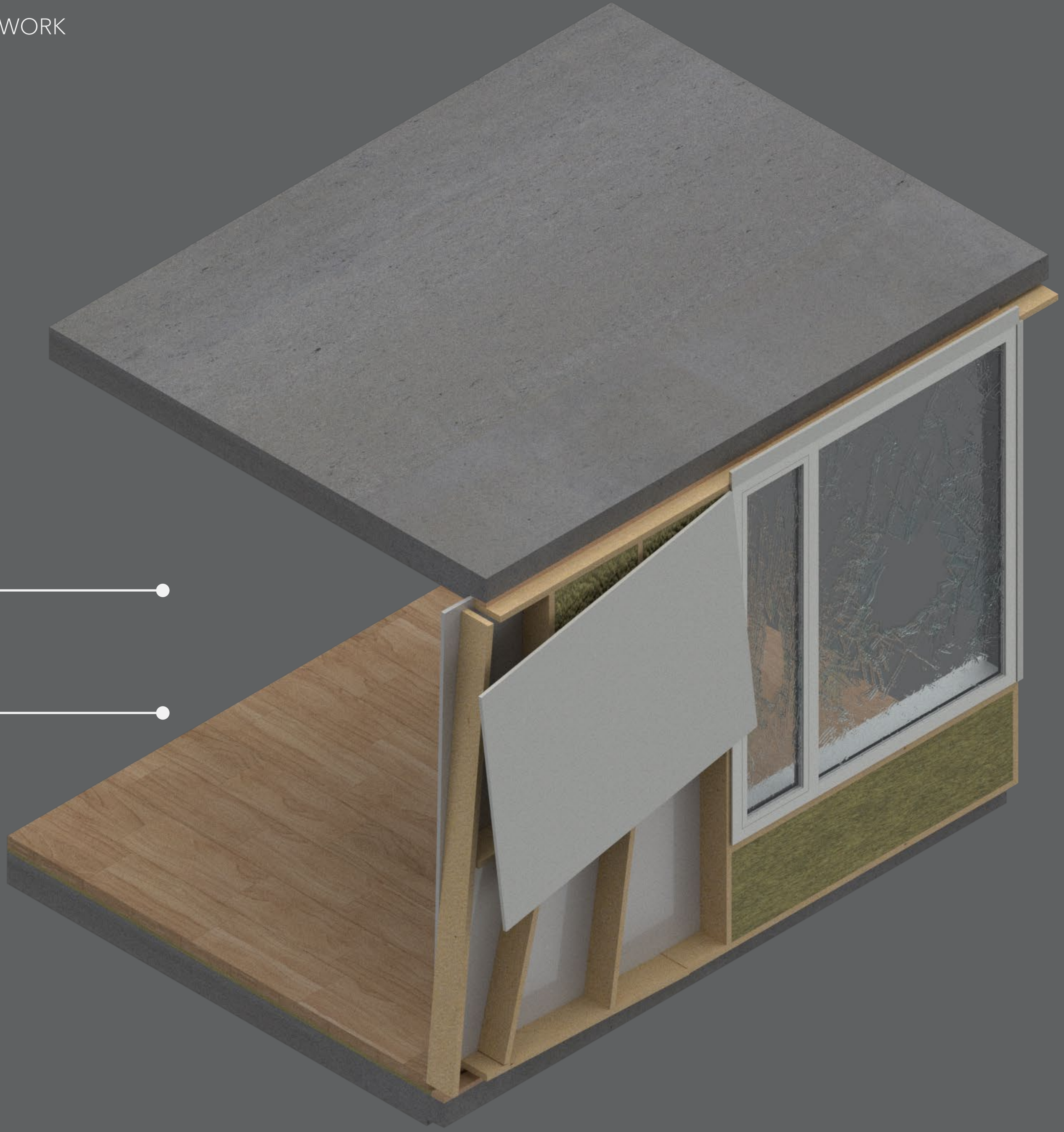




Building Response



Seismic Resilience



Resilience Loss

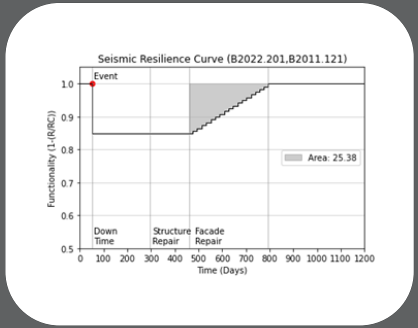
$$Resilience\ Loss = \int_{t_0}^{t_1} [1 - Q(t)]\,\mathrm{d}t$$

Economic Loss

Total facade repair cost

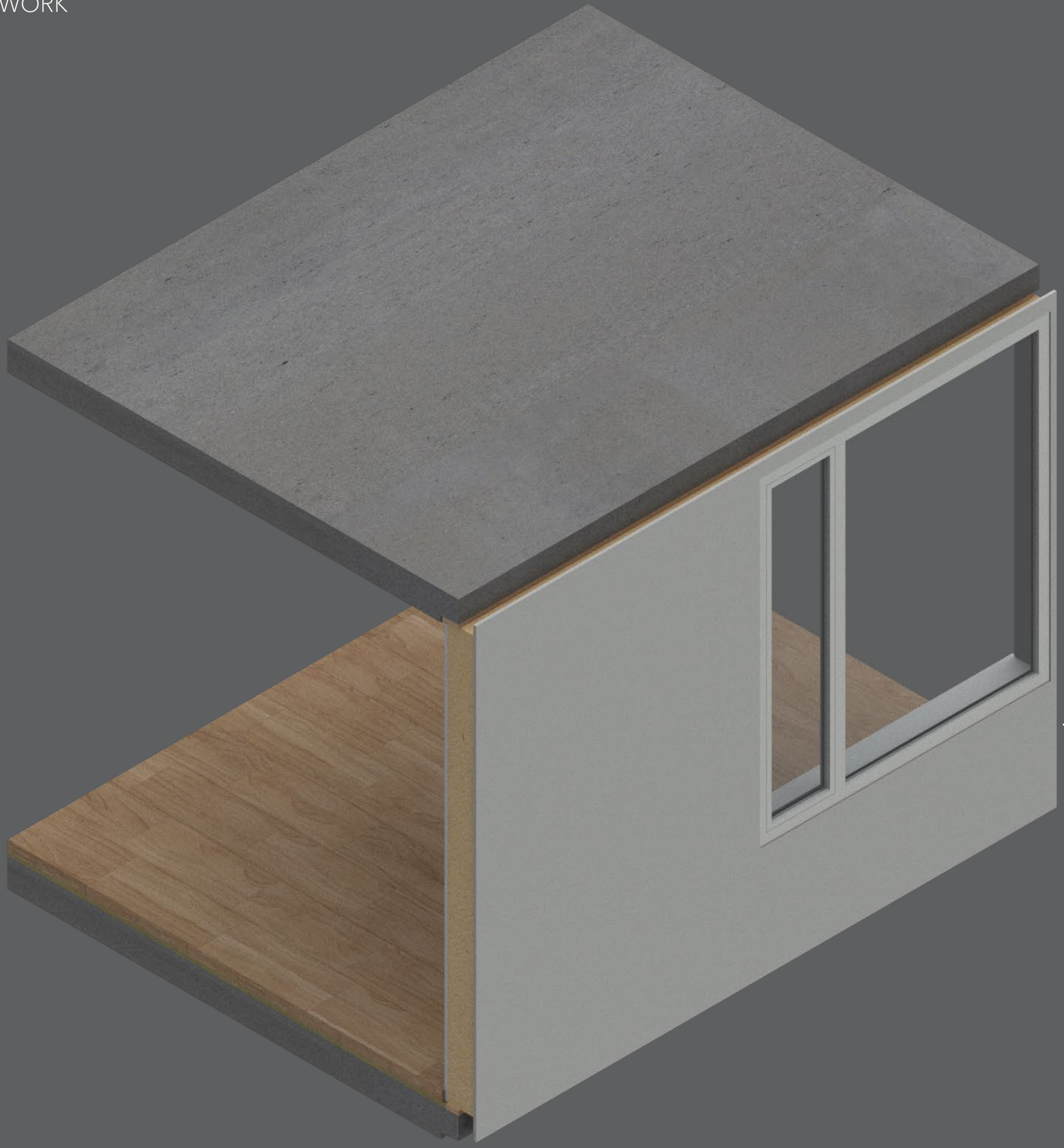
Functionality Curve

Functionality drop, downtime, and recovery through repairment



$$Q(t) = 1 - \frac{Repair\ Cost}{Replacement\ Cost}$$

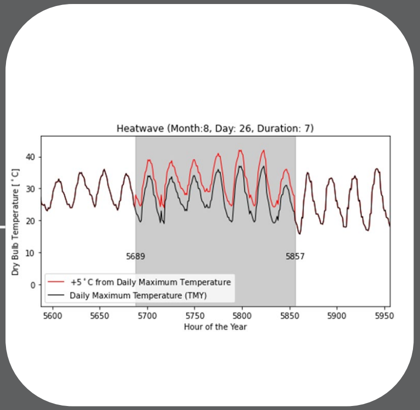
Heat Hazard



Heatwave

Daily maximum temperature exceeding 5 °C for five consecutive days

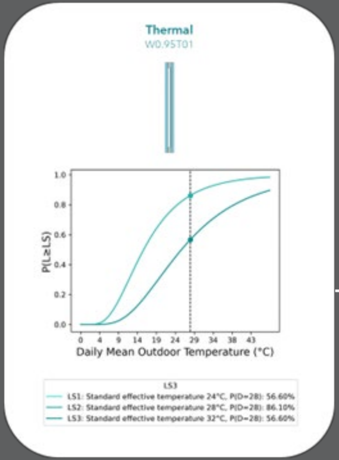
Tout

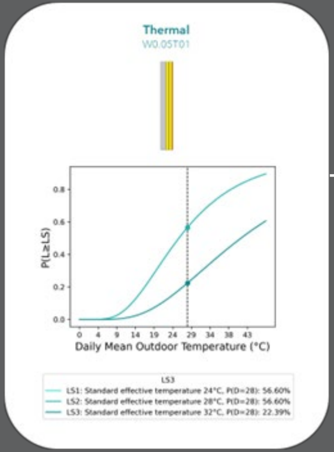


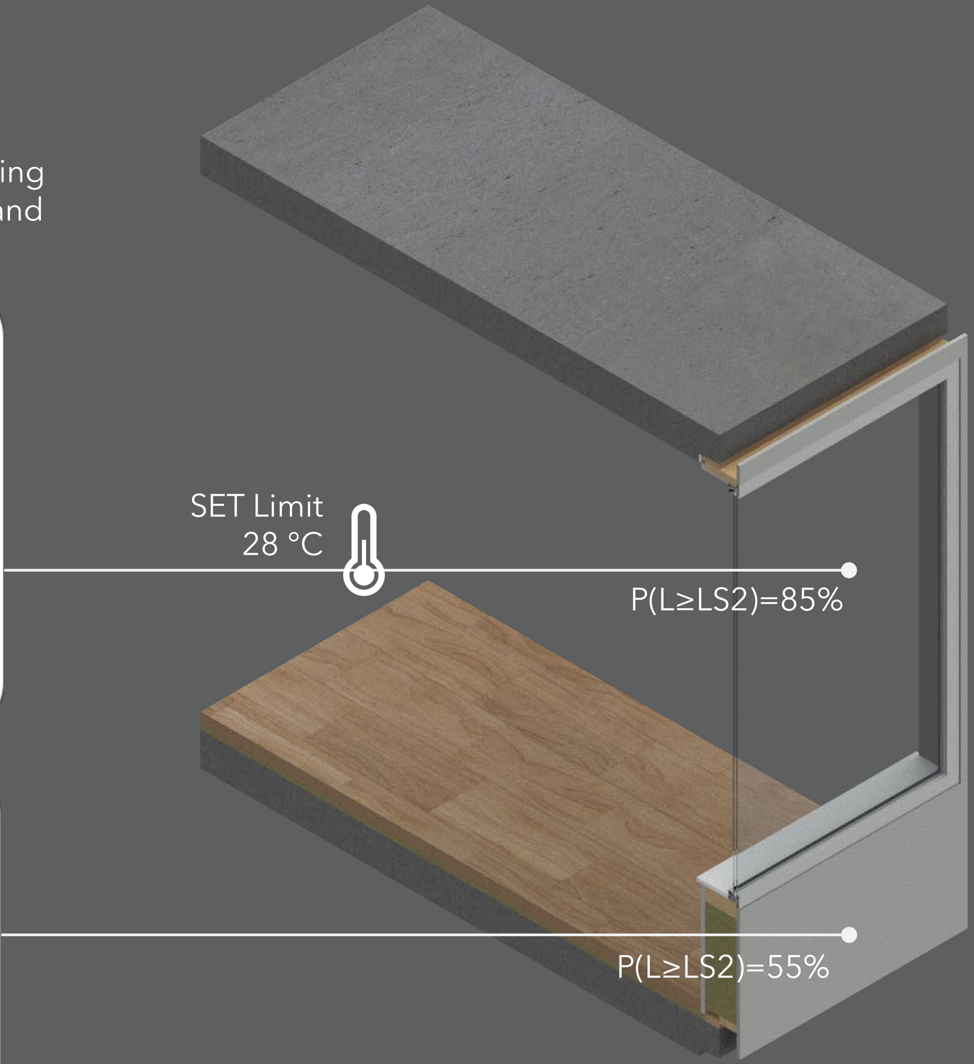
Thermal Fragility

Fragility Curve

Probability of exceeding SET limit, given demand parameter







Demand Parameter

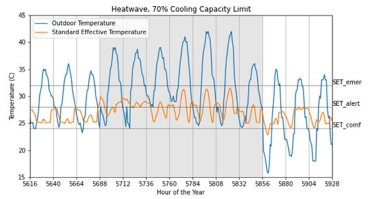
Outdoor Air Temperature

Tout = 28 °C

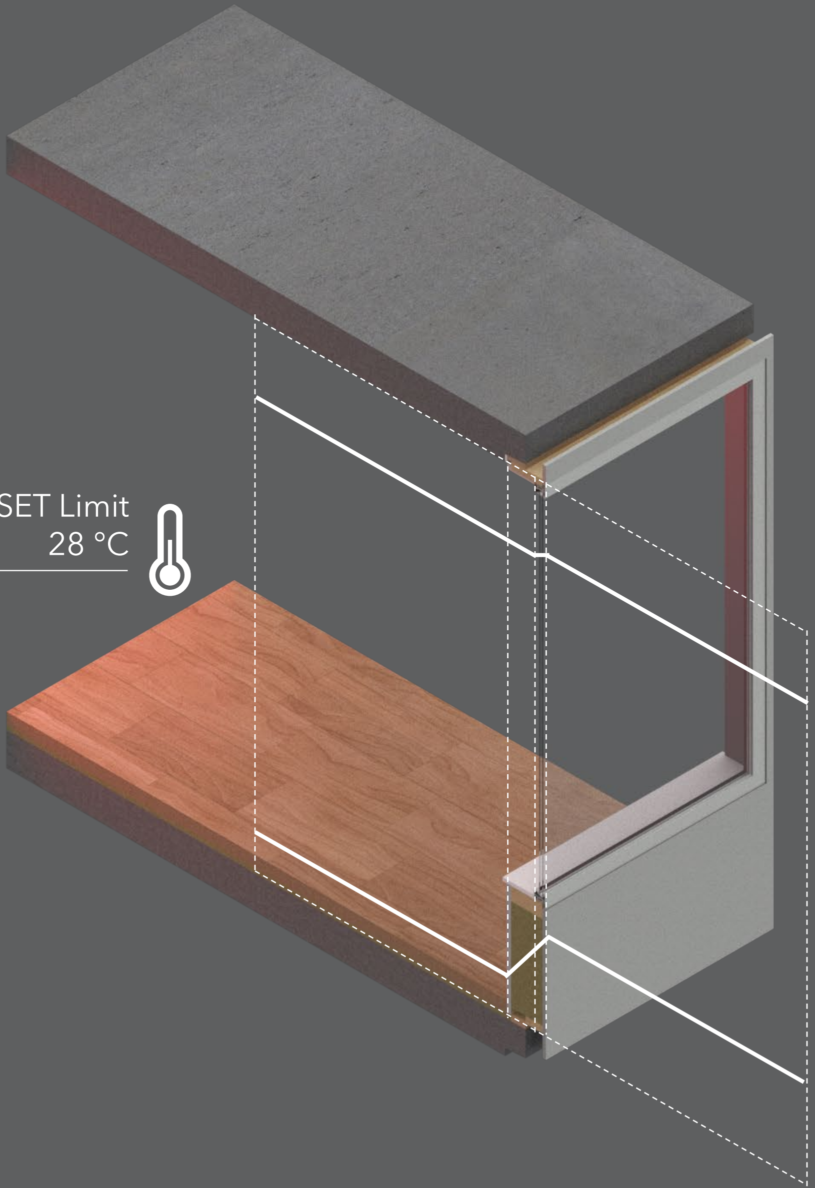
Building Response

Limit State

Standard Effective Temperature (SET)



SET Limit
28 °C



Demand Parameter

Outdoor Air Temperature

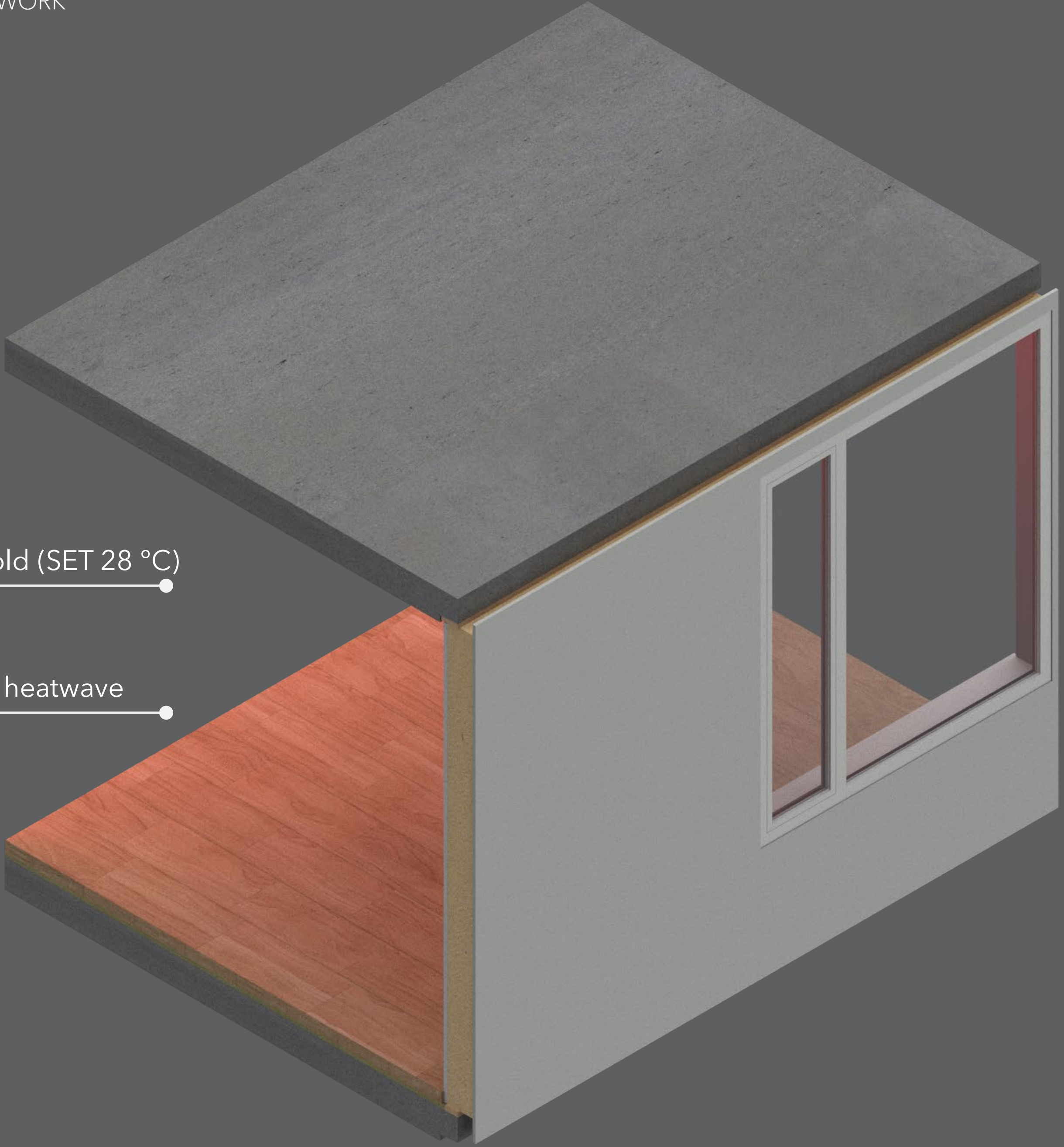
Thermal Resilience

Resilience Loss

Degree hours above comfort threshold (SET 28 °C)

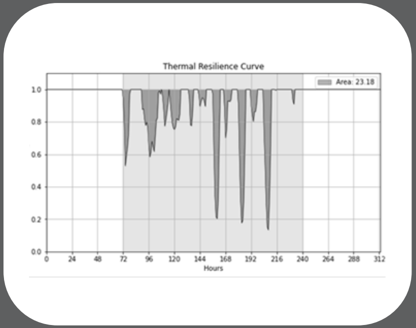
Economic Loss

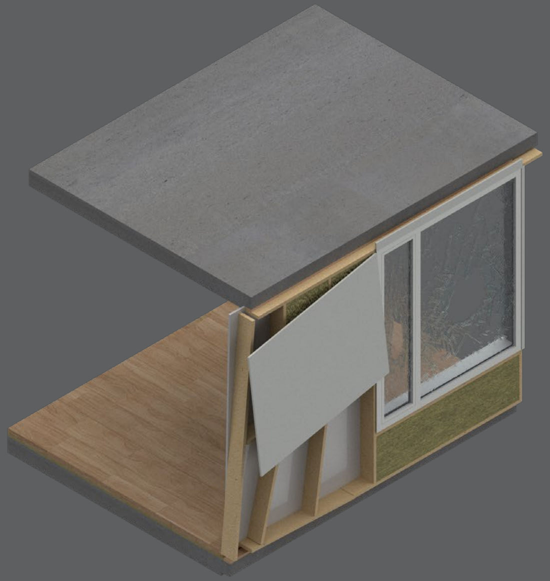
Energy cost spent on cooling during heatwave



Functionality Curve

Functionality drop and recovery during heatwave





Seismic

Hazard Spectrum
Hazard

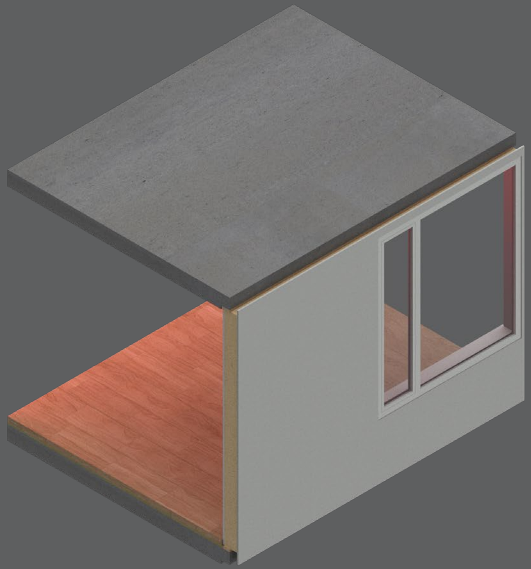
Fragility Curve
Fragility

Inter-story Drift
Demand Parameter

Damage State
Damage

Repair Time
Repair Cost
Recovery

Resilience Loss
Economic Loss
Resilience



Thermal

Heatwave
Hazard

Fragility Curve
Fragility

Tout
Demand Parameter

Exceeding SET Limit
Damage

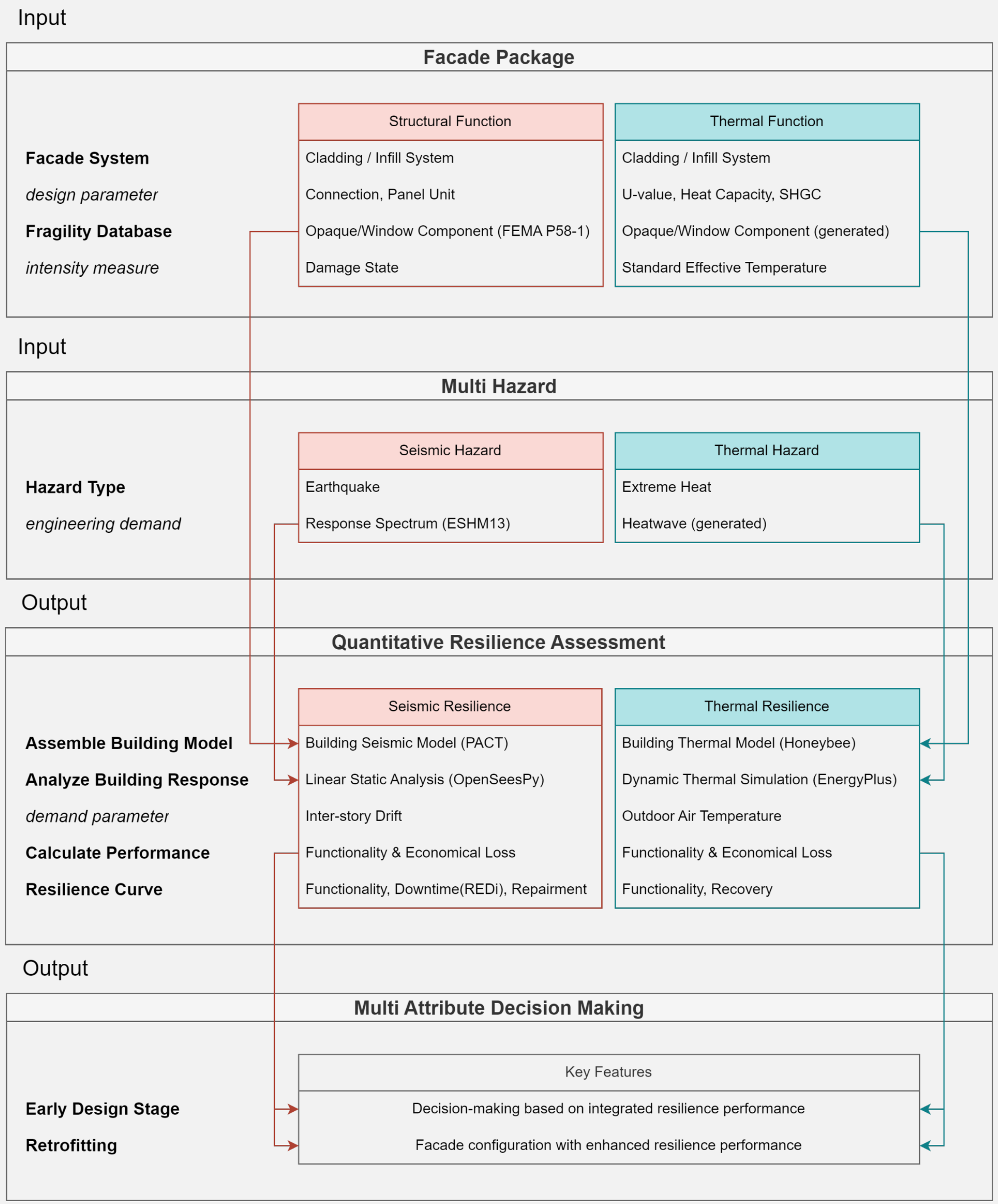
Recover Time
Recover Energy Cost
Recovery

Resilience Loss
Economic Loss
Resilience

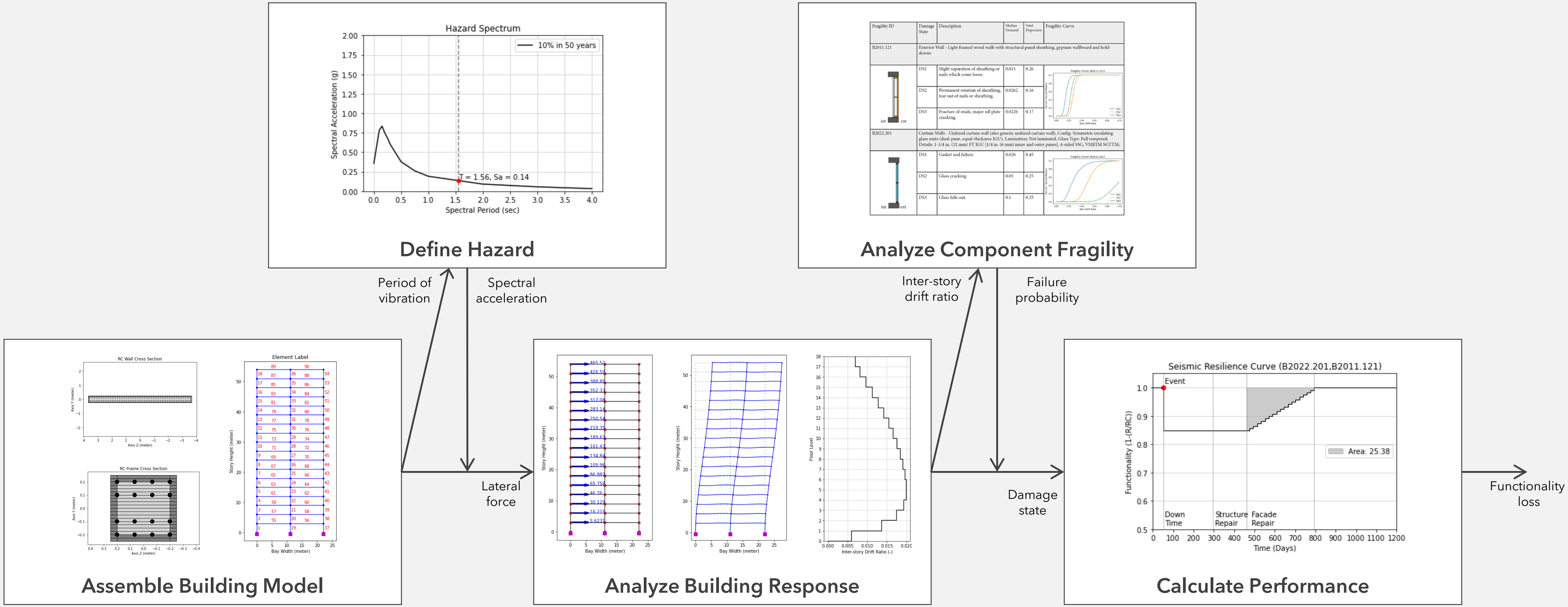
Resilience-based
Facade Design Framework

Digital Workflow

RESILIENCE BASED FACADE DESIGN FRAMEWORK



How to Quantify Seismic Resilience?



How to Quantify Seismic Resilience?

python

- Data processing
- Visualization

Define Hazard

- Hazard model (ESHM13)
- Hazard spectra

Analyze Component Fragility

- Fragility database
- Fragility specification

FEMA P-58-1 Catalog No. 1894-5

Assemble Building Model

- Building model
- Finite element model

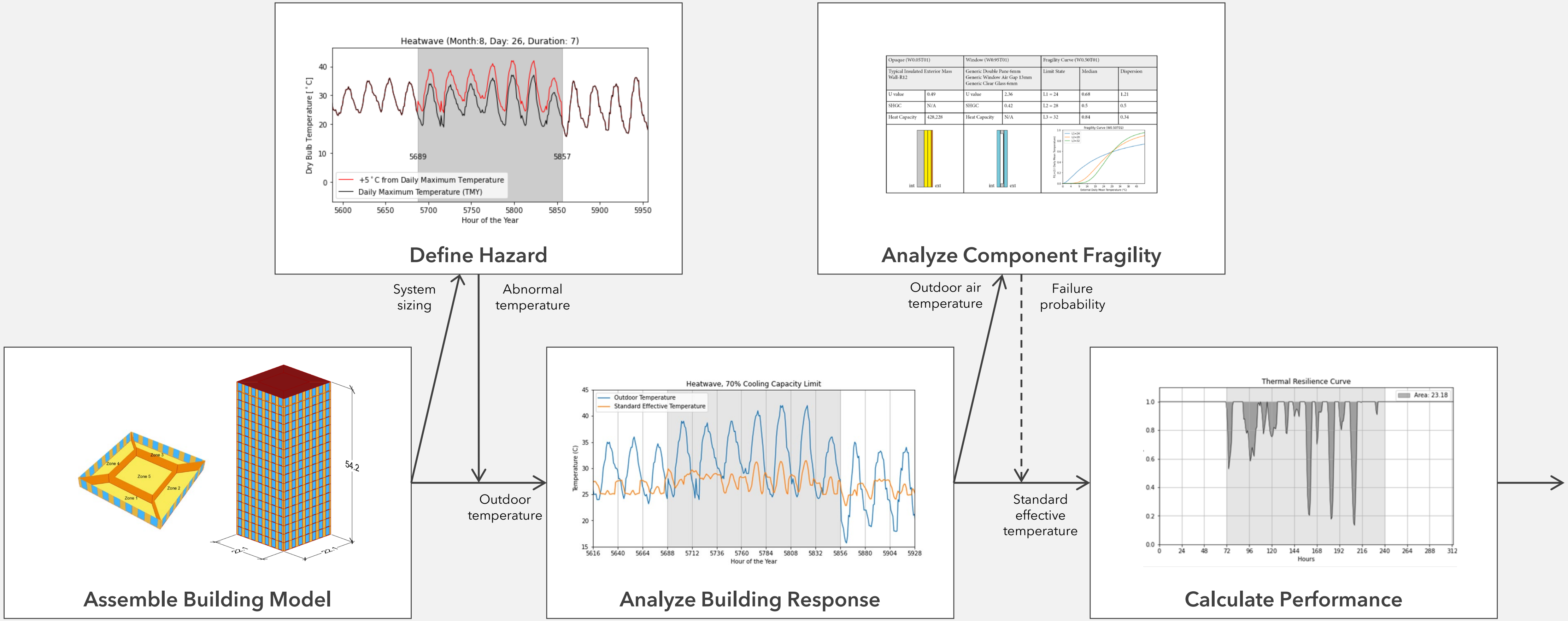
Analyze Building Response

- Standard in design load
- Linear static analysis

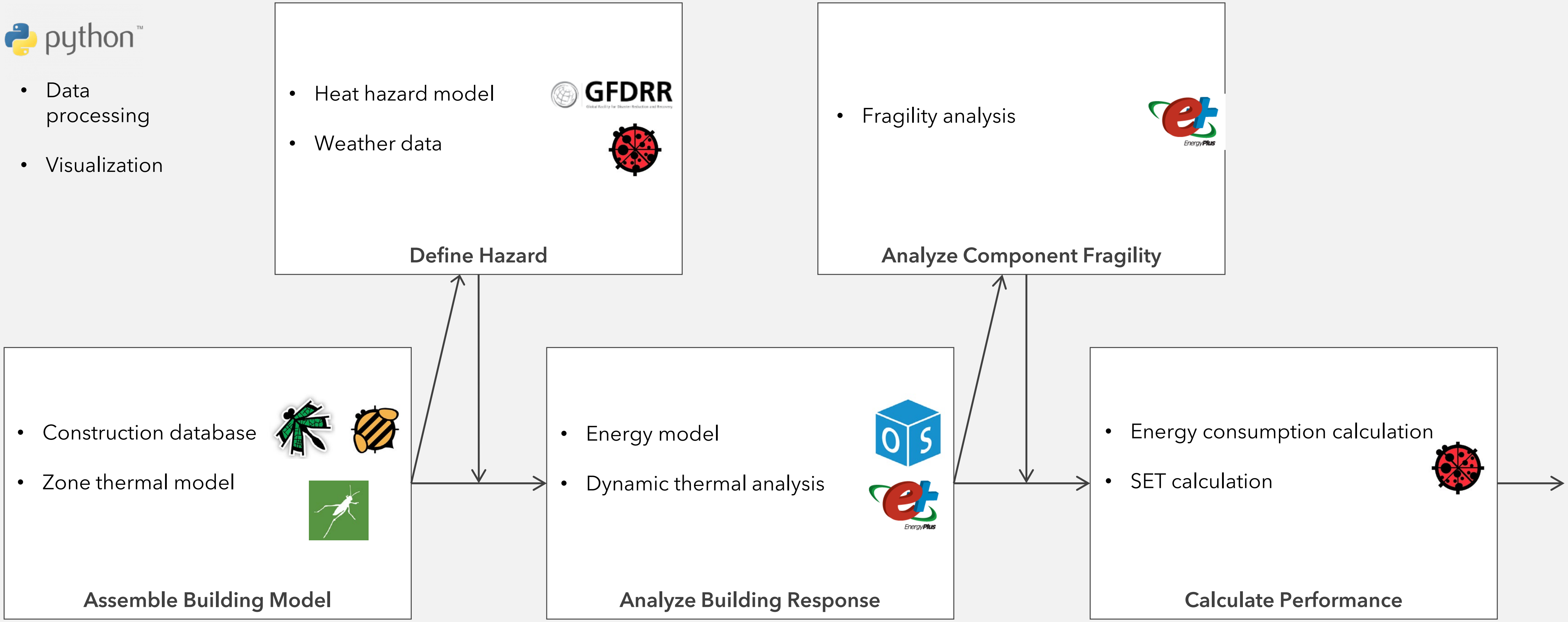
Calculate Performance

- Repair cost / time calculation
- Downtime calculation

How to Quantify Thermal Resilience?



How to Quantify Thermal Resilience?



State of Art

1

Framework

2

Case Study

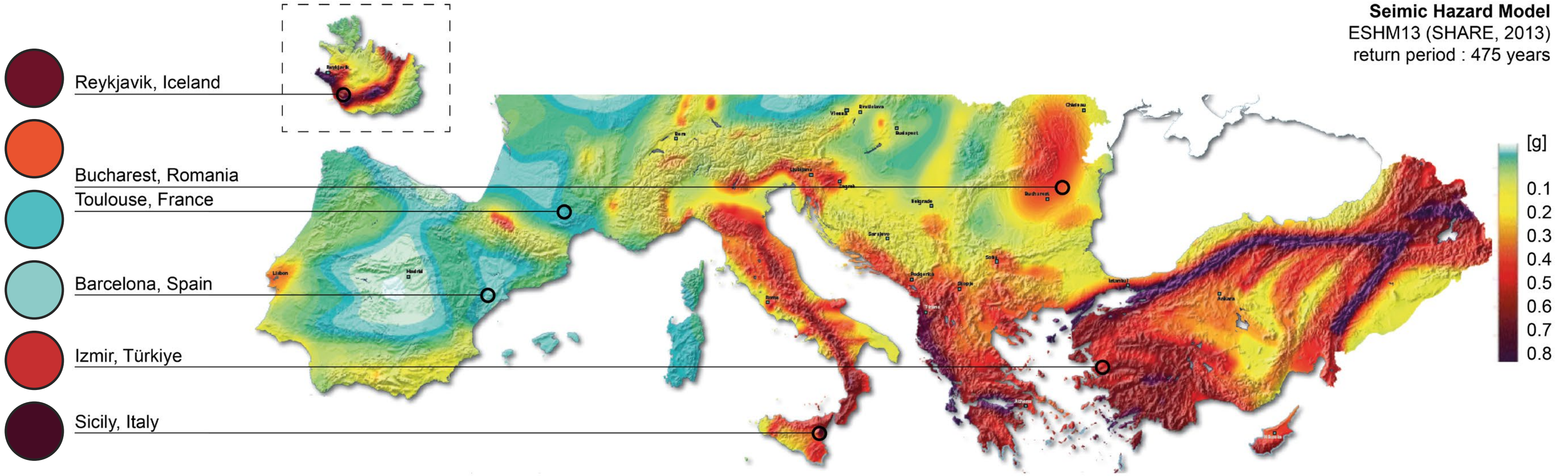
Boundary Condition

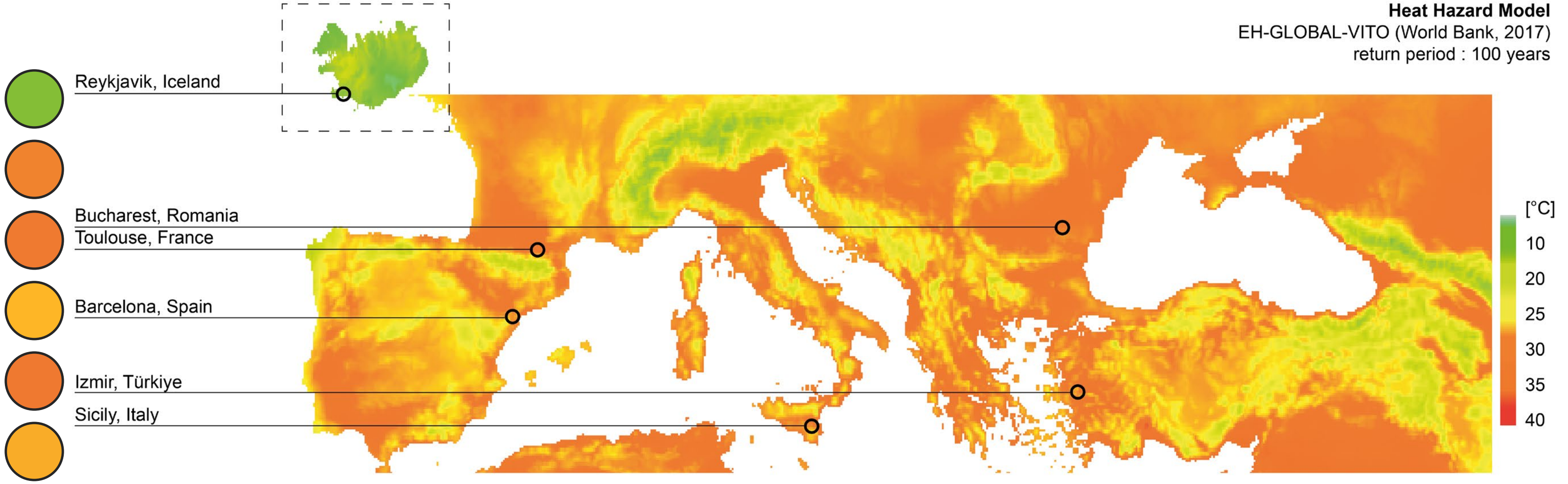
3

Evaluation

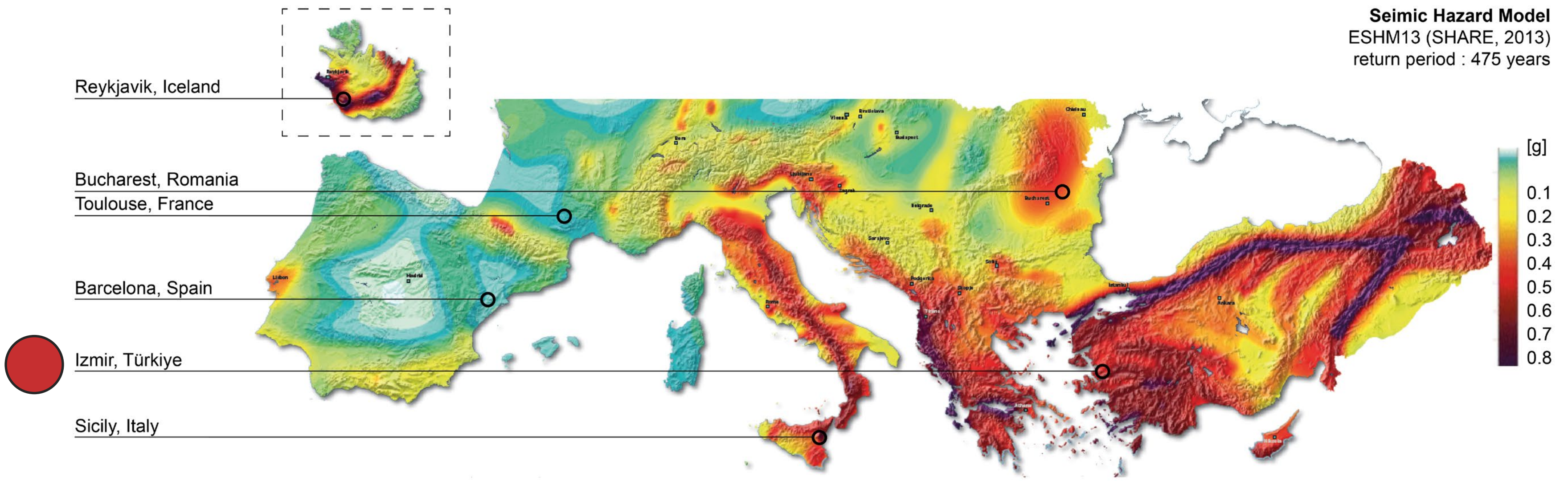
4

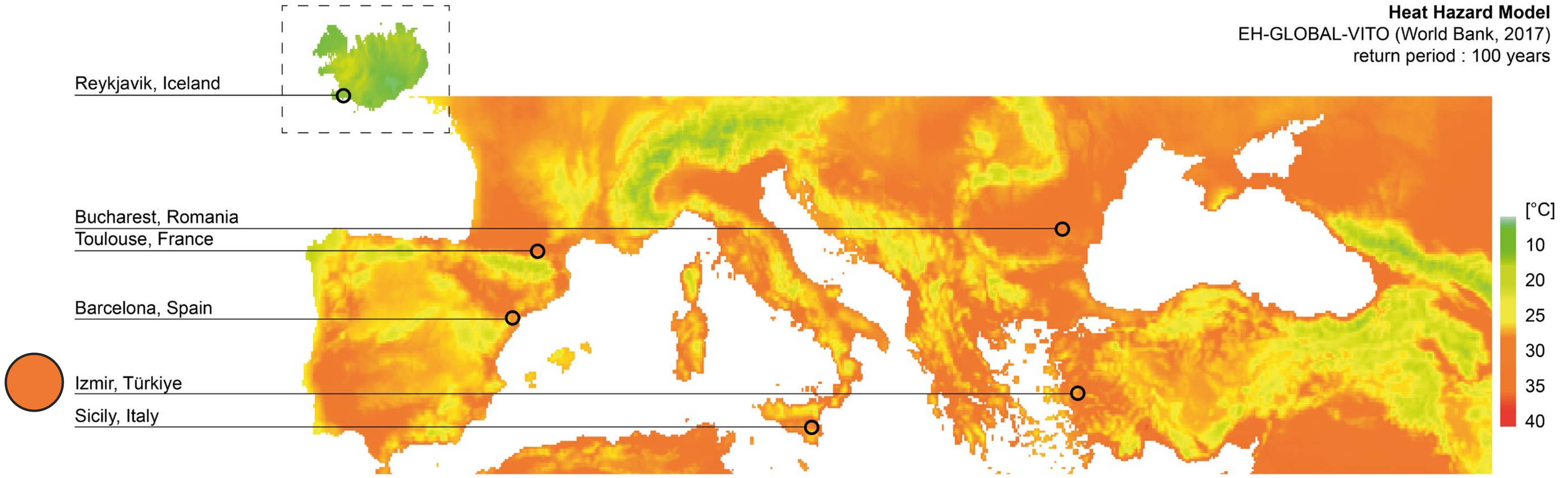
Project Location



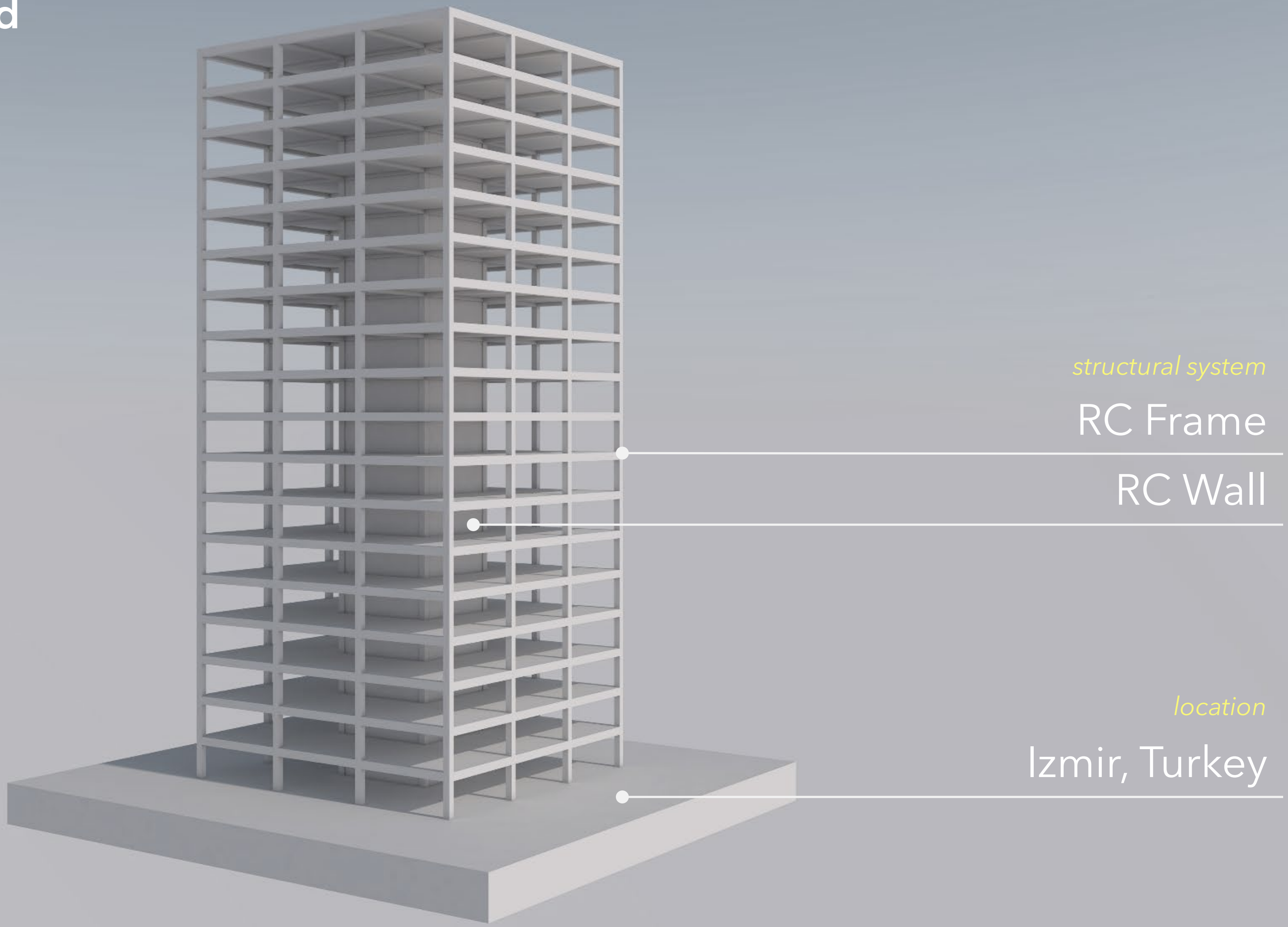


Project Location





18-story office building with seismic and heat hazard



18-story office building with seismic and heat hazard

facade system

Infill / Cladding System
WWR 50%

structural system

RC Frame

RC Wall

location

Izmir, Turkey

Measurement Settings

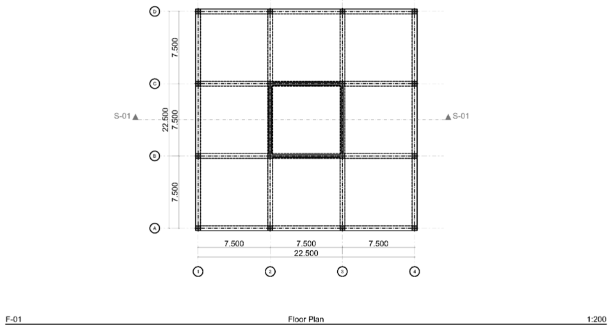
Seismic-resistant structure

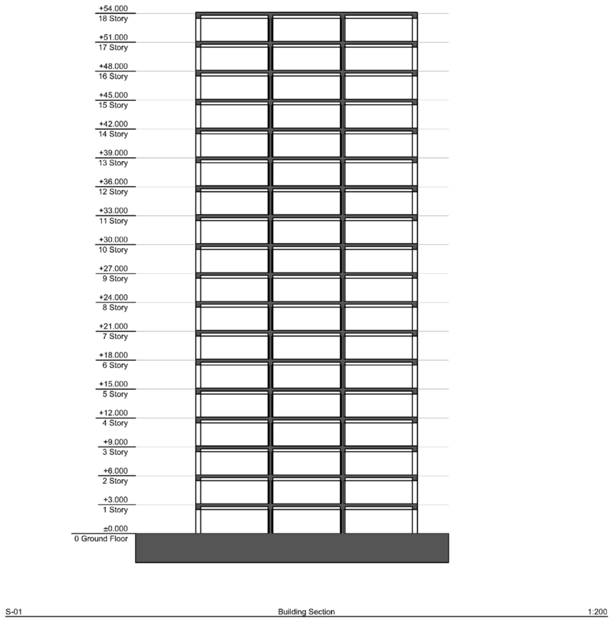
A dual system of RC moment-resisting frames and RC shear walls. (ASCE7-10)

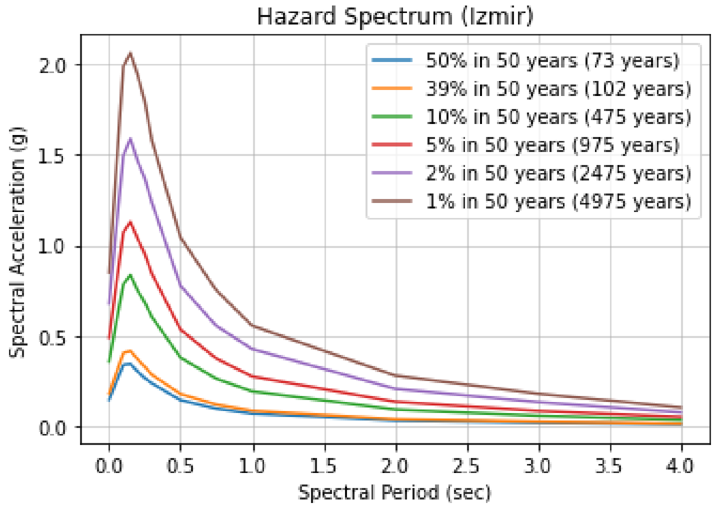
Fundamental period of vibration (T=1.56 sec) determined based on structure stiffness and height.

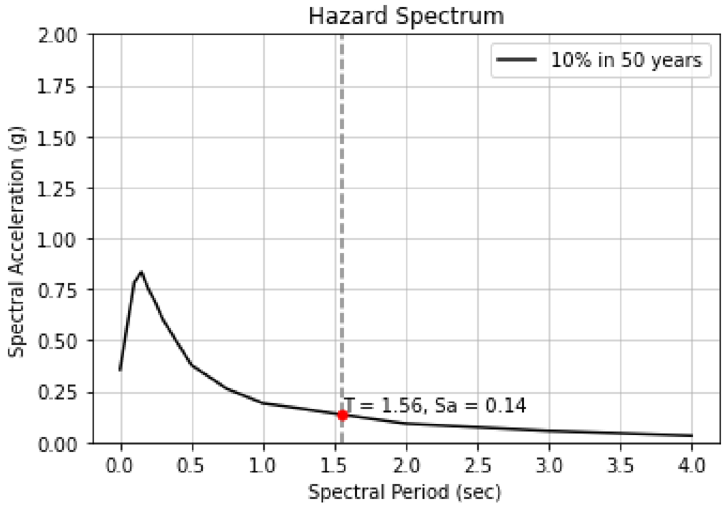
Hazard Intensity

Earthquake ground shaking with a return period of 475 years.









Measurement Settings

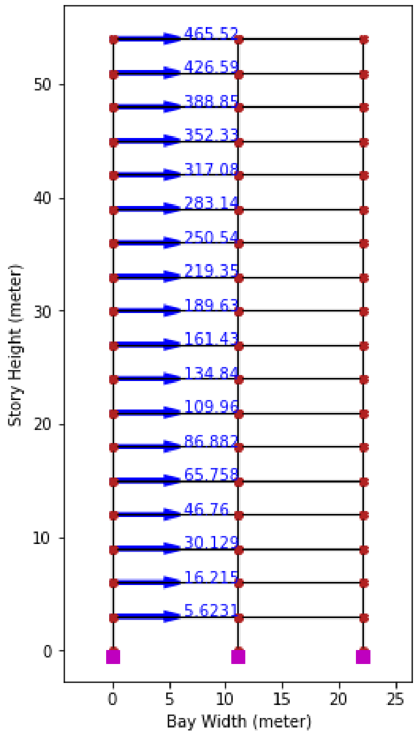
Linear Static Analysis

Equivalent lateral force method is a simplified way to incorporate the effects of inelastic dynamic response into a linear static analysis.

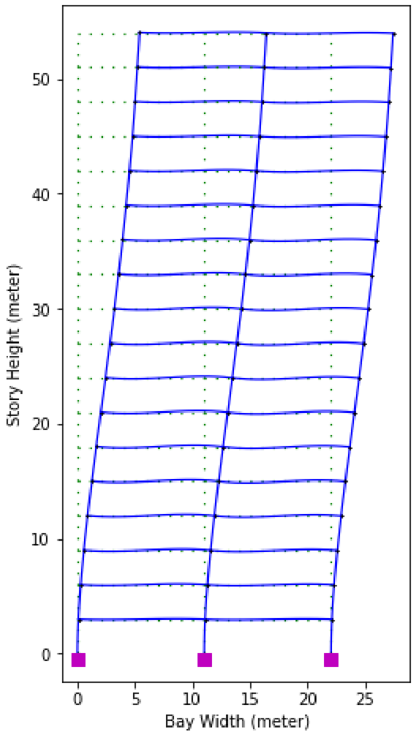
Inter-story Drift Ratio

Damage demand parameter of building structure under earthquake loads.

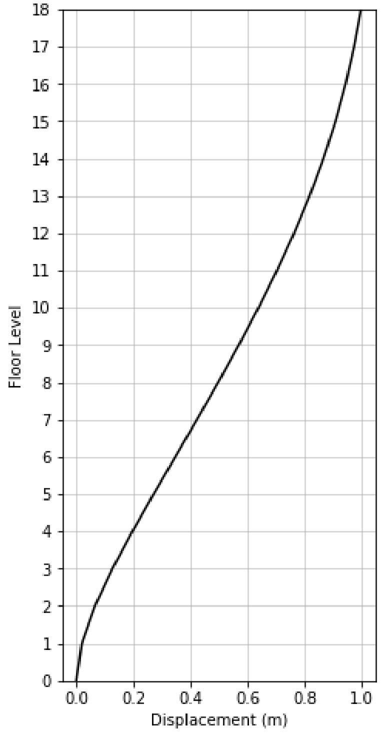
Adjustment factor applied to account for the impact of higher modes and inelastic behavior.



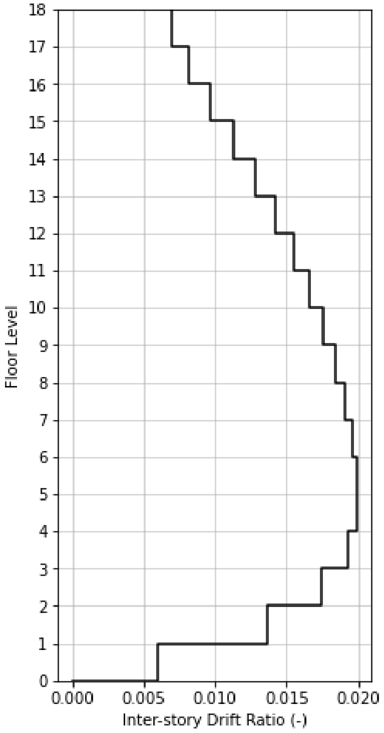
Vertical distribution of seismic forces



Frame deformation



Floor displacement



Inter-story drift ratio

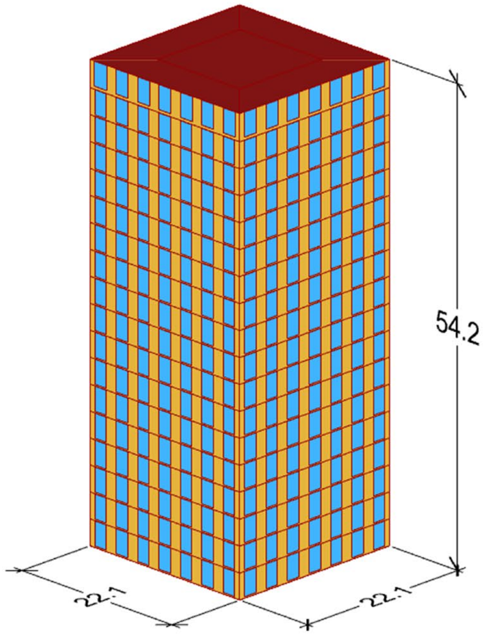
Measurement Settings

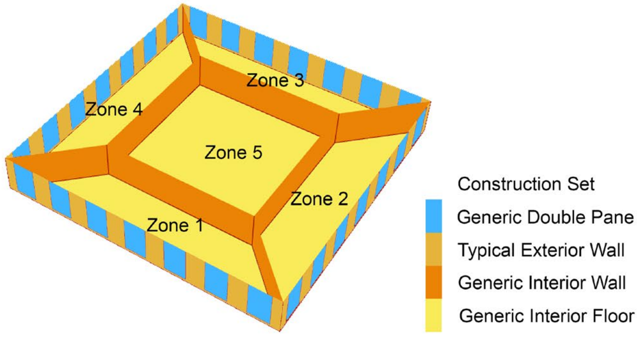
Multi Thermal Zone

Each floor is divided into a core and a perimeter zone with a depth of 5m. The boundary condition between floors is adiabatic. Energy simulation is conducted separately for each floor. The SET is measured for Zone 2, which is the south-oriented perimeter zone.

Weather Data

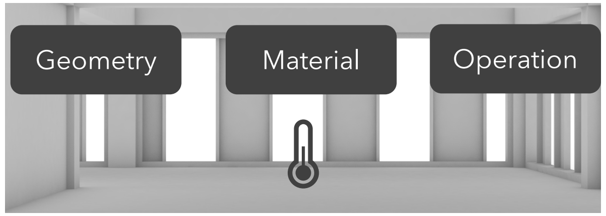
The TMY (period 1989-2021) weather data of Izmir is used as a baseline for system sizing. A heatwave is applied to the "typical summer week" in the DDY file by increasing the dry bulb temperature by 5°C.





Measurement Settings

Factors that influence thermal performance



Building Geometry

WWR	Fixed 50%
Shading	Fixed Unavailable
Orientation	Fixed South

Facade Material Property

U Value	Variable -
Heat Capacity	Variable -
SHGC	Variable -

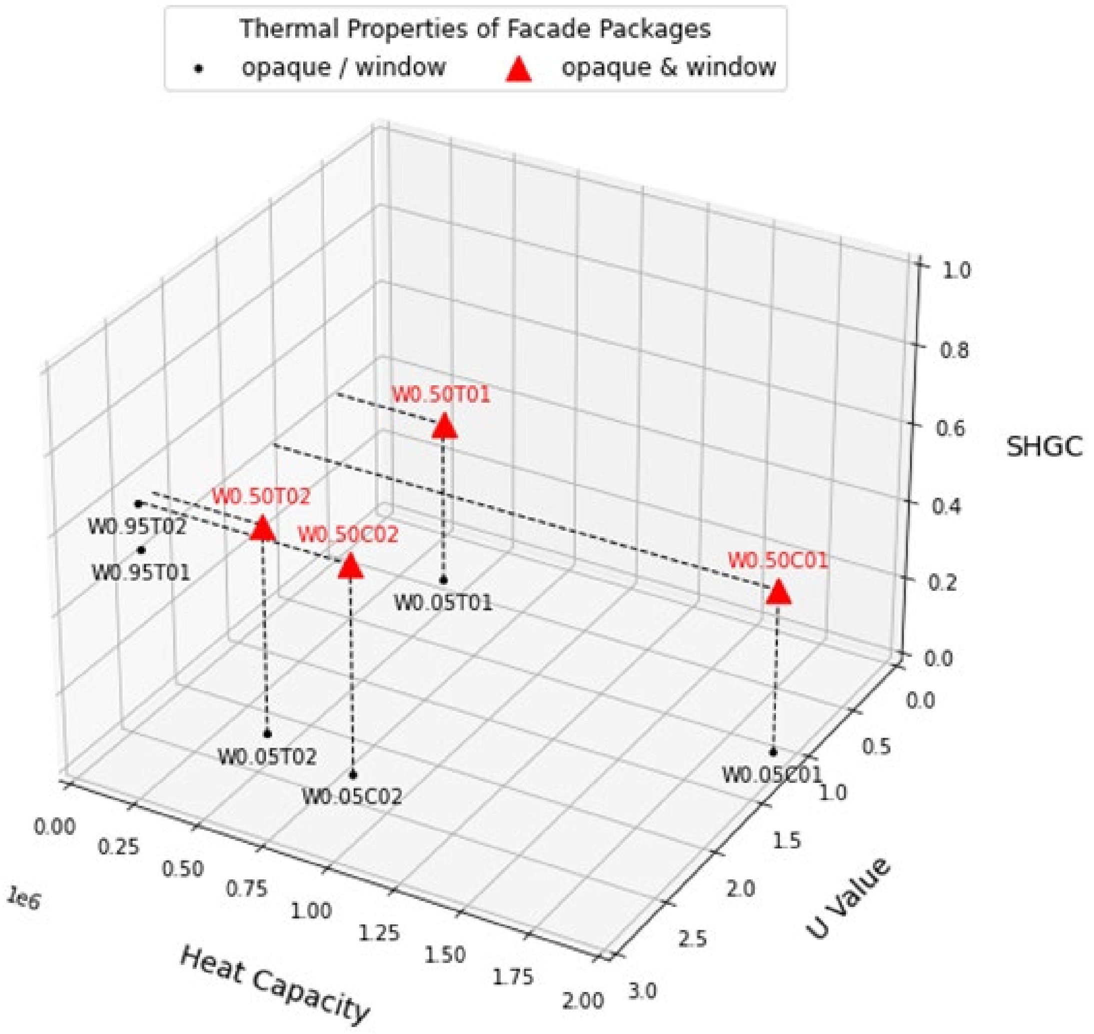
Building Operation

Natural Ventilation	Fixed Unavailable
Mechanical Ventilation	Fixed ACH 3
Cooling	Fixed 70% Capacity

Measurement Settings

Facade Material Property

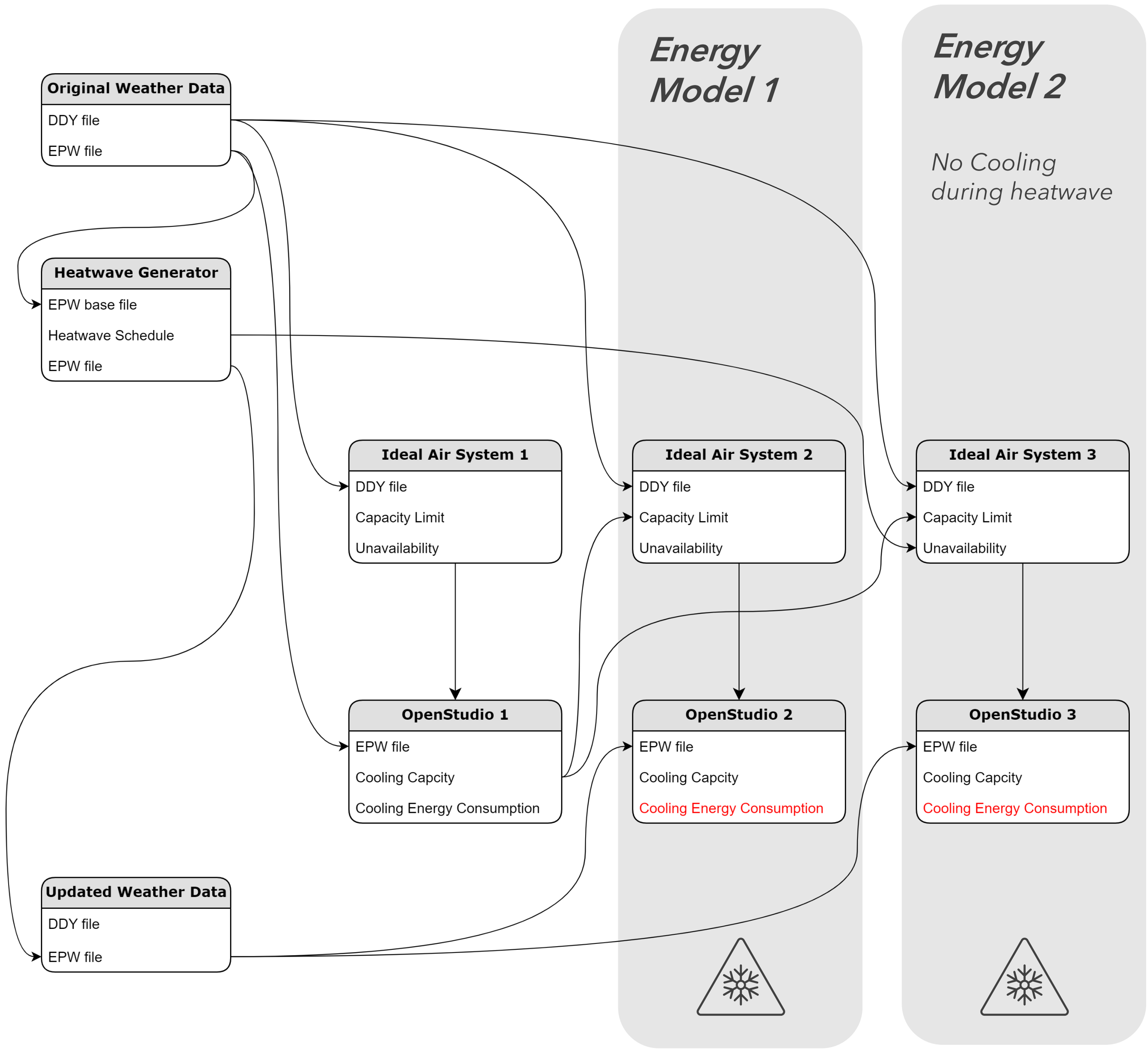
U Value	Variable -
Heat Capacity	Variable -
SHGC	Variable -



Measurement Settings

Cooling Energy Model

Energy model with/without cooling system during heatwave is simulated to quantify extra energy consumption caused by a heatwave.



Measurement Settings

Energy Model 1

The first two days fails to maintain 24°C during occupied periods. SET follows the outdoor temperature peaks.

Zone Total Cooling Energy (kWh) : 510.27

Electricity Tariff (€/kWh) : 0.2525

Cooling Energy Cost (€): 128.84

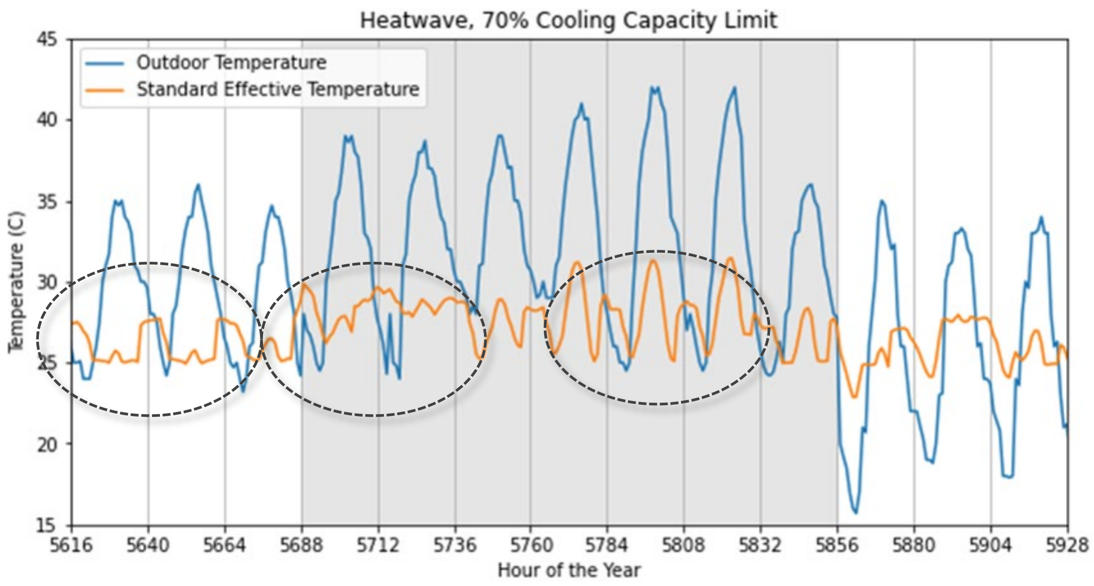
Energy Model 2

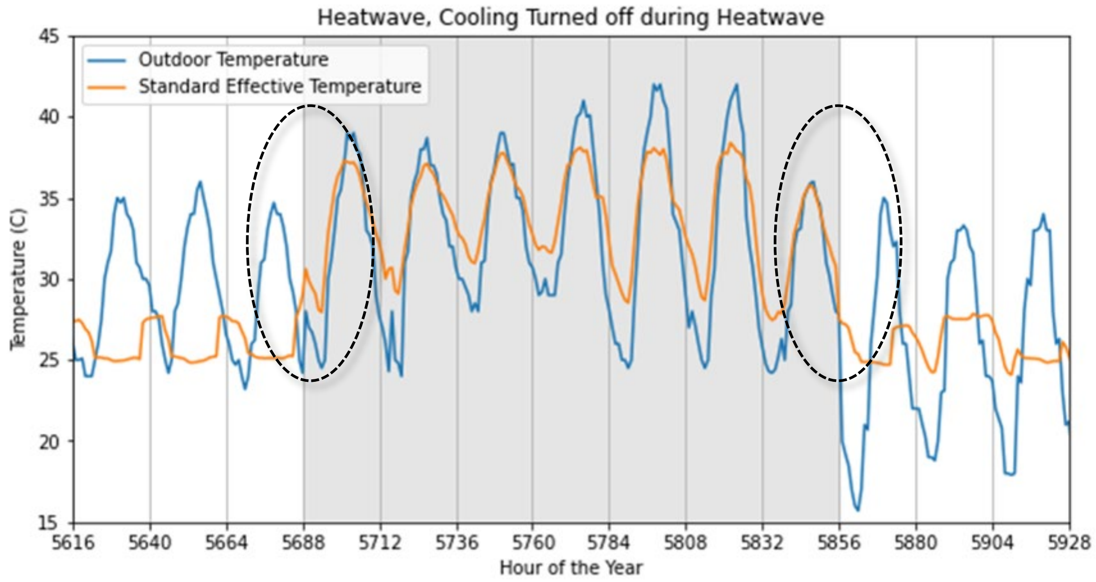
Cooling system's peak load during heatwave occur at the beginning and end of the period.

Zone Total Cooling Energy (kWh) : 404.78

Electricity Tariff (€/kWh) : 0.2525

Cooling Energy Cost (€): 102.20





State of Art

1

Framework

2

Case Study

Results

3

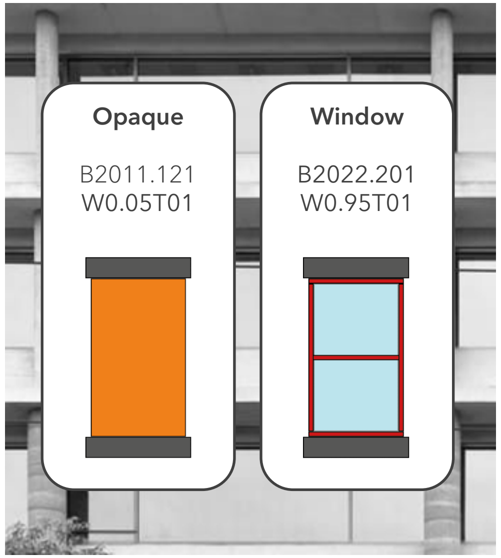
Evaluation

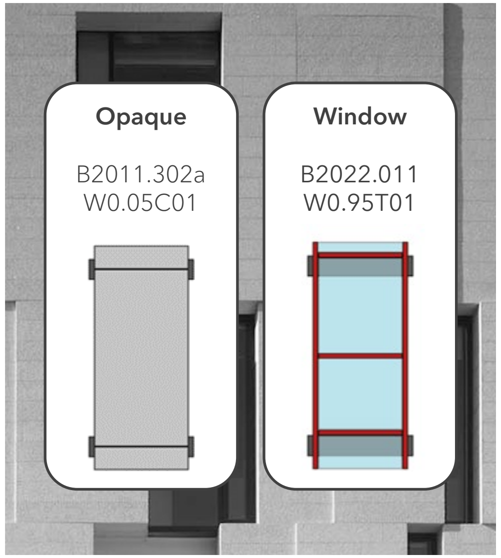
4

Decision Making
in early design stages

Which facade system is more resilient?

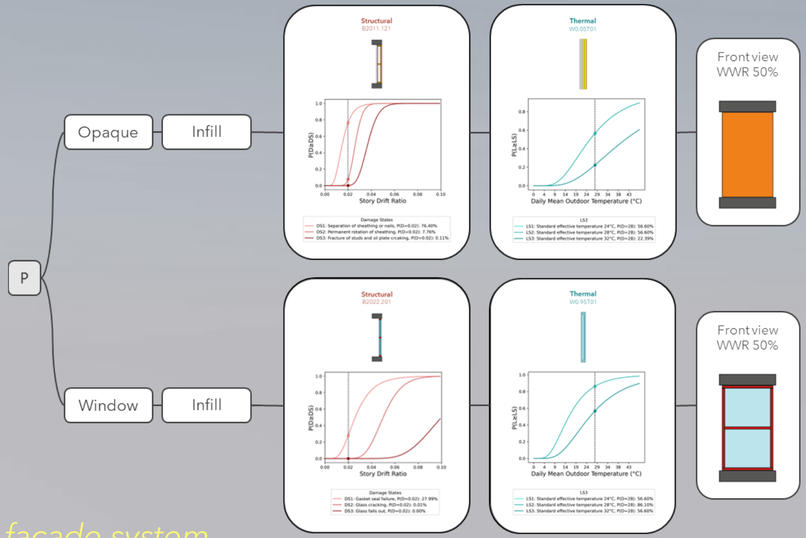
Decision Making
in early design stages



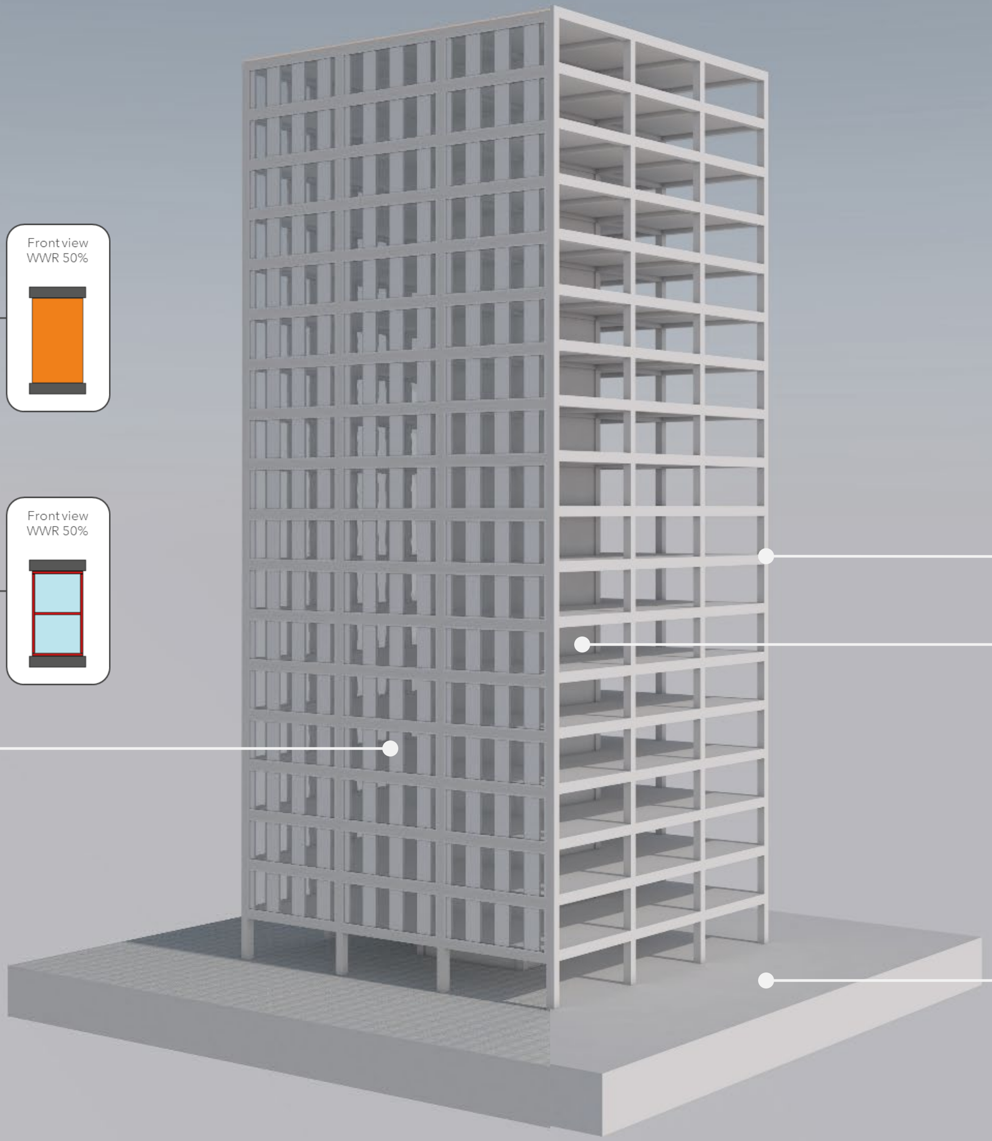


Which facade system is more resilient?

Stud wall Infill & Unitized Window



facade system



structural system

RC Frame

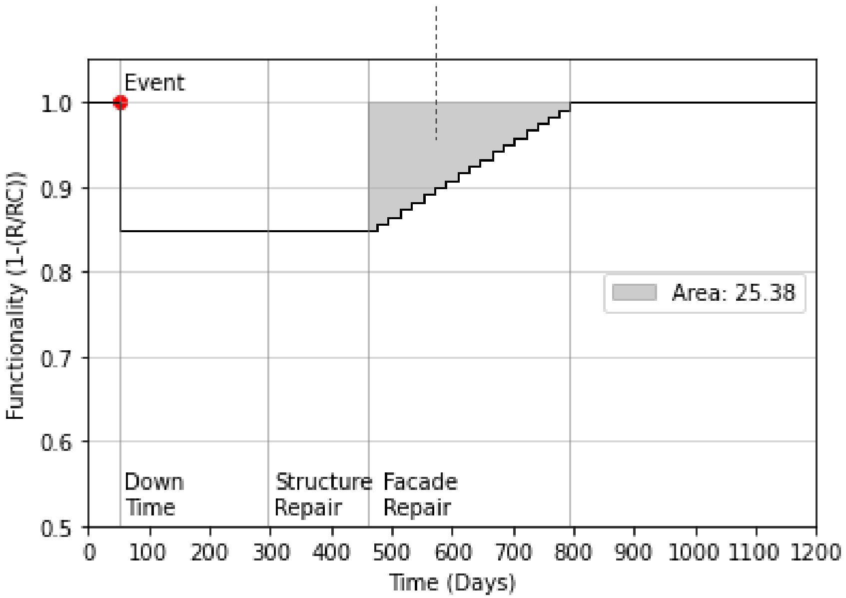
RC Wall

location

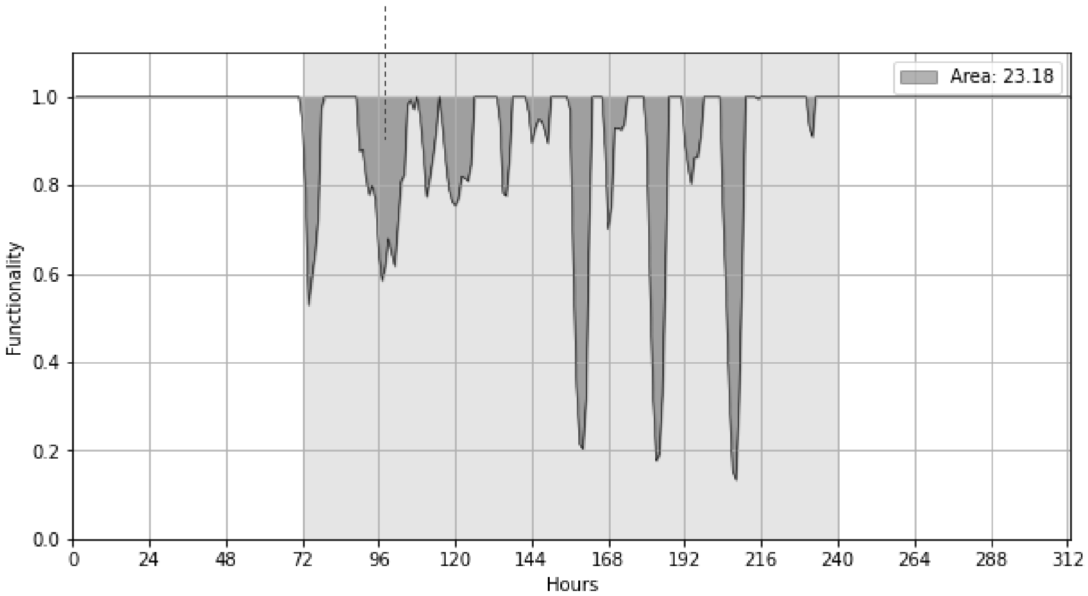
Izmir, Turkey

Studwall Infill & Unitized Window

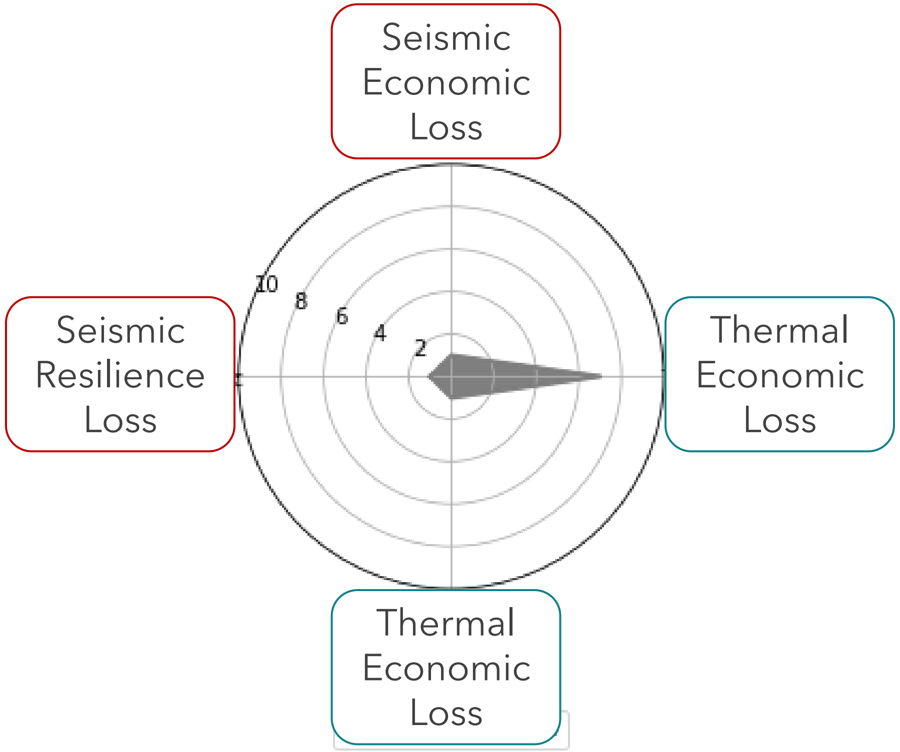
Seismic Resilience Loss



Thermal Resilience Loss



Studwall Infill & Unitized Window



Studwall Infill & Unitized Window

Project Description

Building location	Izmir
Building program	office
Structural system	RC dual

Facade Package

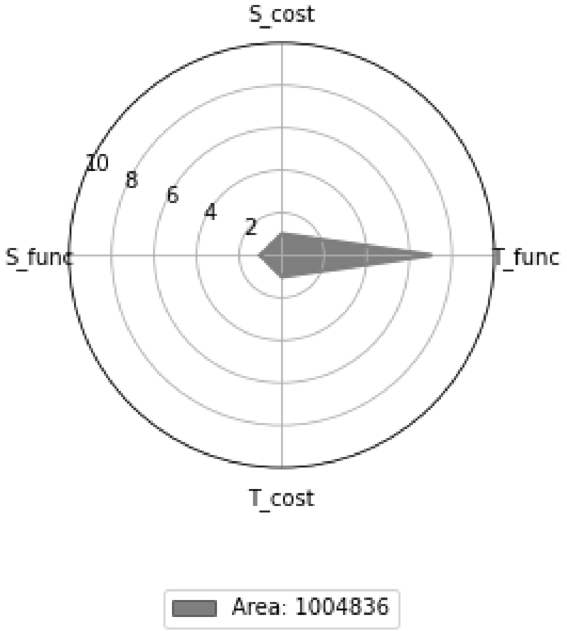
Total facade area	4860 m^2
Window to wall ratio	50 %

Opaque

B2011.121
W0.05T01

Window

B2022.201
W0.95T01



Total resilience loss

1004836

Seismic resilience loss

25.37

Seismic economic loss

639761.17

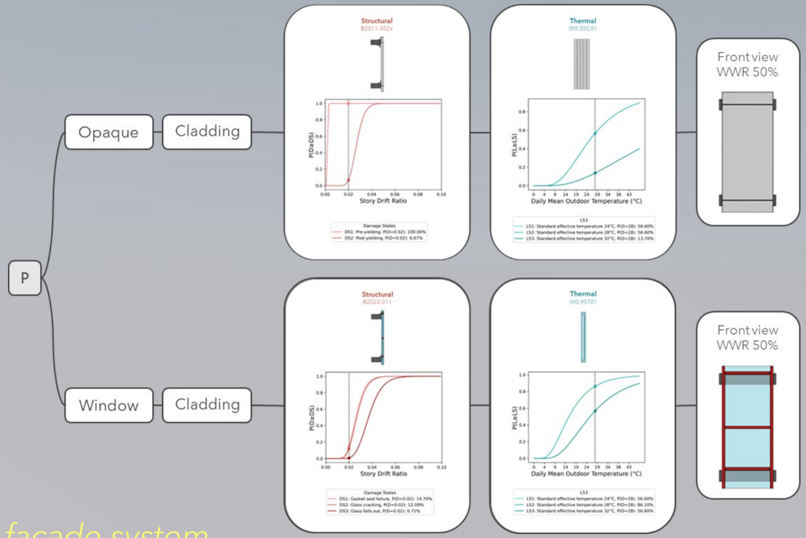
Thermal resilience loss

63.27

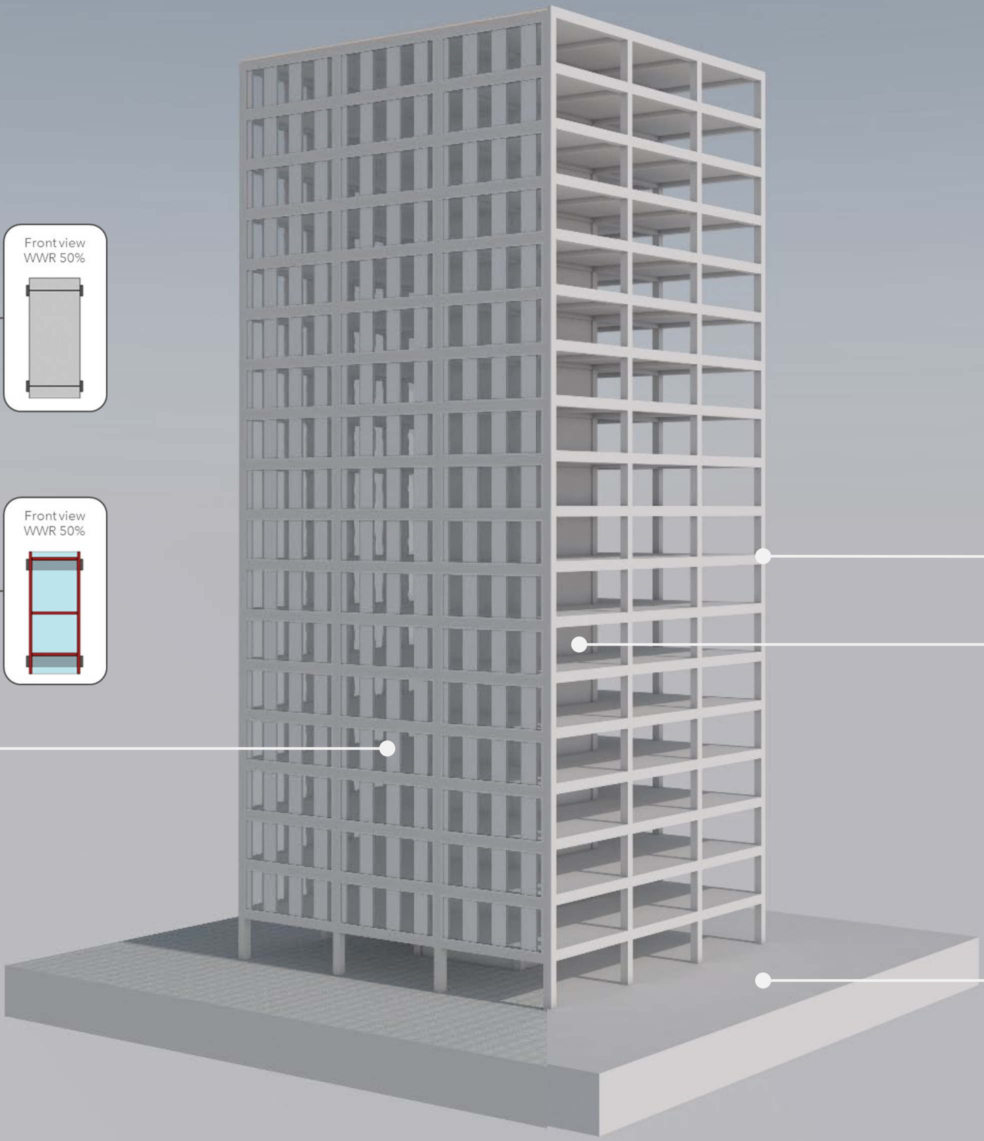
Thermal economic loss

100.04

Concrete Cladding & Curtainwall Window



facade system



structural system

RC Frame

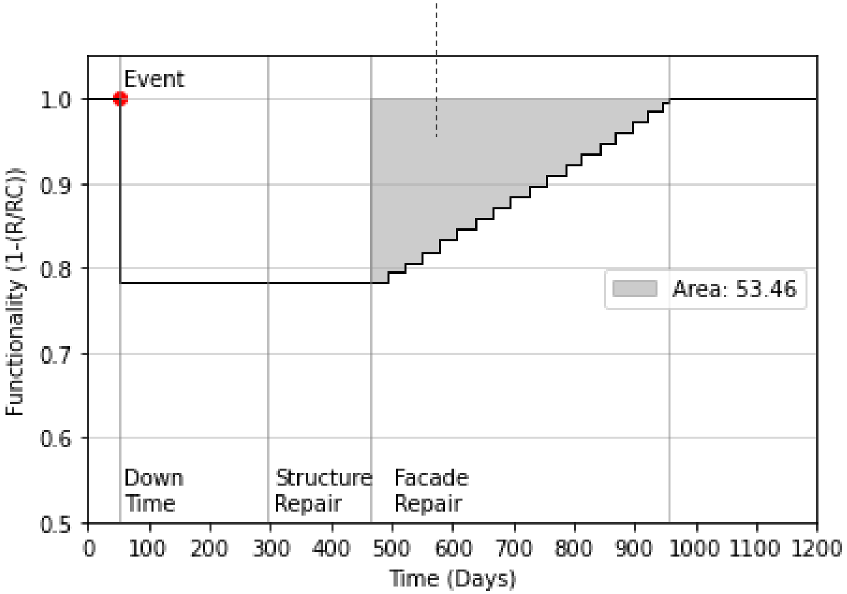
RC Wall

location

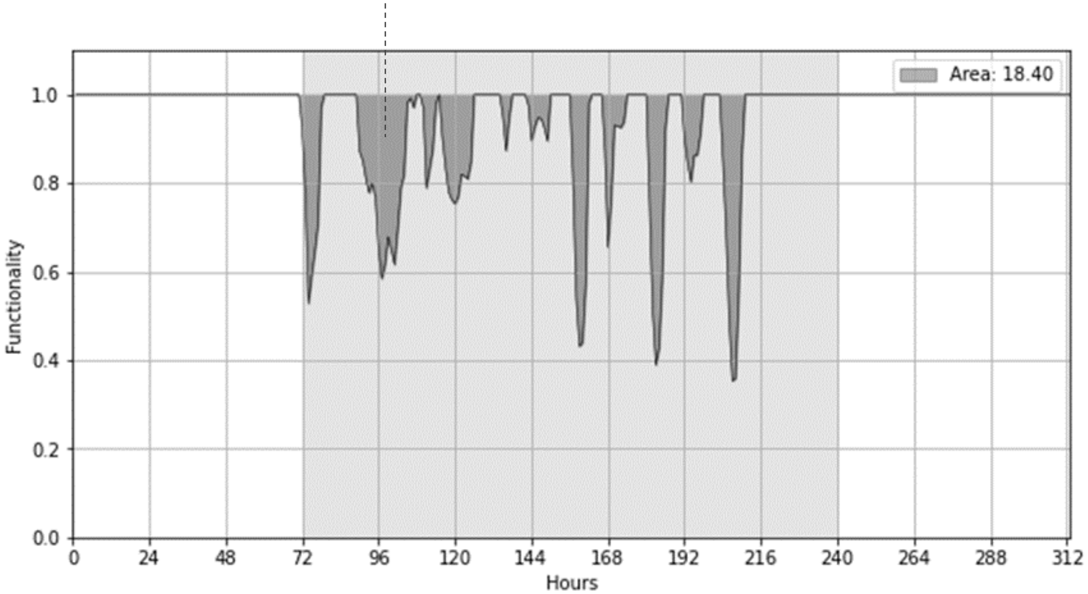
Izmir, Turkey

Concrete Cladding & Curtainwall Window

Seismic Resilience Loss



Thermal Resilience Loss



Concrete Cladding & Curtainwall Window

Project Description	
Building location	Izmir
Building program	office
Structural system	RC dual

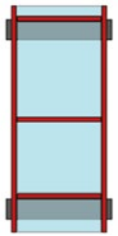
Facade Package	
Total facade area	4860 m^2
Window to wall ratio	50 %

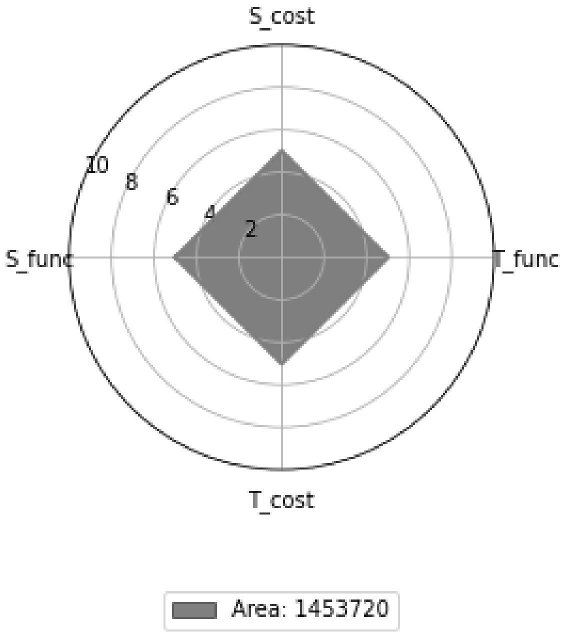
Opaque

B2011.302a
W0.05C01

Window

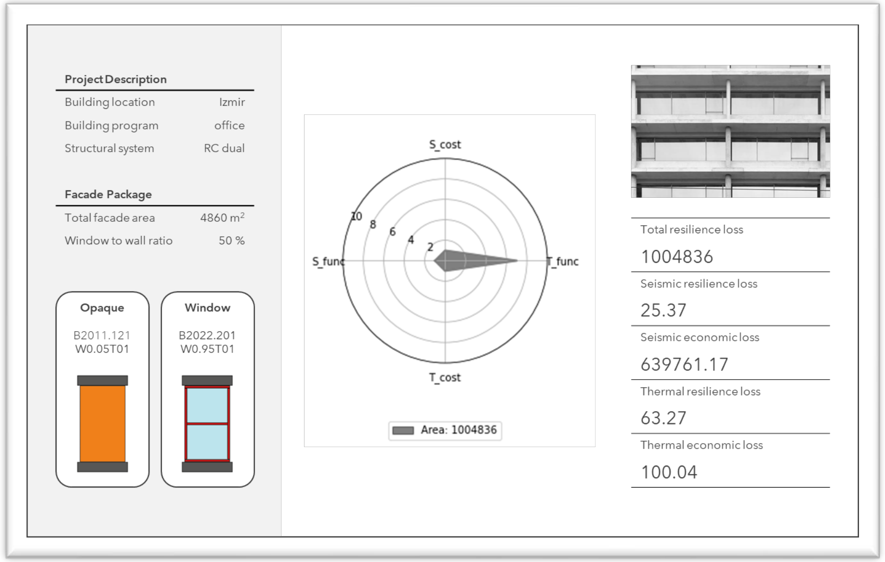
B2022.011
W0.95T01

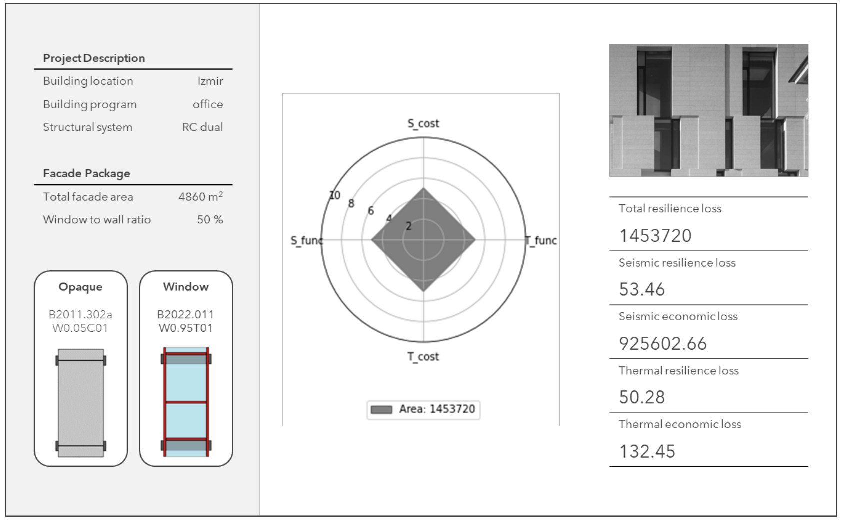




Total resilience loss	1453720
Seismic resilience loss	53.46
Seismic economic loss	925602.66
Thermal resilience loss	50.28
Thermal economic loss	132.45

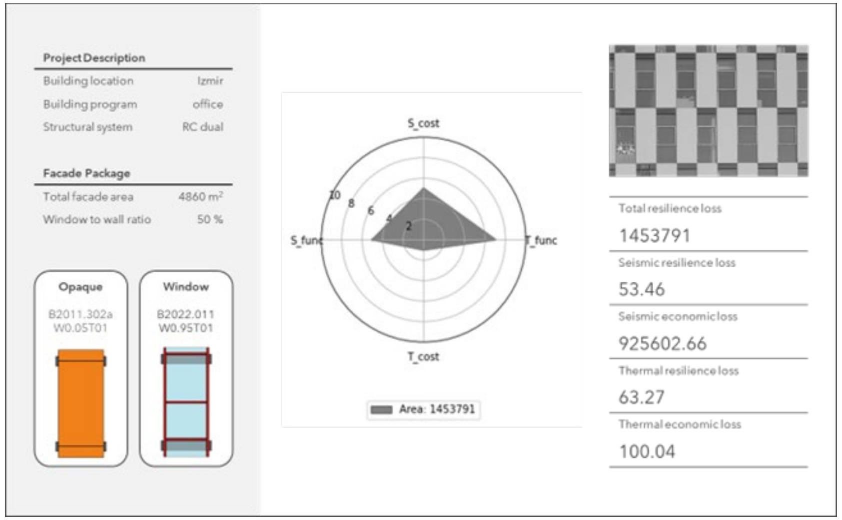
Decision Making
in early design stages

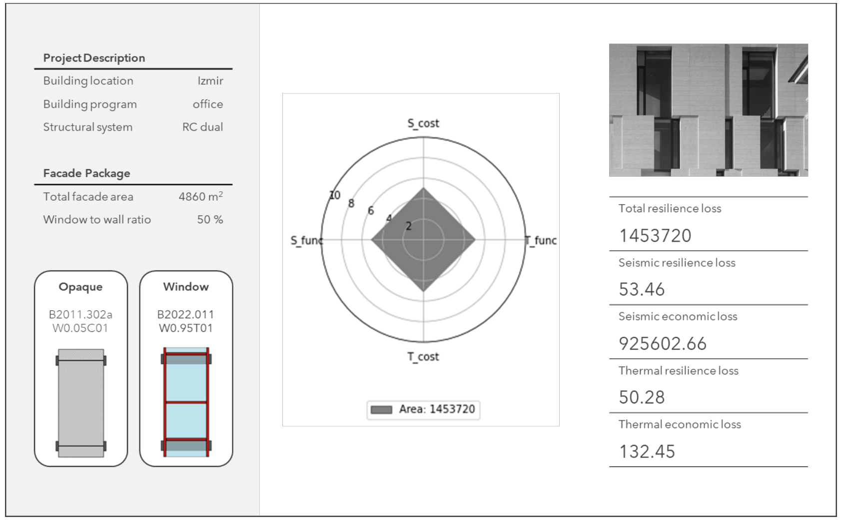




Which facade system is more resilient?

Decision Making
in early design stages

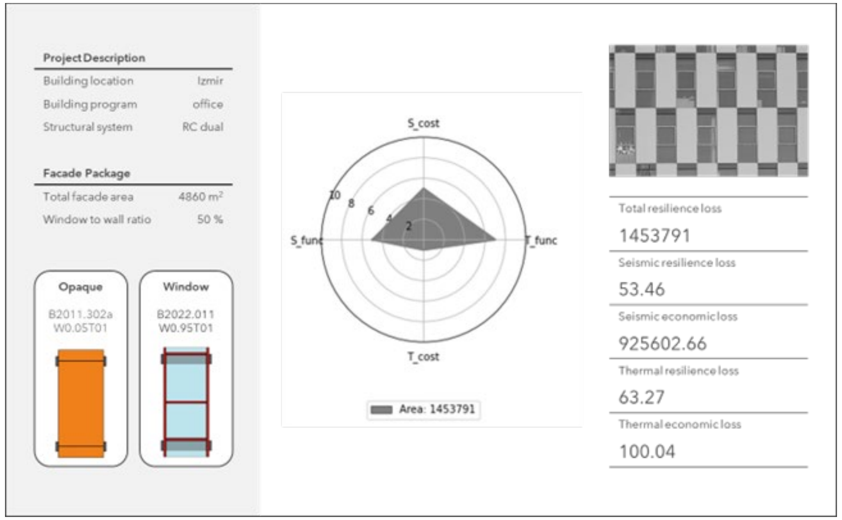


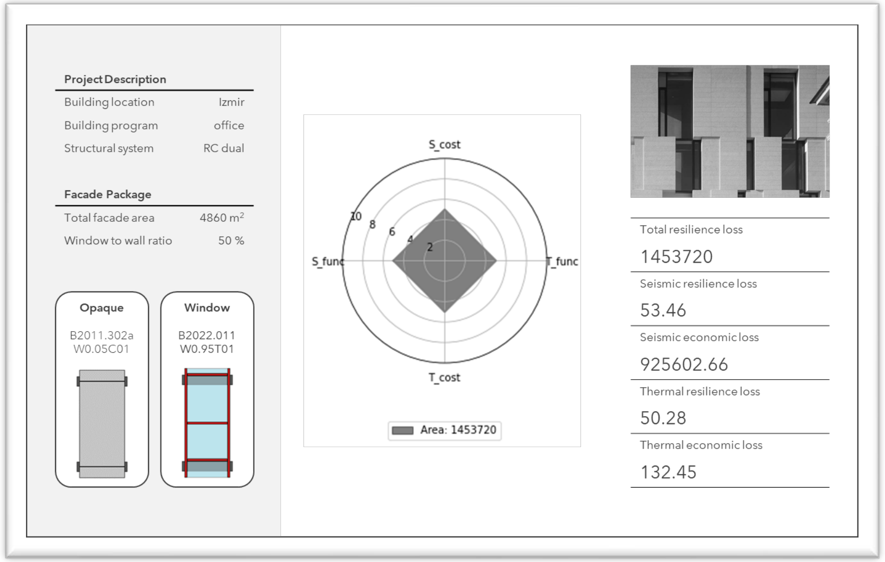


Which facade system is more resilient?

e.g., hospital (thermal functionality loss can't be compromised)

Decision Making
in early design stages

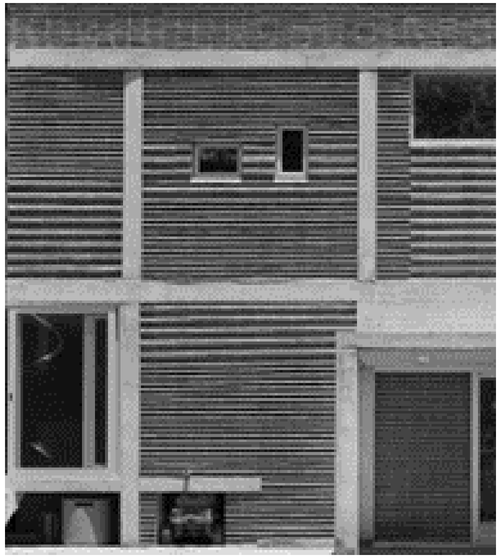




Which facade system is more resilient?

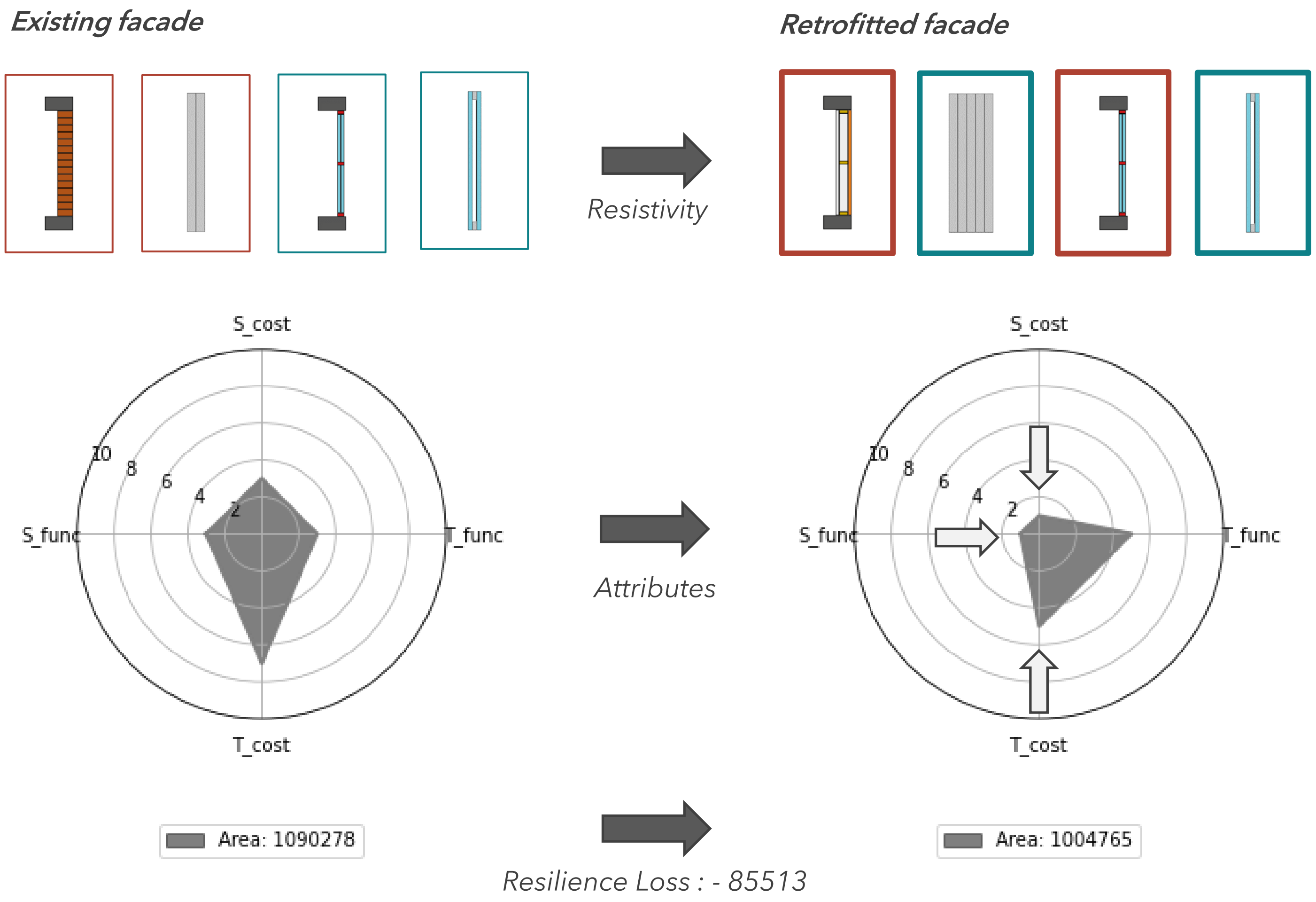
e.g., hospital (thermal functionality loss can't be compromised)

Decision Making
for retrofitting

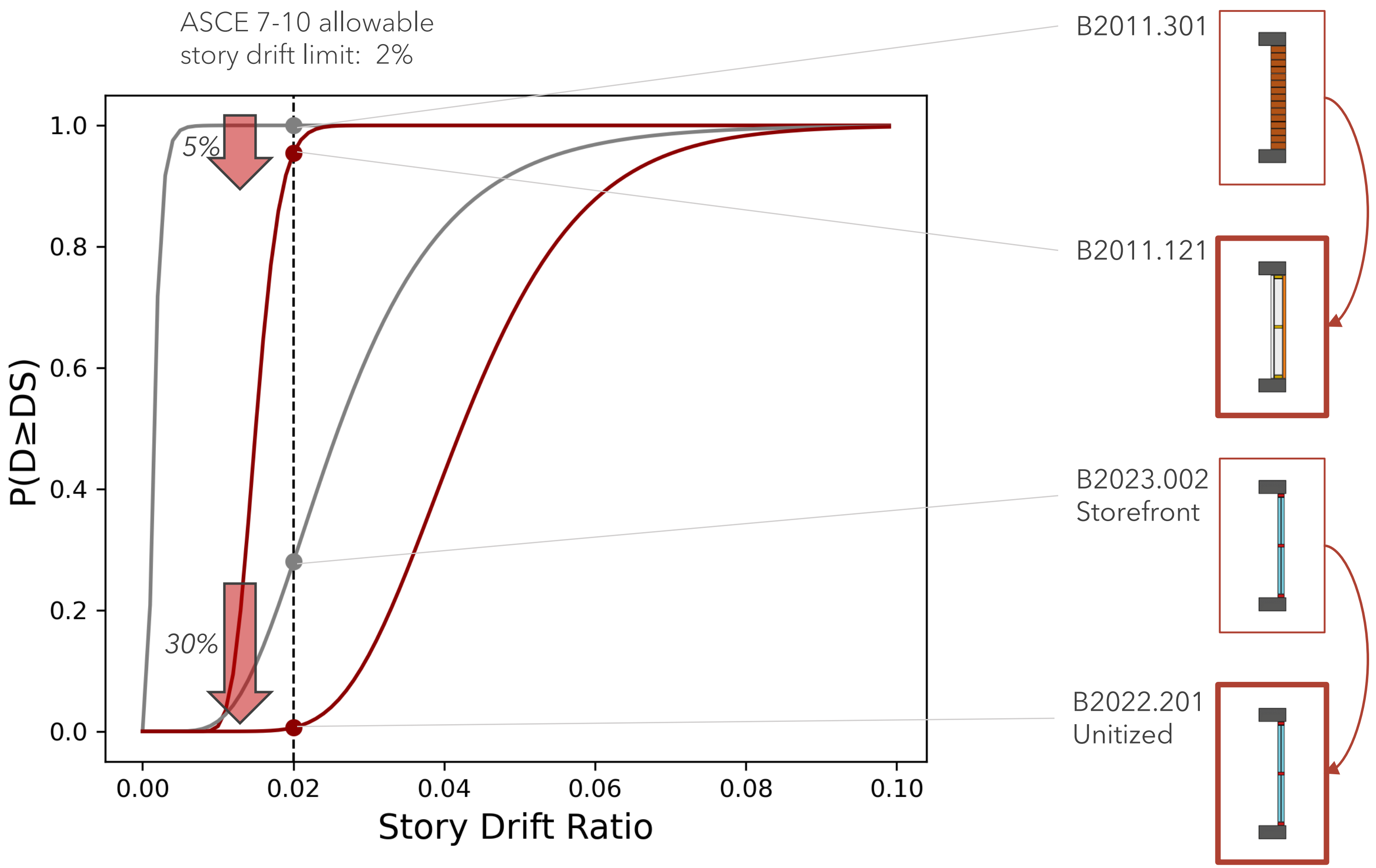


How to make the existing facade more resilient?

Decision Making
for retrofitting

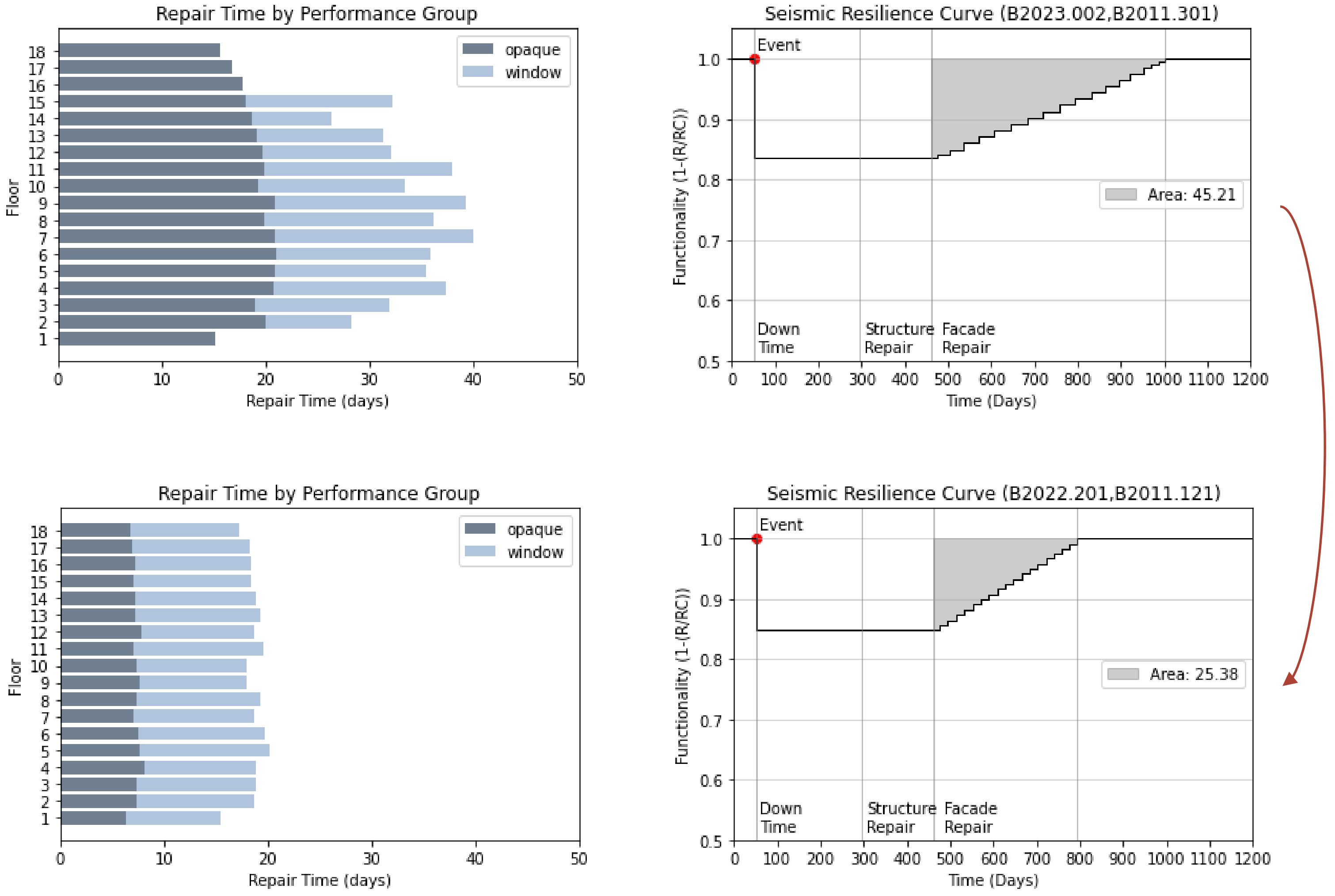


Retrofit Strategy
Improving Seismic Resistivity



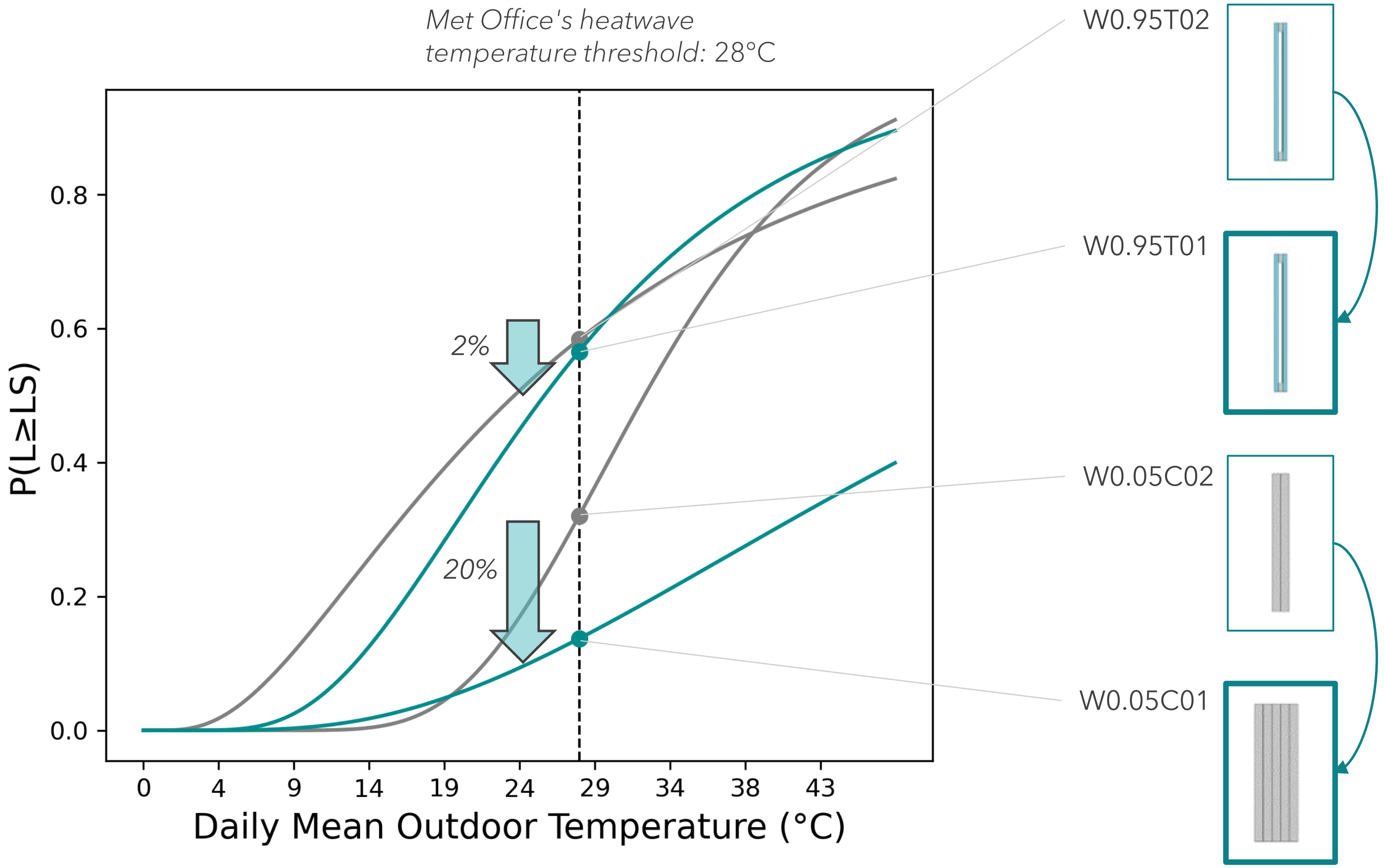
Retrofit Strategy

Improving Seismic Resistivity

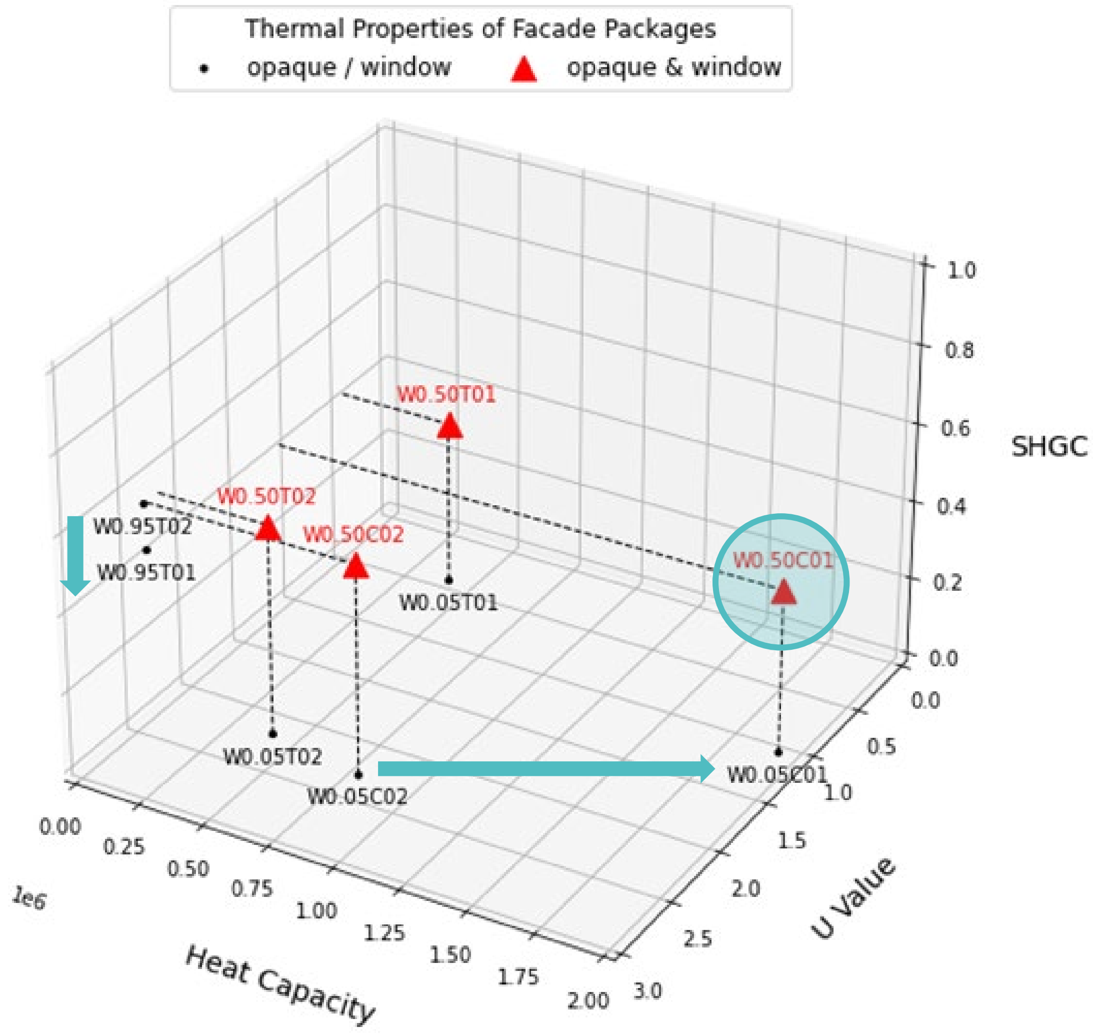


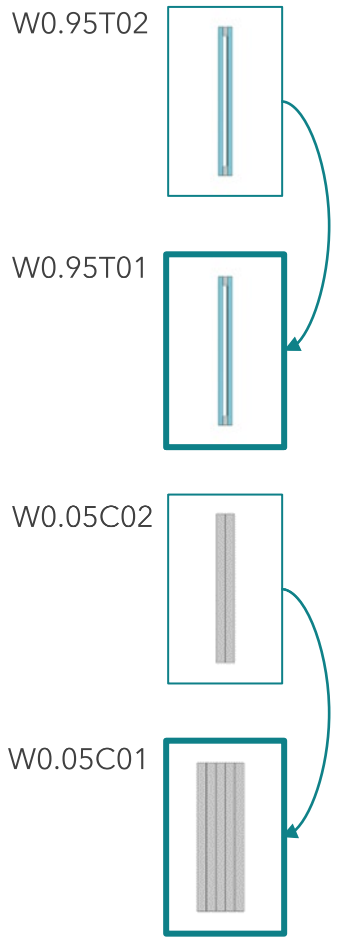
Retrofit Strategy

Improving Thermal Resistivity



Retrofit Strategy
Improving Thermal Resistivity

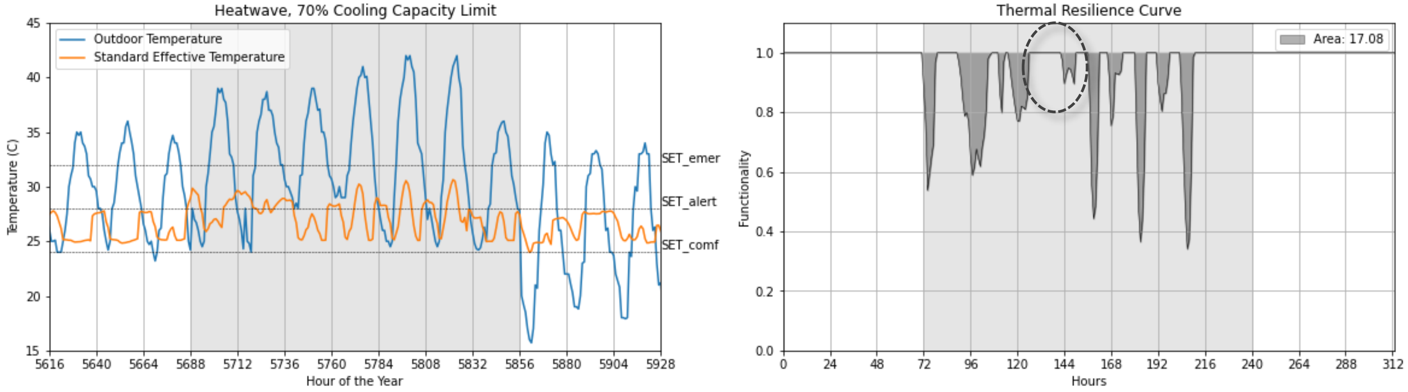




Retrofit Strategy
Improving Thermal Resistivity

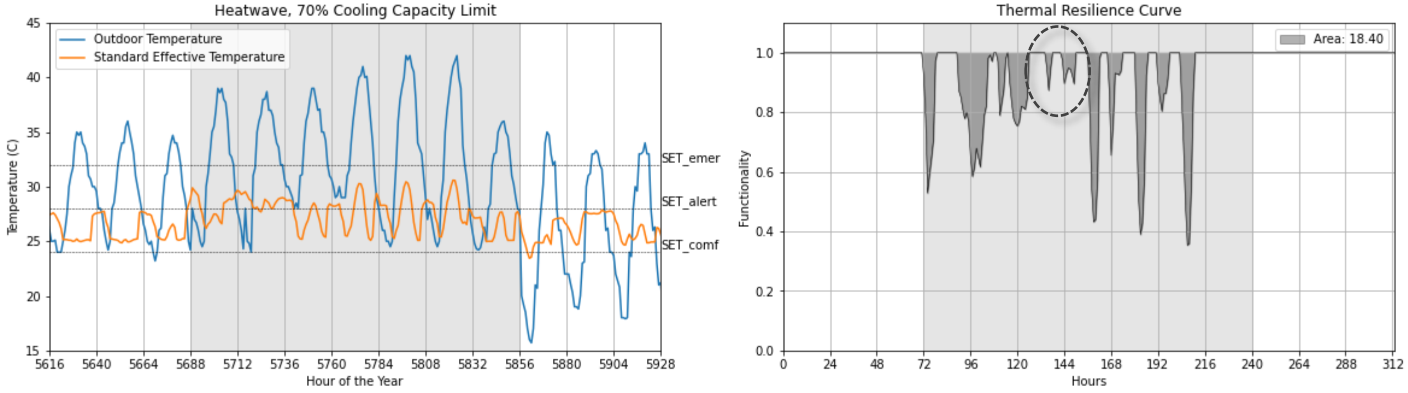
<u>During Heatwave (168Hours)</u>
Loss Cost (€) 39.26
Loss Time (degree-hours) : 17.08

Floor 10



<u>During Heatwave (168Hours)</u>
Loss Cost (€) 38.77
Loss Time (degree-hours) : 18.40

Floor 10



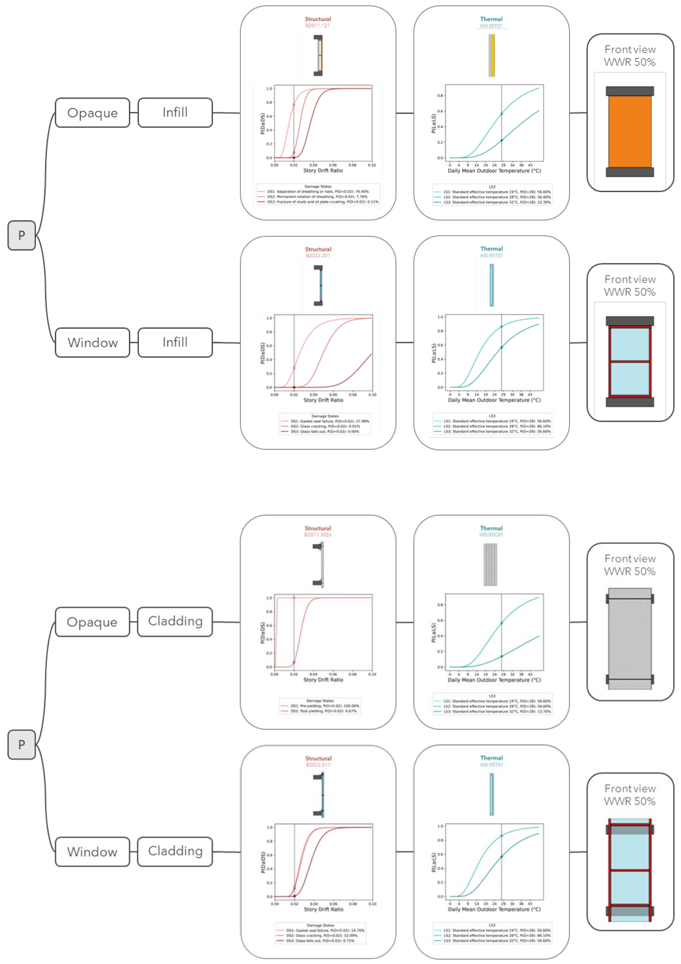
State of Art	Framework	Case Study	Evaluation
1	2	3	4

Research Question

What **methodology** can be developed to assess the resilience of facade systems under multiple hazards, and how can this methodology be integrated into the facade design process?

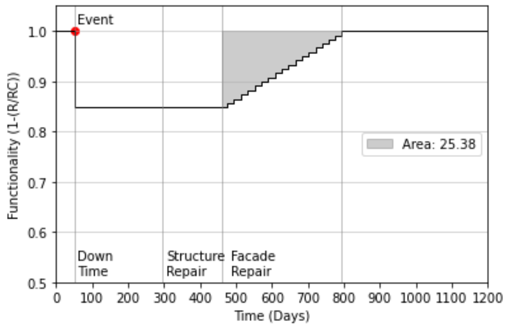
Key Takeaways

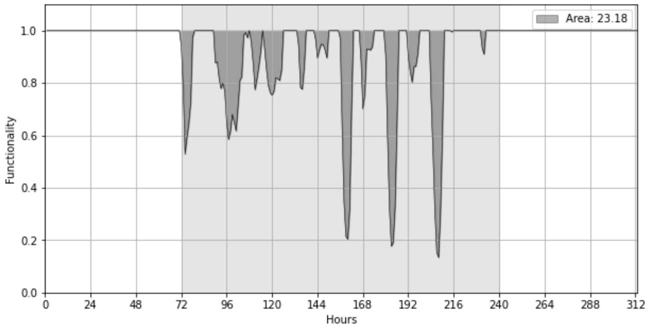
① Assessing resilience of facade systems under multi hazard



Key Takeaways

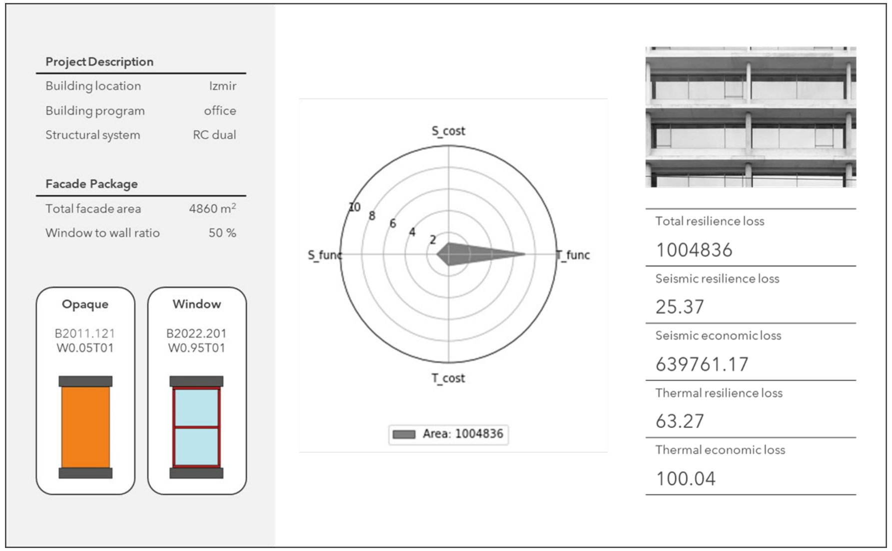
① Assessing resilience of facade systems under multi hazard





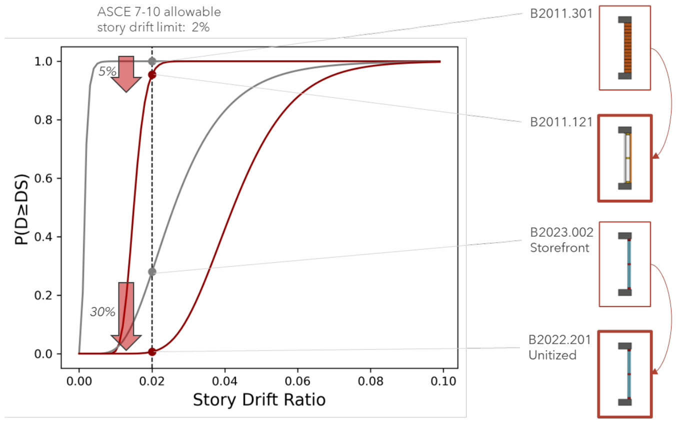
Key Takeaways

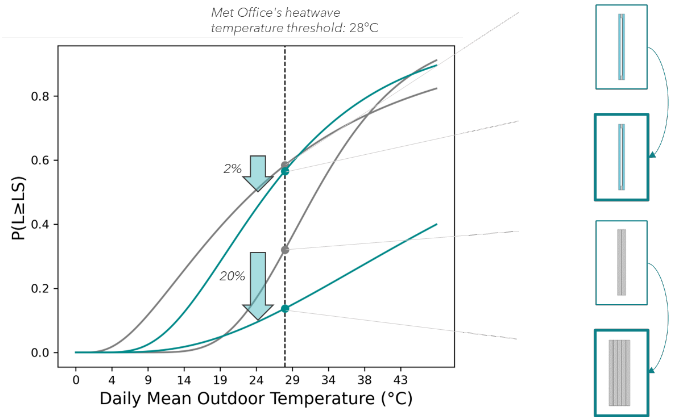
② Metrics for comparing the resilience of facade systems



Key Takeaways

③ Implementation of resilience-based approach in facade design





Future Research

Validity*

Relevance**

Flexibility***

Future Research
validity *
relevance **
flexibility ***

Input

Facade Package

	Structural Function	Thermal Function	
Design Parameter	(depends on database availability)	**U-value, Heat Capacity, SHGC**	local construction ***
Intensity Measure	**Damage State 1,2,3** (damage standard varies by facade system)	**Limit State 1,2,3** (standard effective temperature exceeding 24°C, 28°C, 32°C)	threshold *
Failure Probability	**Fragility Curve**	**Fragility Curve**	fitting method *

Input

Multi Hazard

	Seismic Hazard	Thermal Hazard	
Engineering Demand	**Response Spectrum** (spectral acceleration at the fundamental period of vibration)	**Weather Data including Heatwave** (outdoor air temperature during 7 days of heatwave)	hazard model *

Output

Quantitative Resilience Assessment

	Seismic Resilience	Thermal Resilience	
Demand Parameter	**Inter-story Drift**	**Outdoor Air Temperature**	direct relevance **
Resilience Loss	**1- Repair Cost / Replacement Cost**	**Degree Hours above Threshold**	
Economic Loss	**Repair Cost**	**Energy Cost Difference with/without Cooling**	local cost ***

Output

Multi Attribute Decision Making

	Seismic Performance	Thermal Performance	
Comparison Standard	**Seismic Design Code Limit**	**Heatwave Temperature Threshold**	threshold *
Resilience Attribute	**Resilience Loss, Economic Loss**	**Resilience Loss, Economic Loss**	direct relevance **

Future Research

Validity

- SET Threshold for mechanically conditioned spaces
- SET Threshold outside the comfort range

- Validation of thermal fragility function
- Threshold value for comparing failure probabilities

- Hourly weather data from heat hazard model

Future Research

Relevance

- Direct relevance between demand parameter and intensity measure
- Thermal resilience loss directly due to facade

Future Research

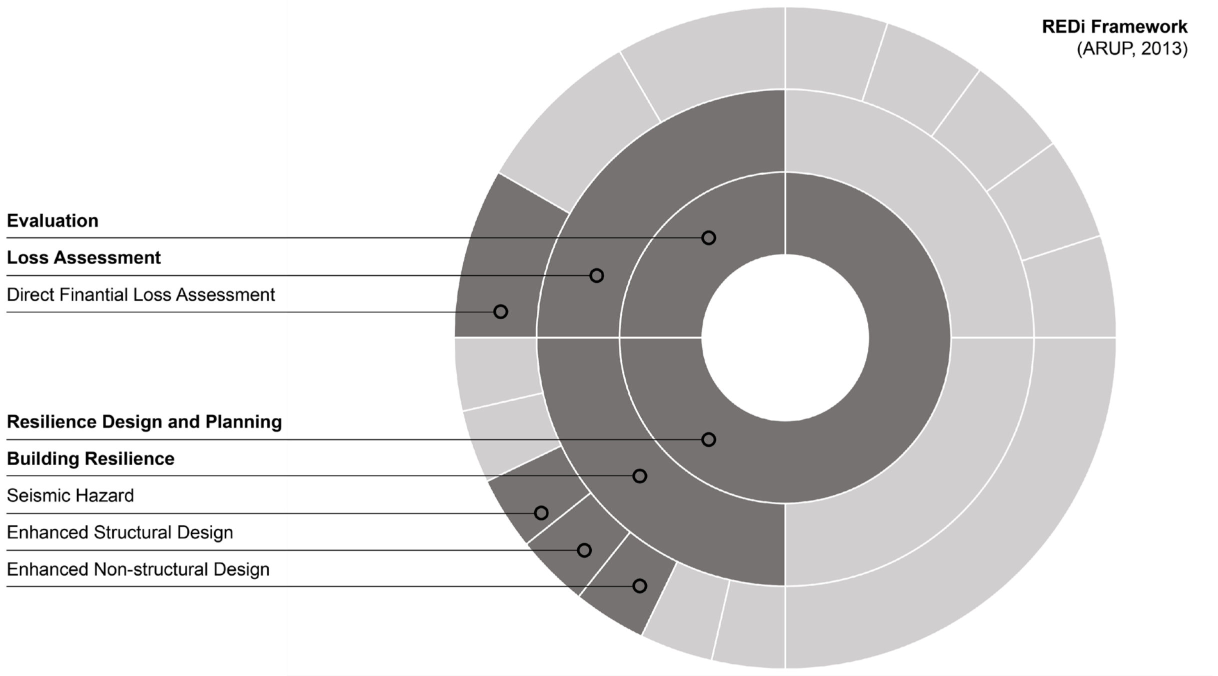
Flexibility

- Fragility functions for local facade construction
- Pricing tariff based on locations

Reflection

Social Impact

- Facade Resilience Rating
- Robust digital tool
- Project-specific



Thank you

Q&A

MSc Graduation Presentation on:

Resilience-based Facade Design Framework

Kyujin Kim

TUDelft

presenter

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Delft University of Technology

Building Technology Track

Class of 2023

supervisors

Simona Bianchi I Structural Design & Mechanics

Alessandra Luna Navarro I Façade & Product Design

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Jonathan Ciurlanti I Arup Amsterdam

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Willem Korthals Altes I Urban Development Management