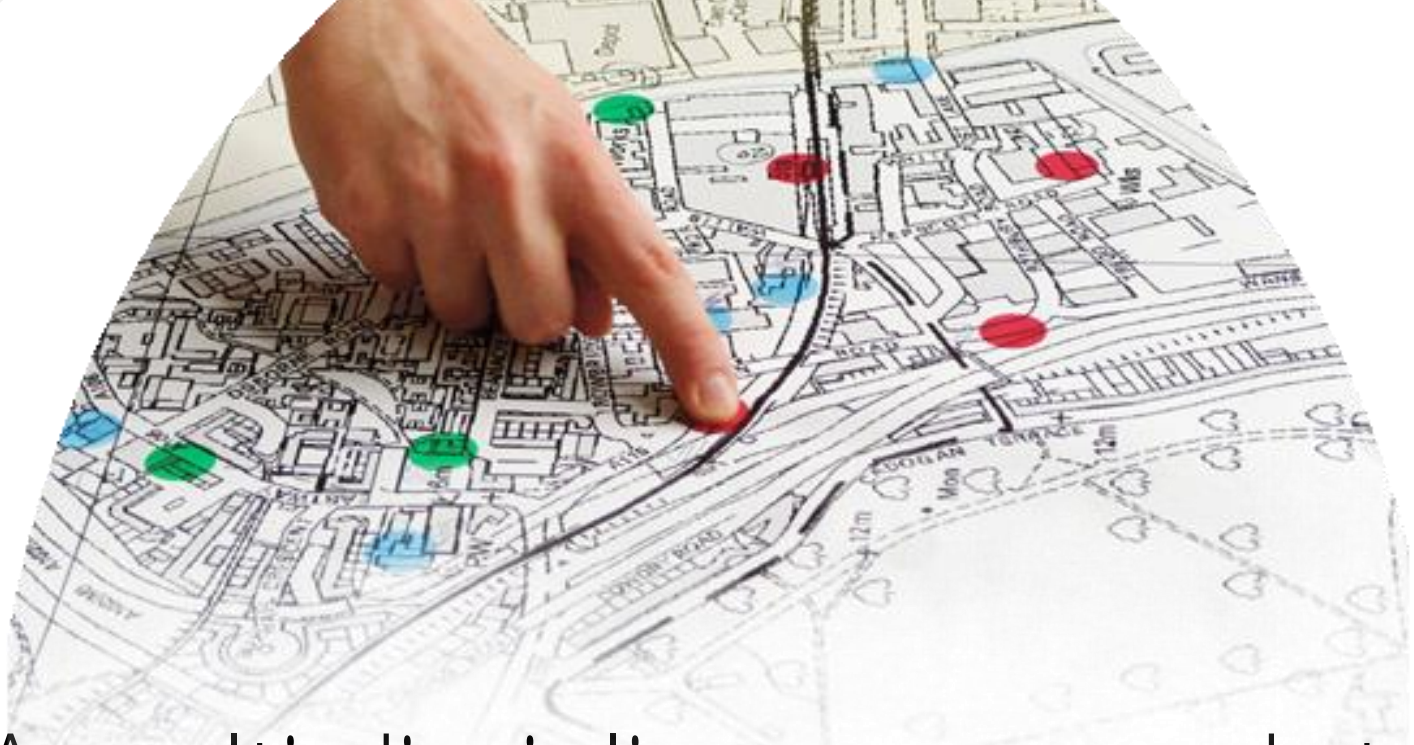


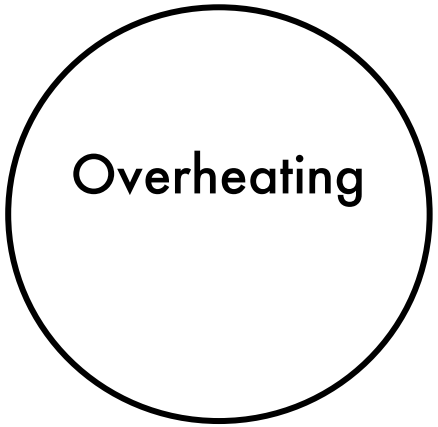
A multi-disciplinary approach to assessing the influence of facade on outdoor thermal comfort

The case study of Acquabella district, Milan

TU Delft

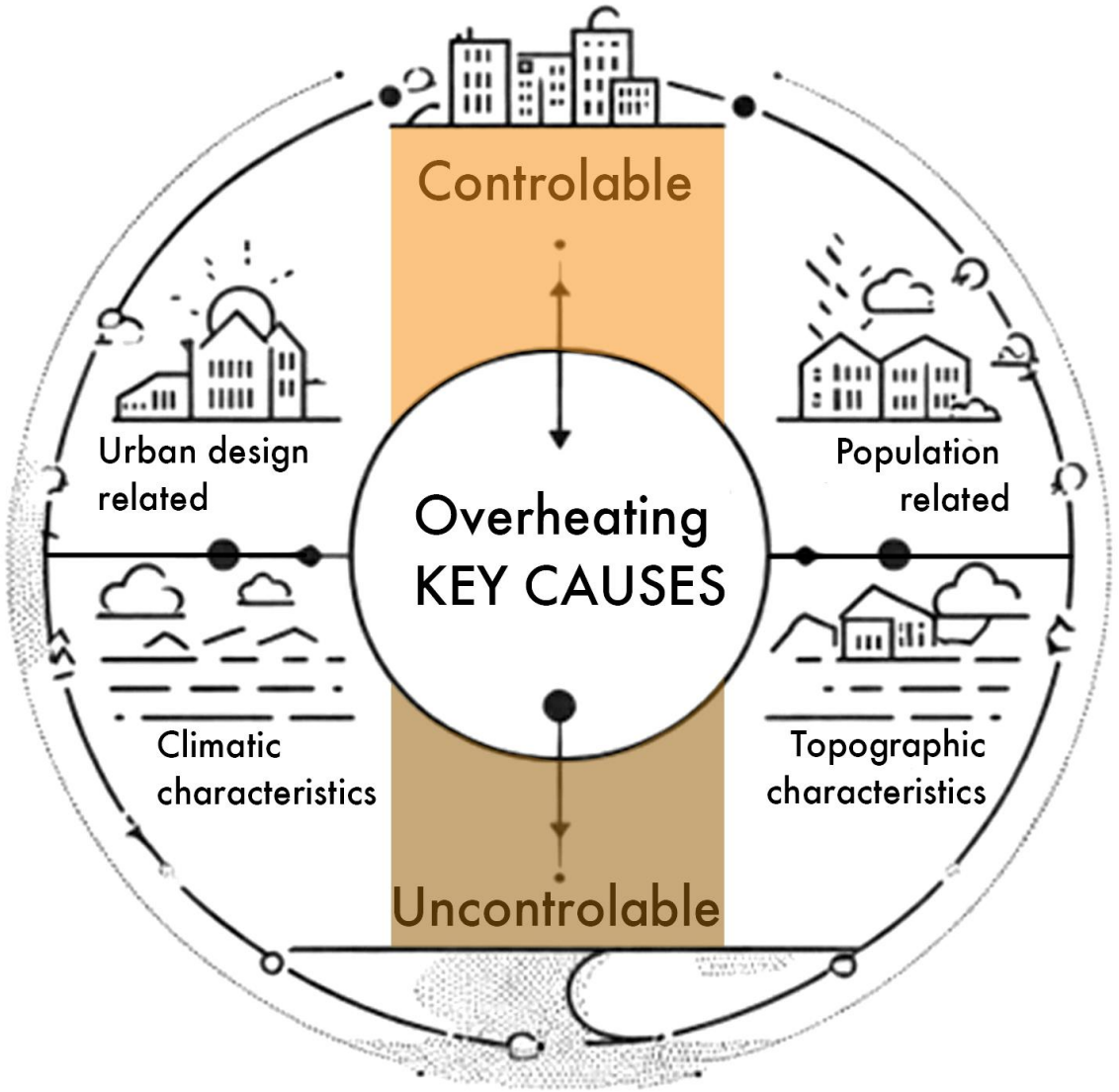

Research Framework
Case Study
Workflow
Results
Discussion

Background



Urban Heat Island effect :Cities demonstrate higher temperatures than rural areas.

Background


Controlable
Urban design related
Population related
Overheating KEY CAUSES
Climatic characteristics
Topographic characteristics
Uncontrolable

Challenges of increased temperatures?

Challenges of increased temperatures

Increased building cooling energy consumption

Elevated ground-level ozone

Health problems

Thermal discomfort

Challenges of increased temperatures

- Increased building cooling energy consumption
- Elevated ground-level ozone
- Health problems
- Thermal discomfort

Challenges of increased temperatures

- Increased building cooling energy consumption
- Elevated ground-level ozone
- Health problems
- Thermal discomfort

Challenges of increased temperatures

- Increased building cooling energy consumption
- Elevated ground-level ozone
- Health problems
- **Thermal discomfort**

Definition

Variables

Thermal Perception

Indices

Methods

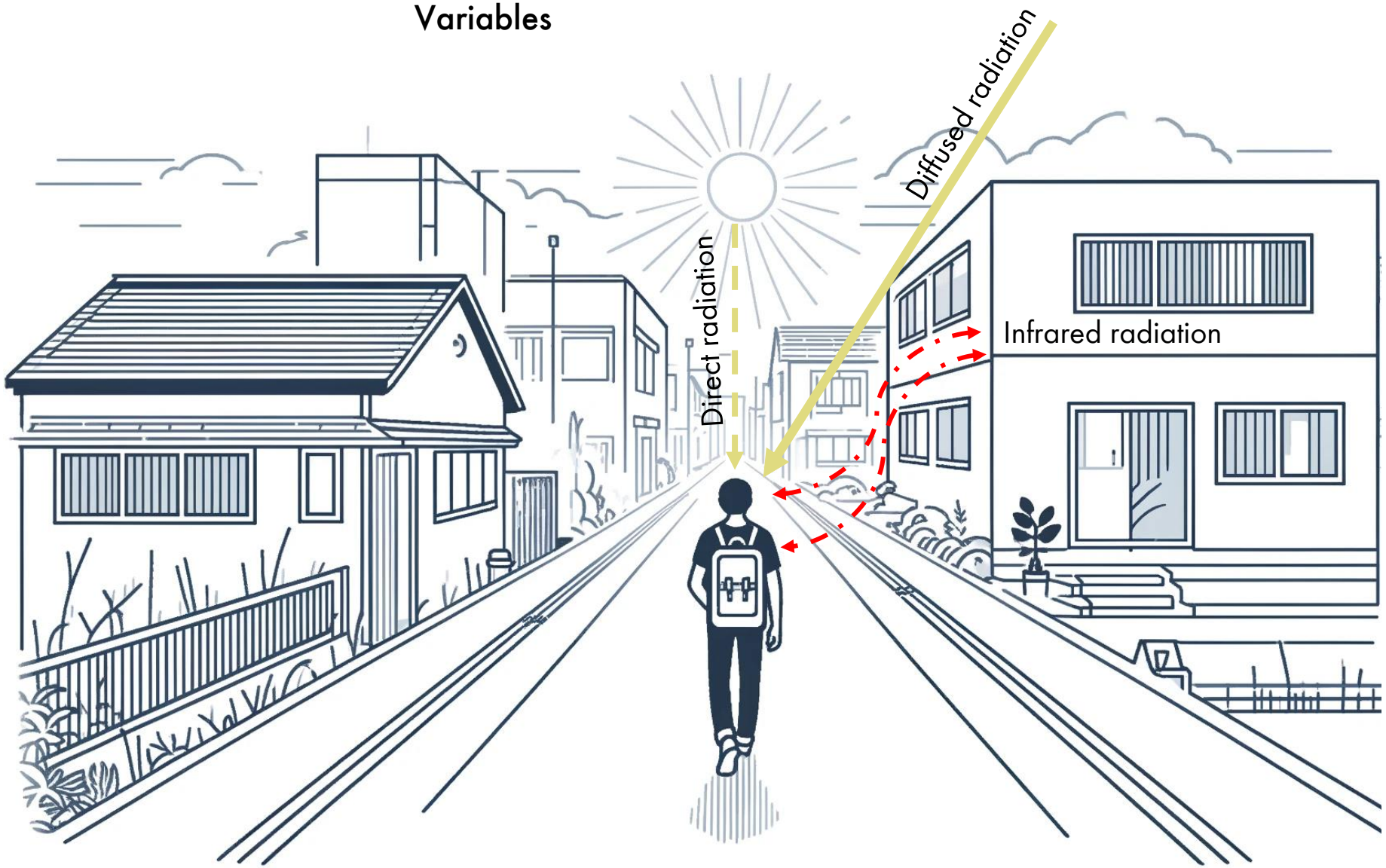
Aesthetics influence

Outdoor Thermal Comfort

Definition

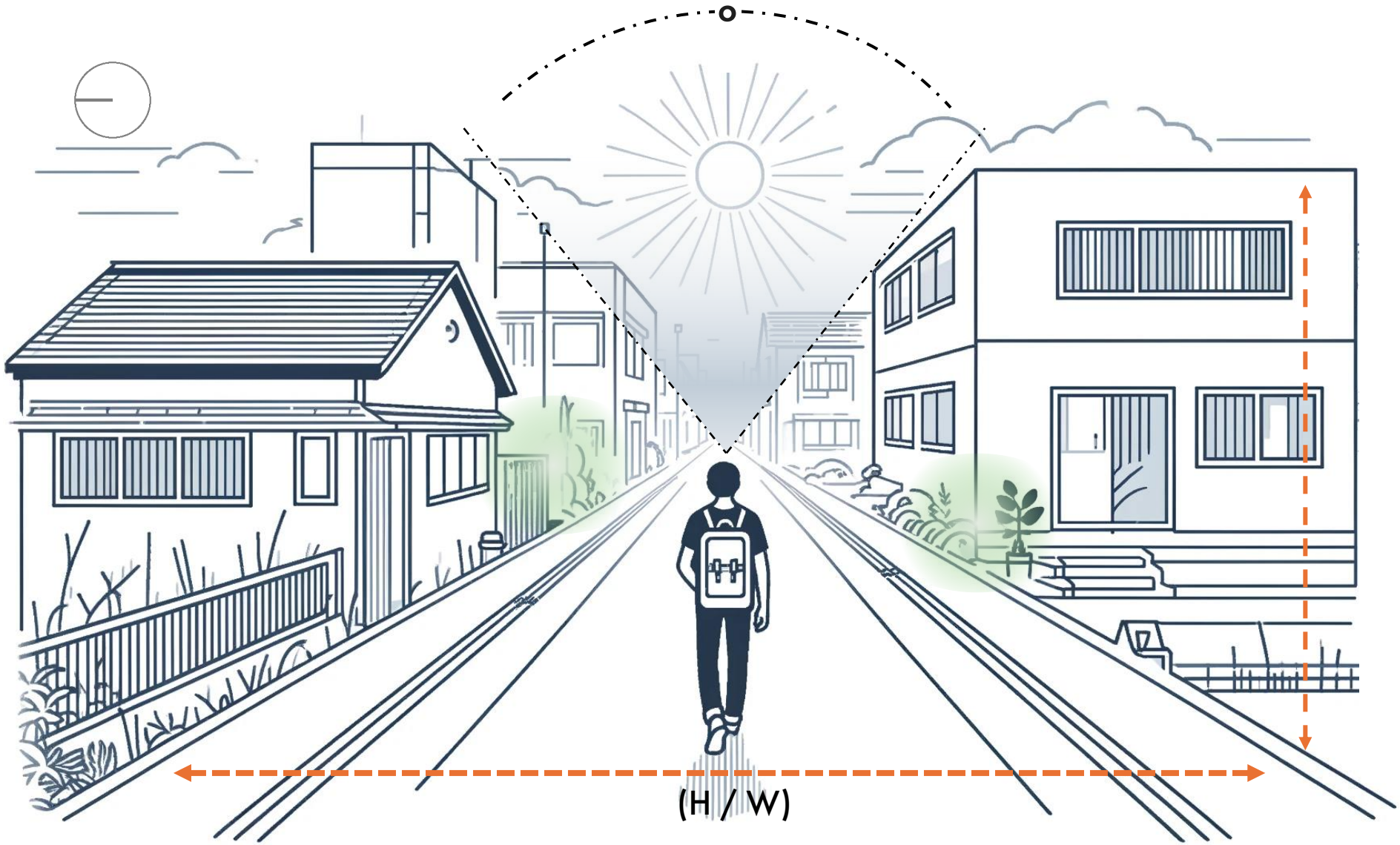
Thermal Comfort : A state of mind that expresses satisfaction with the thermal environment.

Variables



- Air Temperature
- Humidity
- Wind Velocity & Direction
- Solar Radiation
- Mean Radiant Temperature

Built environment



- Aspect ratio (AR)
- Sky View Factor (SVF)
- Orientation
- Neighborhood Geometry
- Vegetation
- Water bodies
- Surface Properties

Thermal Perception

Thermal Perception is subjective and different for every individual.

Influenced by:

- Personal characteristics
- Physiological acclimatization
- Behavioral adaptation
- Psychological adaptation

Thermal Perception

Subjective perception:
- Clothing Factor
- Activity level
- Personal characteristics
- Thermal history

Thermal Sensation Vote (TSV):

Very Cold (-3)
Cold (-2)
Cool (-1)
Slightly Cool
Comfortable (0)
Slightly Warm
Warm (+1)
Hot (+2)
Very Hot (+3)

Indices

Thermal comfort indices: COMFA model, (ETU), (ITS), MENEX model, (PT), (SET*), (OUT_SET*), (PET), (PMV), (UTCI).

Empirical indices: (ASV), (TS),(TSV), (MOCI).

Indices based on linear equations: (AT), (DI) , (ESI) ,(PSI), (ET),(H), (HI), (PE), (RSI),(WBGT), (WCI)

		PMV	UTCI	PET	MOCI
Climate	Gr			X	
	Ta	X	X	X	X
	RH	X	X	X	X
	Ws	X	X	X	X
Microclimate	SVF				
	Dr				
	Dfr				
	MRT	X	X	X	X
	St				
	Gt				
	Ba				
	Ga				
Human	Mr	X		X	
	Icl	X	X	X	X

Indices

Thermal comfort indices: COMFA model, (ETU), (ITS), MENEX model, (PT), (SET*), (OUT_SET*), (PET), (PMV), (UTCI).

Empirical indices: (ASV), (TS),(TSV), (MOCI).

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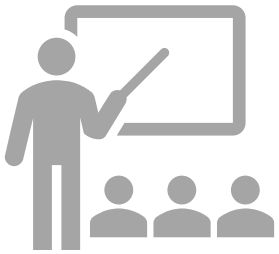
Indices

Thermal comfort indices: COMFA, model, (ETU), (ITS), MENEX model, (PT), (SET*), (OUT_SET*), (PET), (PMV), (UTCI).

Empirical indices: (ASV), (TS),(TSV), (MOCI).

Indices based on linear equations: (AT), (DI) , (ESI) ,(PSI), (ET),(H), (HI), (PE), (RSI),(WBGT), (WCI)

Thermal Sensation Votes (-)	PMV (-)	SET (°C)	UTCI (°C)	PET (°C)	MOCI(-)
Very Cold (-3)	<-2.5		<27	<4	<-2.5
Cold (-2)	(-2.5) - (-1.5)		(-27) - (-13)	4 - 8	(-2.5) - (-1.5)
Cool (-1)	(-1.5) - (-0.5)	< 17	(-13) - 0	8 - 13	(-1.5) - (-0.5)
Slightly Cool	-0.5		0 - 9	13 - 18	-0.5
Comfortable (0)	0	17 - 30	9 - 26	18 - 23	0
Slightly Warm	+0.5			23 - 29	+0.5
Warm (+1)	(+0.5) - (+1.5)	30 - 34	26 - 32	29 - 35	(+0.5) - (+1.5)
Hot (+2)	(+1.5) - (+2.5)	34 - 37	32 - 38	35 - 41	(+1.5) - (+2.5)
Very Hot (+3)	> +2.5	>37	>38	>41	> +2.5



Qualitative Methods:

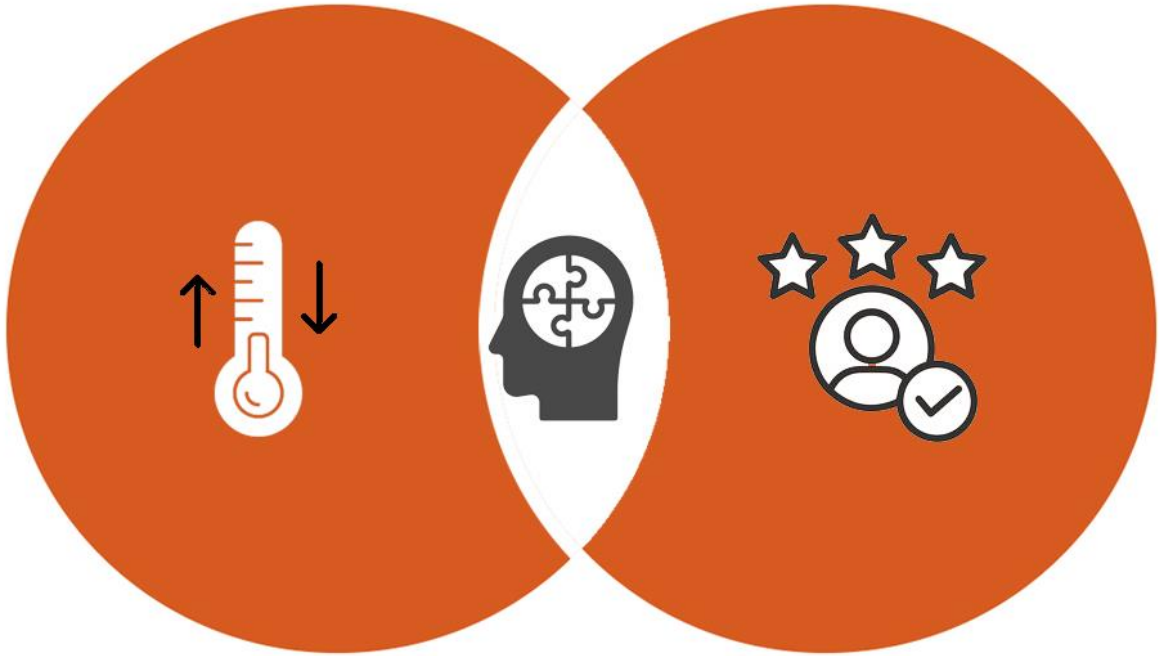
- Open-ended Questionnaires
- Interviews
- Focus Groups
- Workshops
- Mapping and visualization

Quantitative Methods:

- Temperature and Meteorological Measurements
- Thermal Indices
- Comfort Surveys
- Statistical Analysis
- Numerical Simulations

Mixed Methods

Aesthetics influence



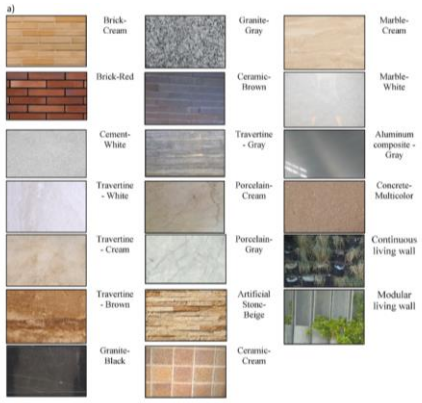
Thermal Perception

Perceived Aesthetic Quality

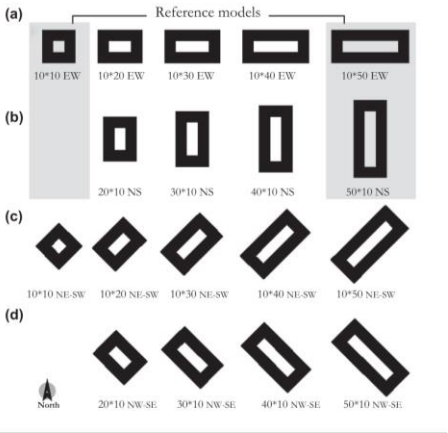
Psychological Adaptation:

- Naturalness
- Expectations
- Experience duration
- Perceived control
- Environmental stimulation

Façade influence on OTC



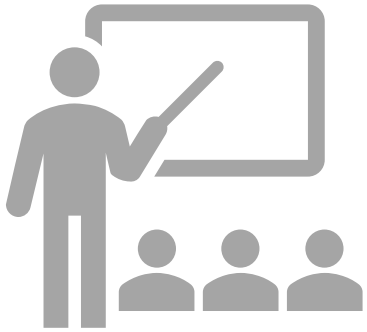
Quantitative Methods



- Surface Properties
  - Emissivity
  - Color
  - Albedo
  - Roughness
  - Vertical Greenery
  - Specific heat capacity
  - ...
- Geometry
  - Orientation
  - Window to wall ratio
  - Location
  - Shading devices
  - Type of glazing
  - ...

Facade → OTC

Problem Statement



Lack of effective **tools** and **methodologies** for evaluating **subjective** experiences related to **façade** influence on **Outdoor Thermal Comfort**.

Research Question

How can a multi-domain mixed-method approach be implemented to assess the influence of facades on outdoor thermal comfort?

Research Question

- **How can a multi-domain mixed-method approach be implemented to assess the influence of facades on outdoor thermal comfort?**

Sub-questions:

- 1. What is outdoor thermal comfort and how is it affected by the built environment?
- 2. What are the tools, workflows, and current methods to measure OTC?
- 3. How can empirical and computational methods be combined to assess Outdoor Thermal Comfort (OTC)?
- 4. How does facade influence urban inhabitants' thermal perception?
- 5. To what extent can the perceptual aesthetics of facades influence pedestrians' perception of the thermal environment?
- Design Question: What facade design solutions can be used to effectively mitigate the overheating and improve outdoor thermal comfort for pedestrians in Acquabella district?

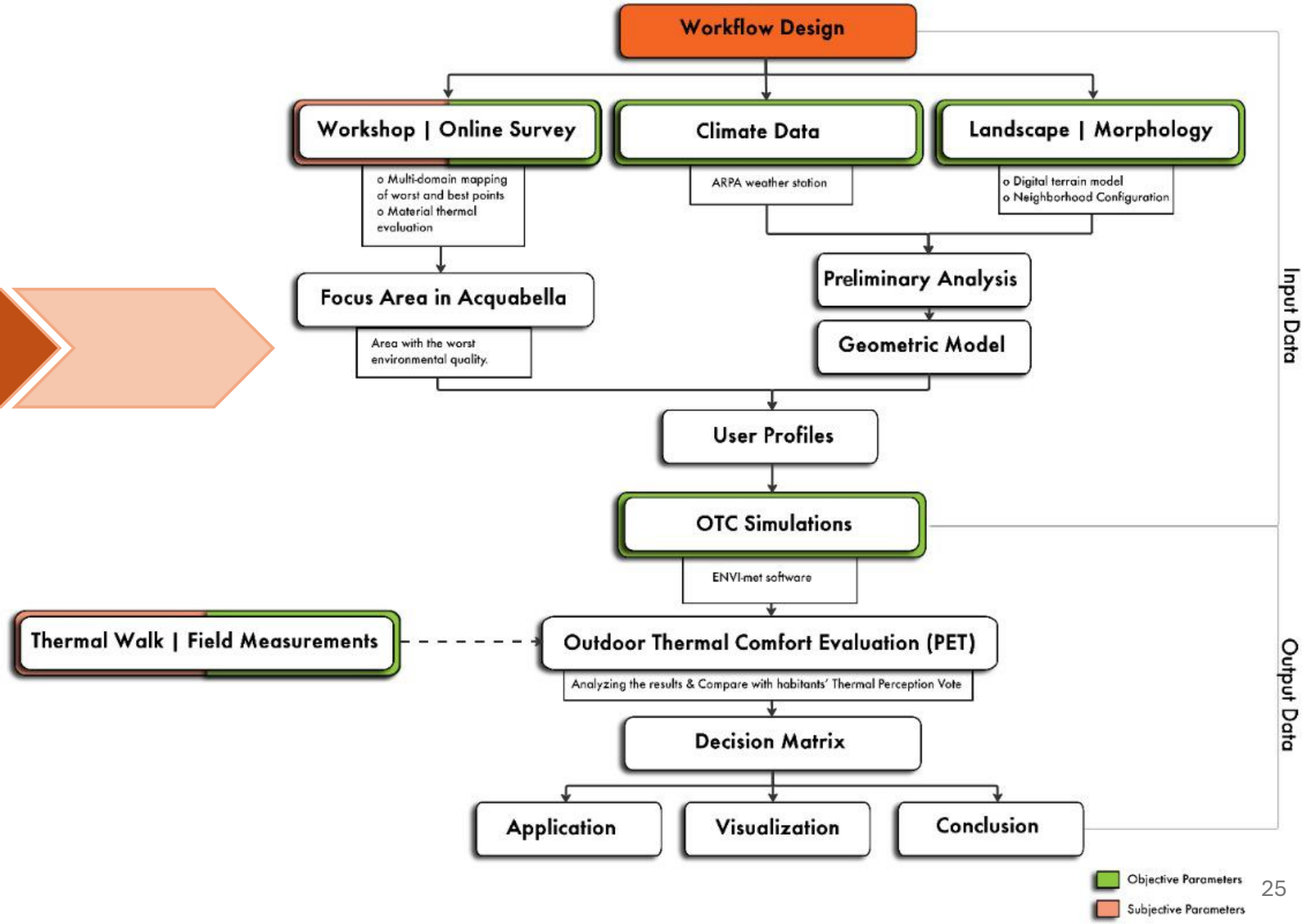
Literature

Methodology

Results

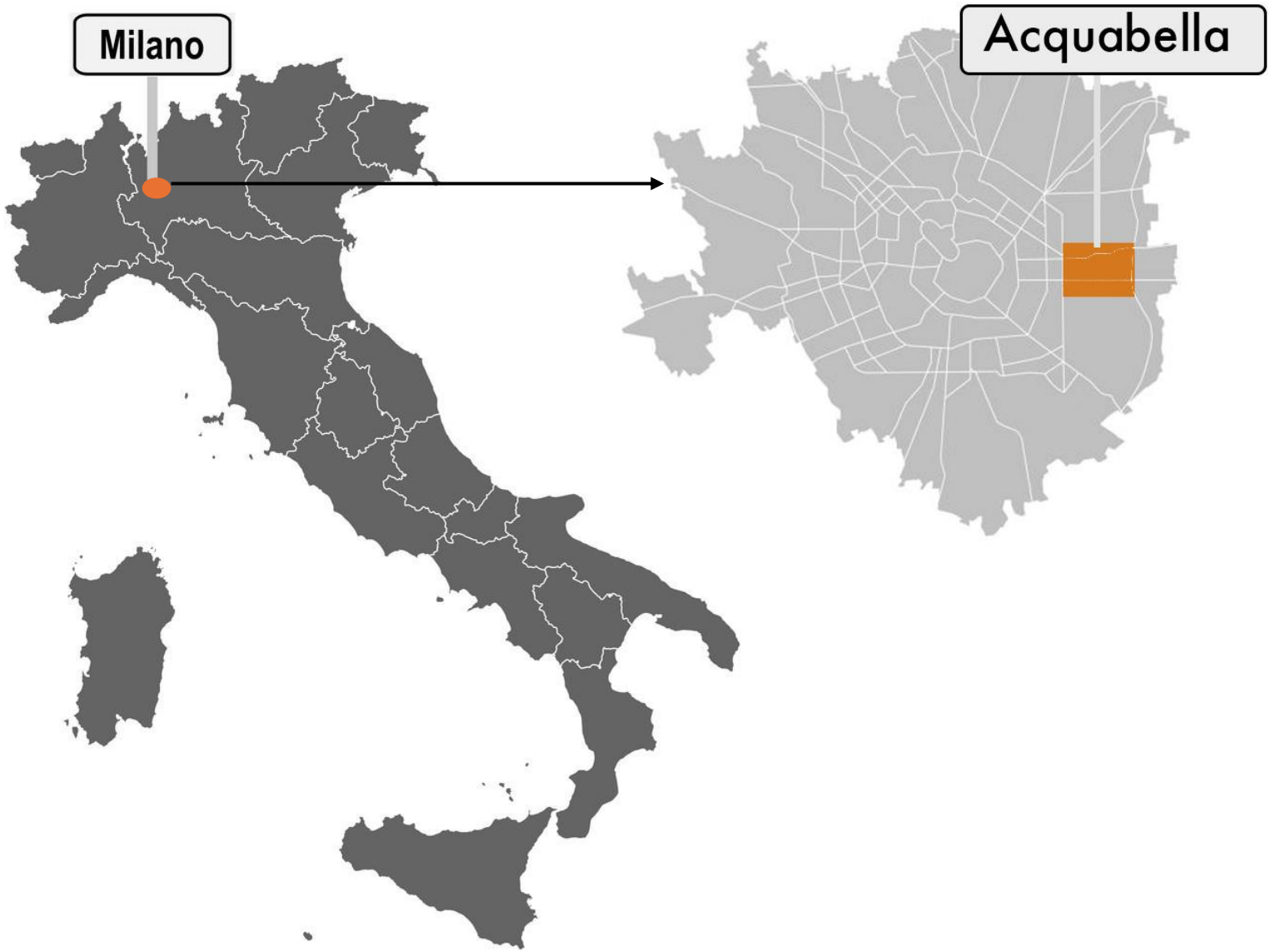
Research Methodology

Workflow Design

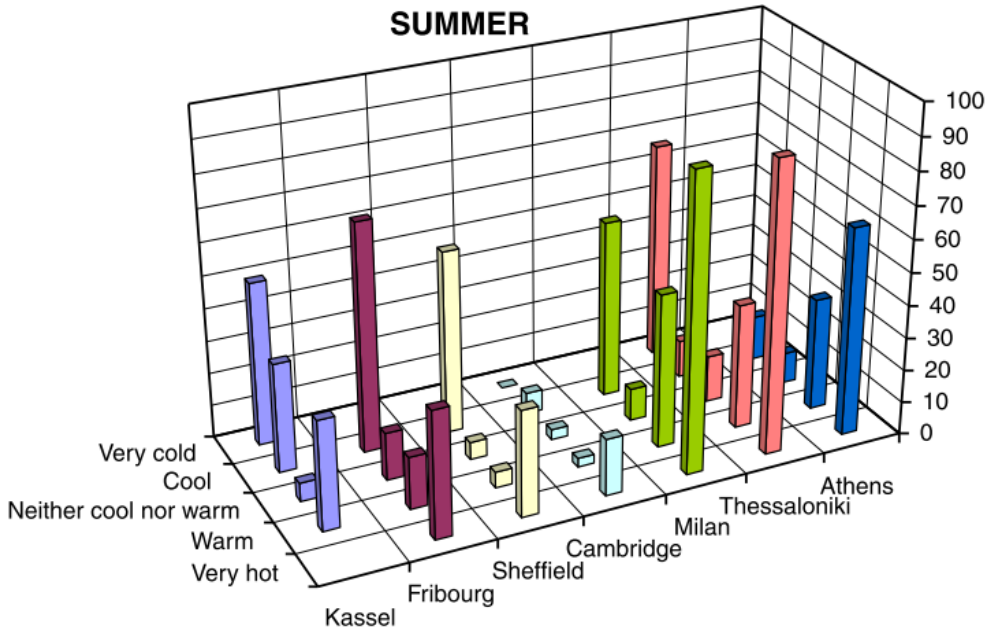



Research Framework
Case Study
OTC Workflow
Results
Discussion

Case study: Milan



Case study: Milan thermal comfort

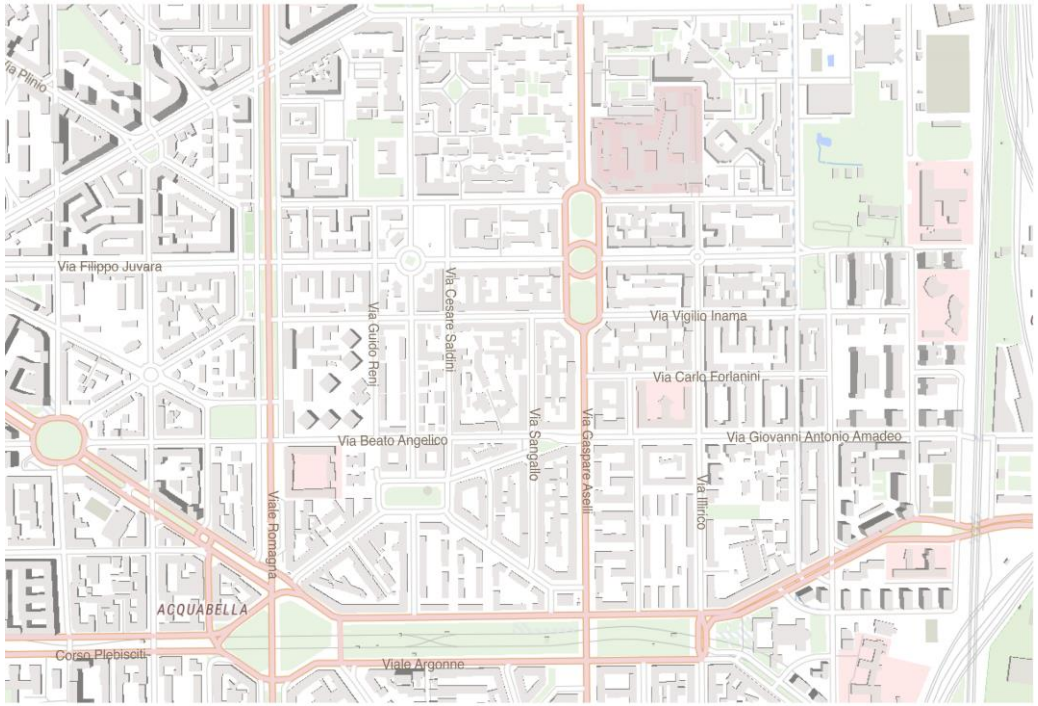


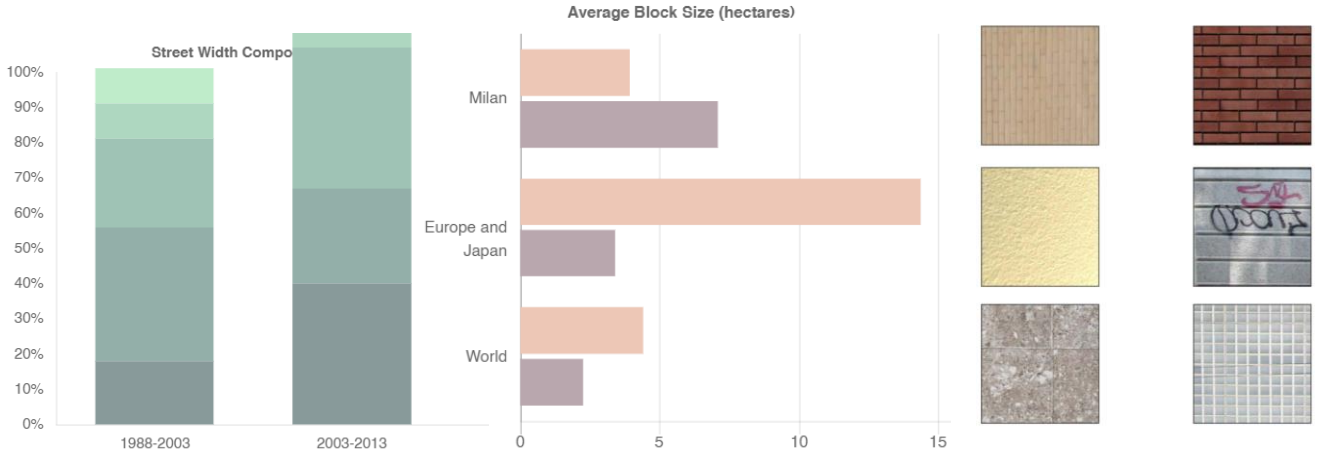
Compact midrise **LCZ 2**

Dense mix of 3-9 storey buildings and few or no trees. Land cover mostly paved. Stone, brick, tile and concrete construction materials.

- Current green canopy of Milan is just 7 % of the urban area. That's well below northern European cities like Germany's Frankfurt at 21.5 % or Amsterdam at nearly 21 %.
- Climate: mid-latitude, four-season humid subtropical climate (Cfa)

Case study: Acquabella district






Research Framework
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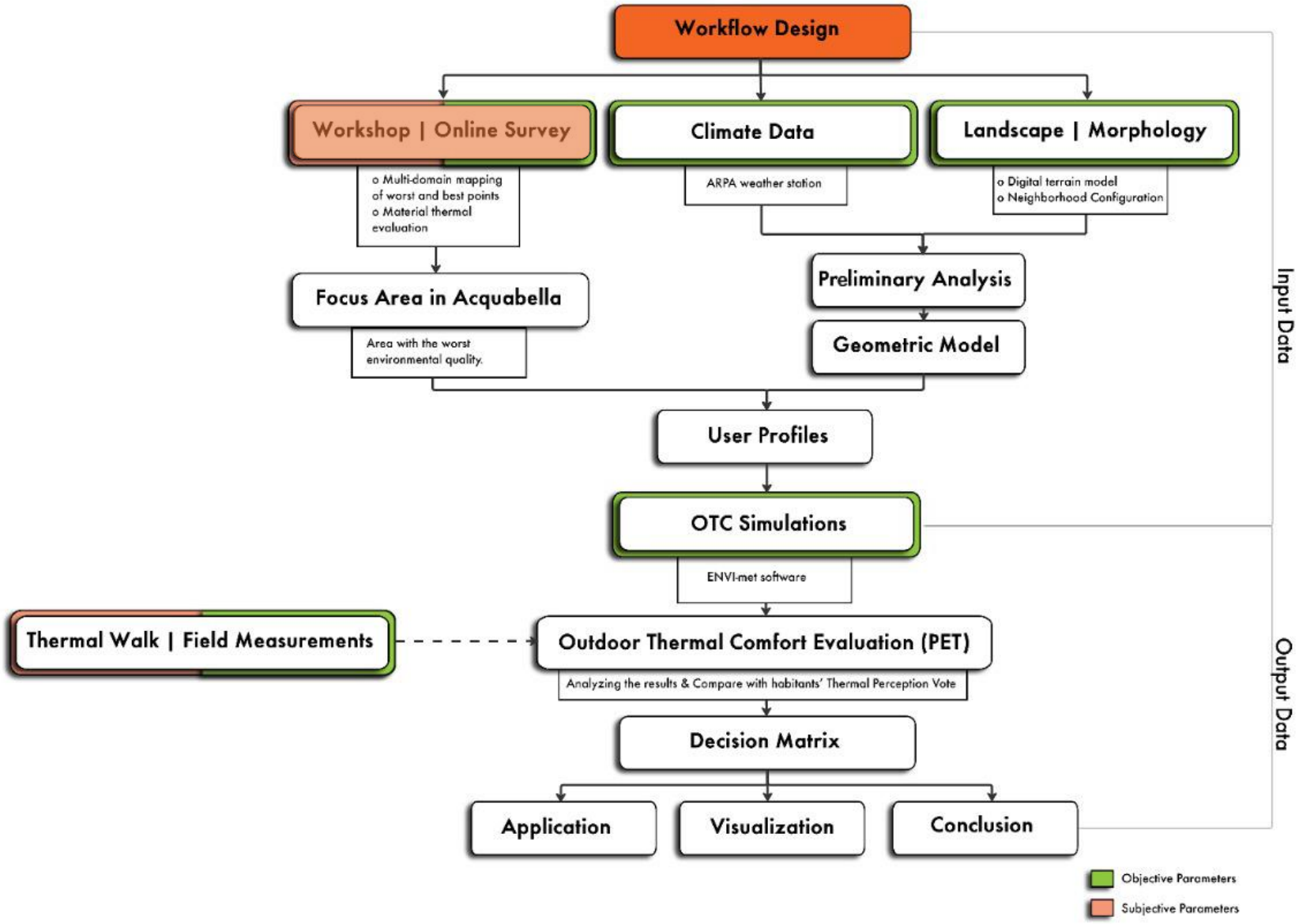
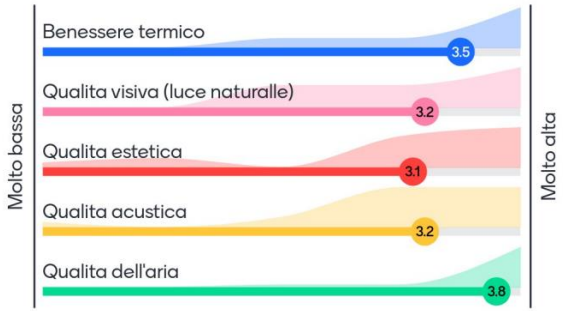
Discussion

OTC Workflow

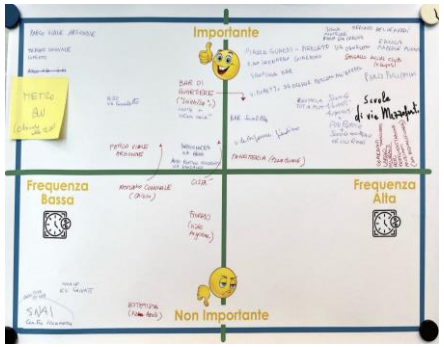


Workshop

Environmental Quality



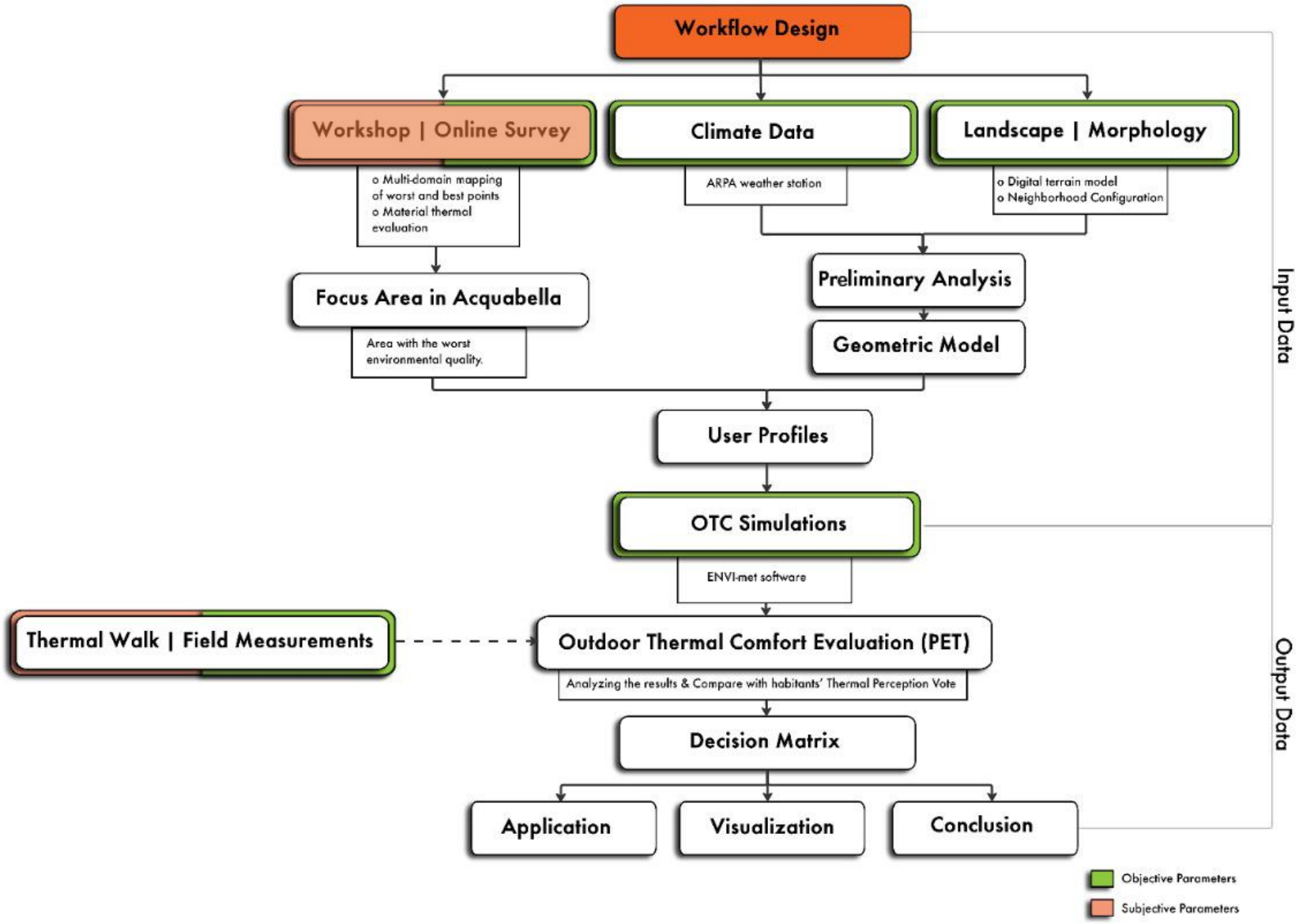
Importance & Frequency



Multi-domain Maps

Perception of Materials

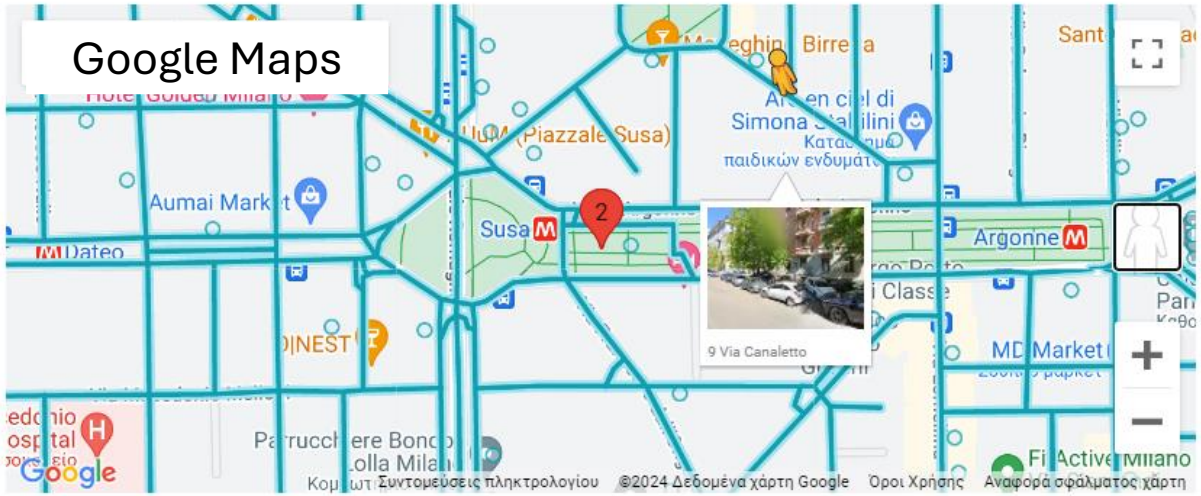
OTC Workflow



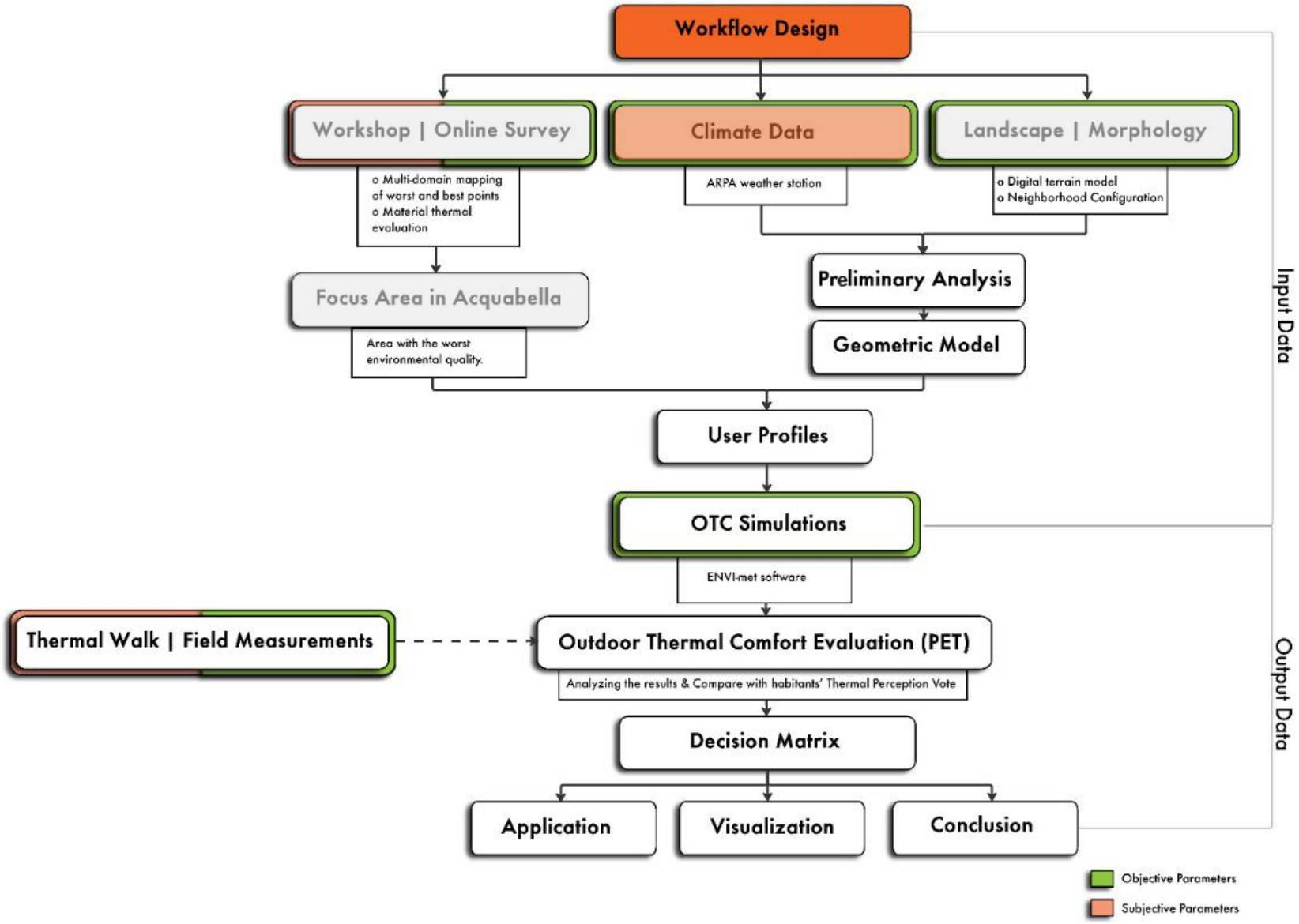
Long-term Survey

- Demographics
- Comfort
- Frequency/ Duration
- Behavior

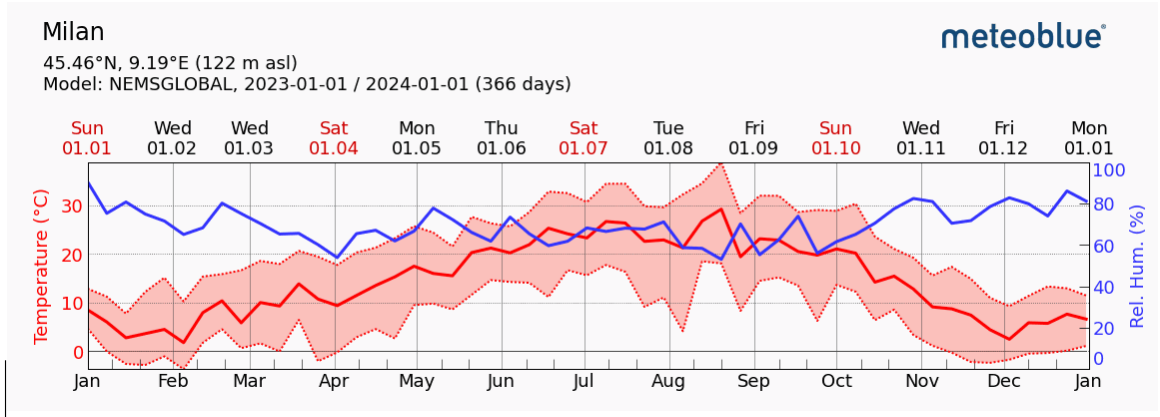
In the map below, mark 1 to 2 public places where you feel UNCOMFORTABLE during hot summer days in Acquabella in terms of temperature. (Move the pin close to the location - PASS question if there are not any)

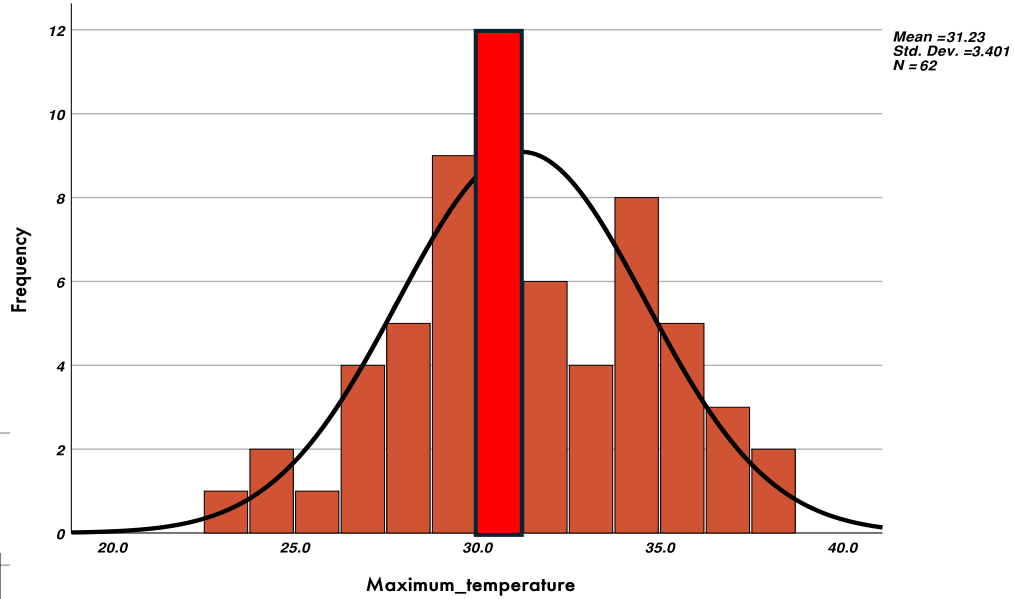


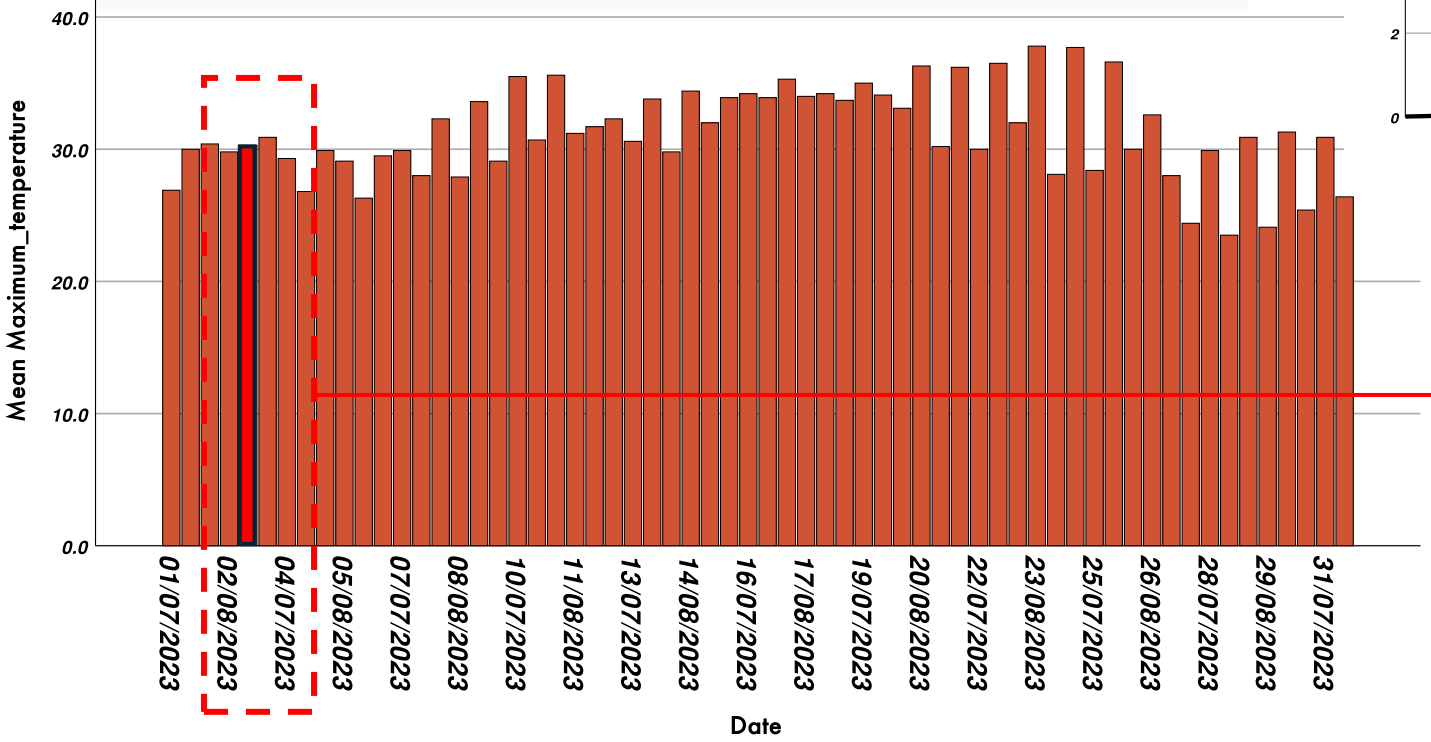
OTC Workflow



Climatic data / simulation day



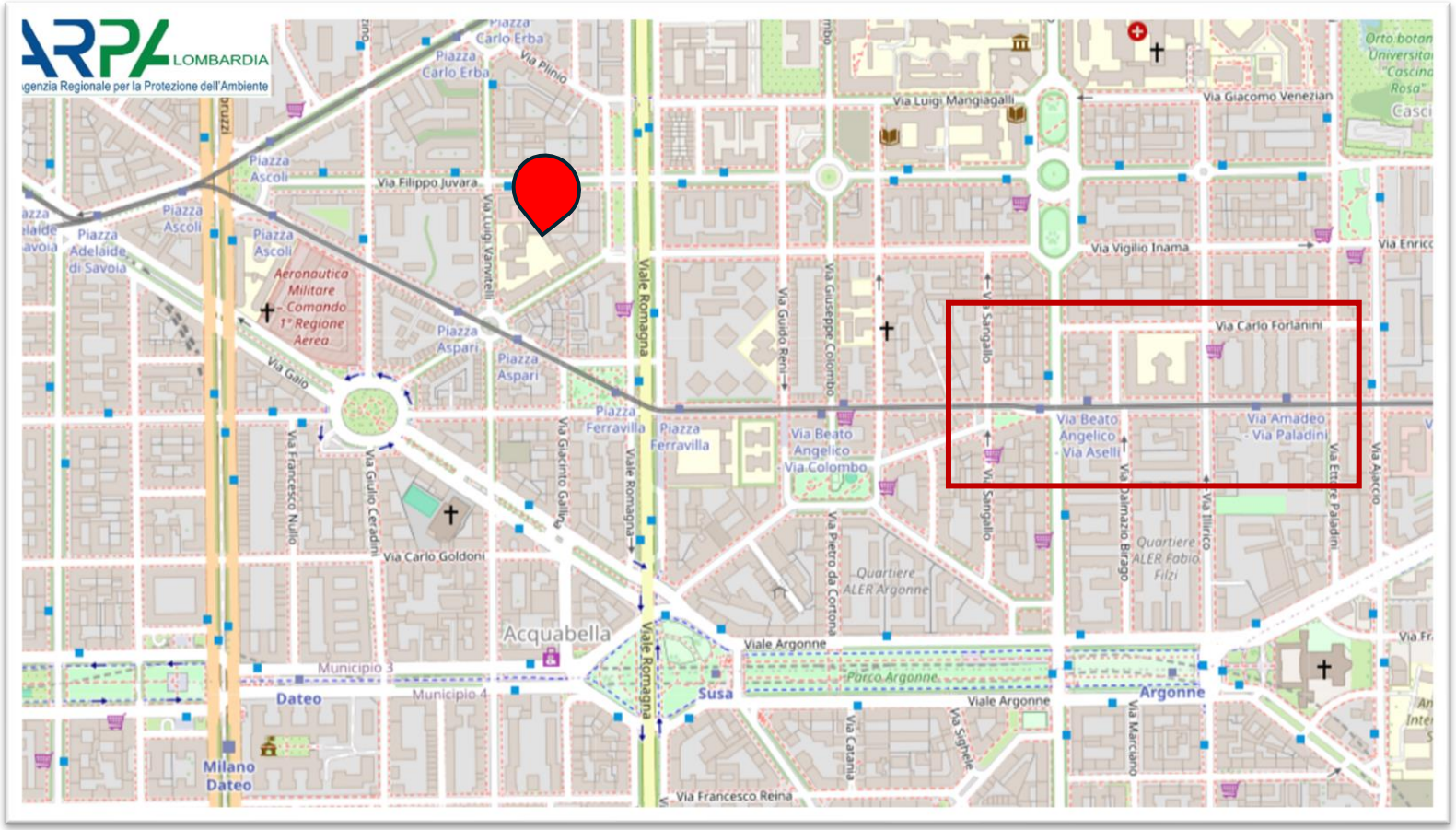




Simulation day:

- 03/08/2023
- Average hottest day of 2023
- Highest minimum Tair of the options

Weather data



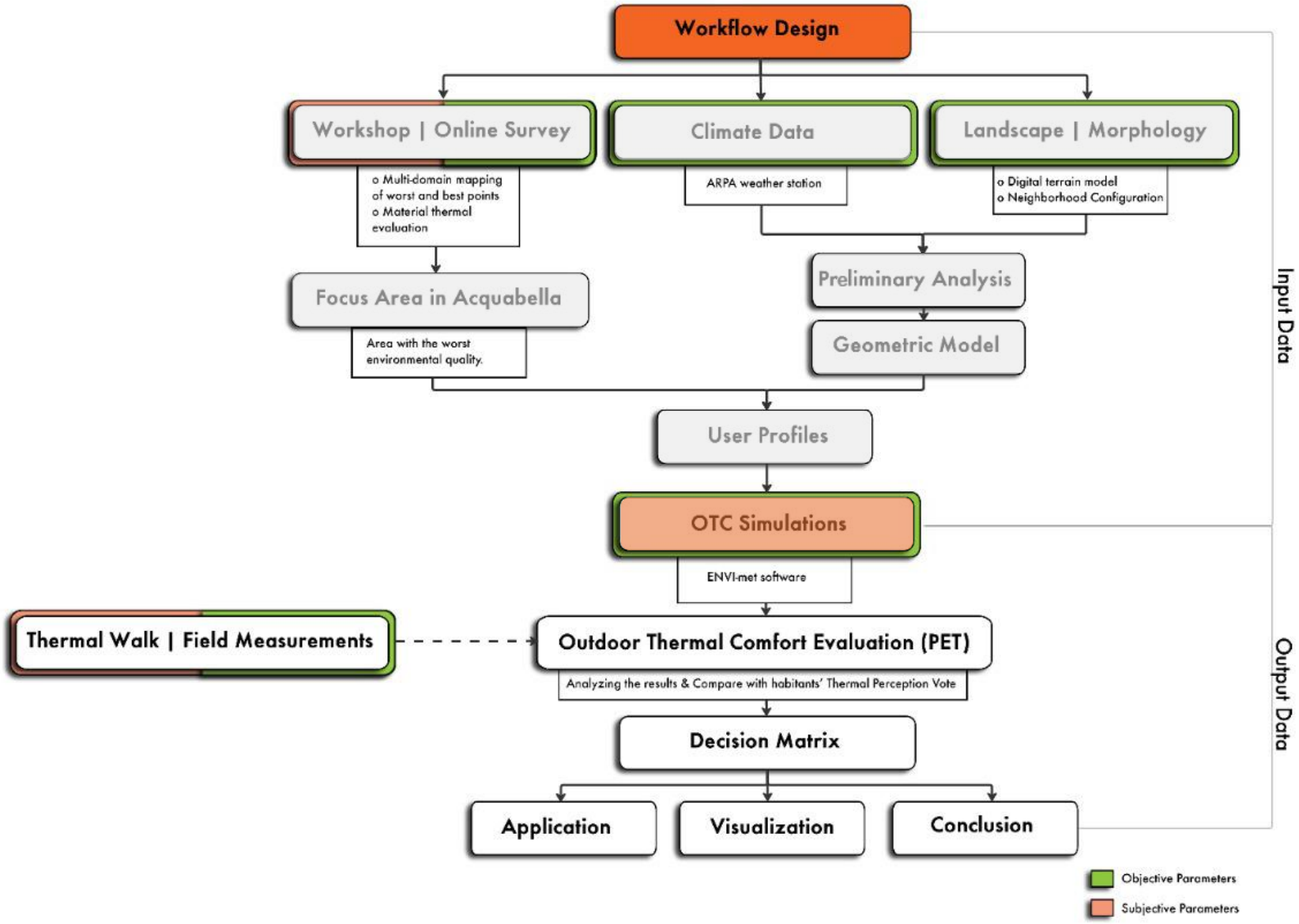
Arpa Lombardia (regional agency for environmental protection):

- 10 sensors in Città Studi area
- Hourly measurements for wind velocity and direction, global radiation, relative humidity, air temperature

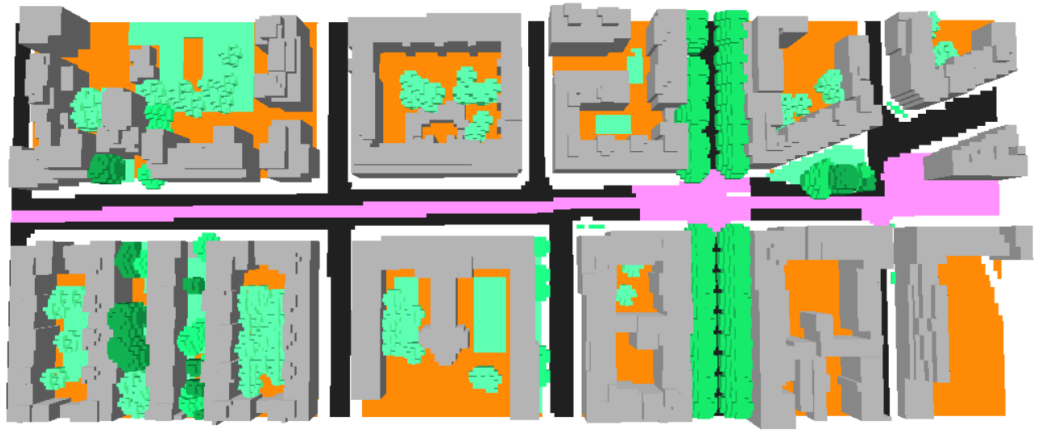
CAMS(Copernicus Atmosphere Monitoring Service) :

- Radiation data (every 10 minutes)

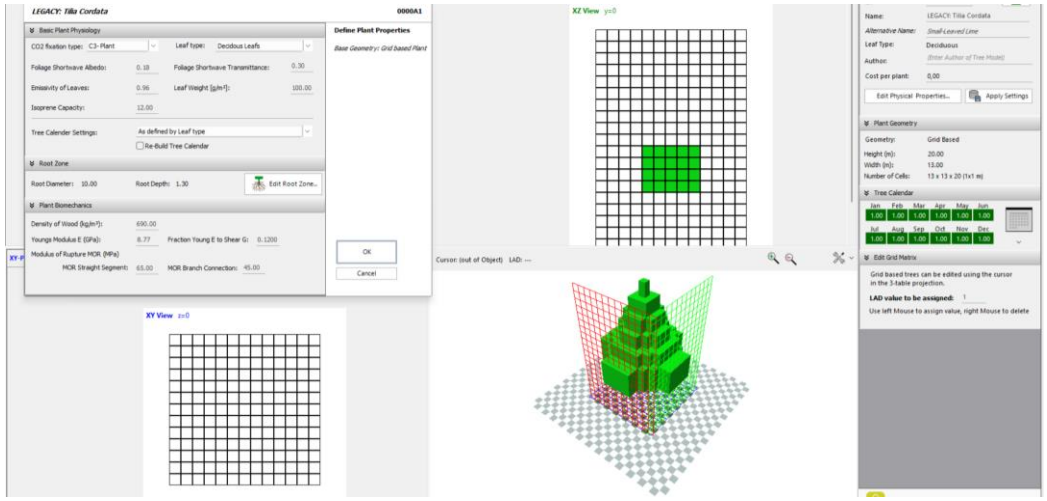
OTC Workflow

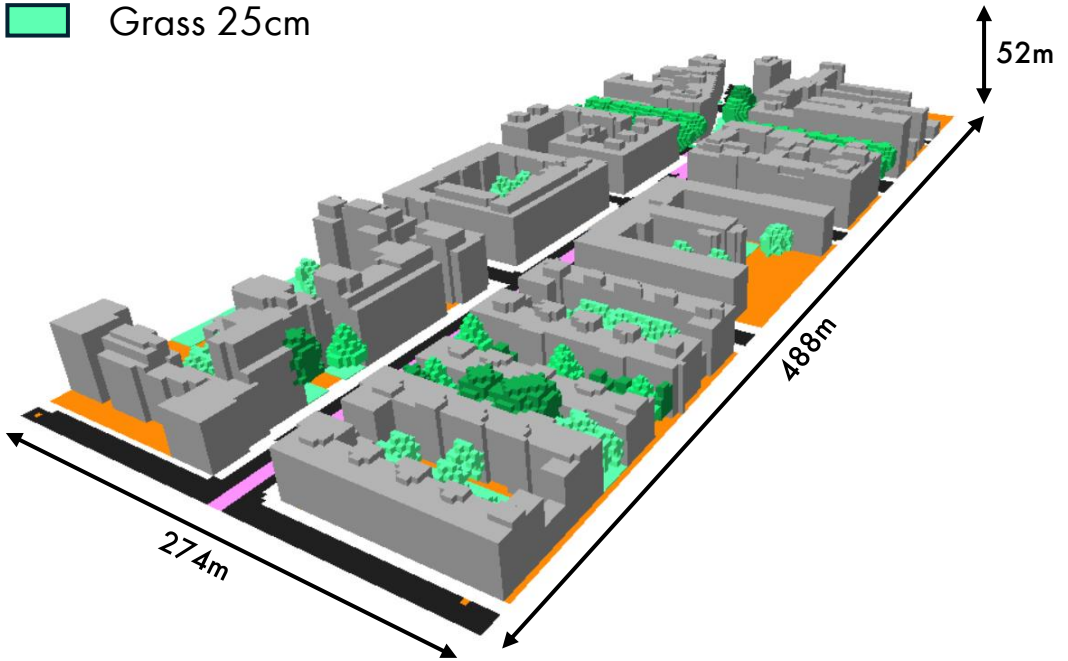


Modeling in Envi-met/ Fixed variables



- Asphalt for street
- Concrete pavement grey for pavements
- Cellar- default soil profile underneath a building
- Basalt brick road
- Grass 25cm

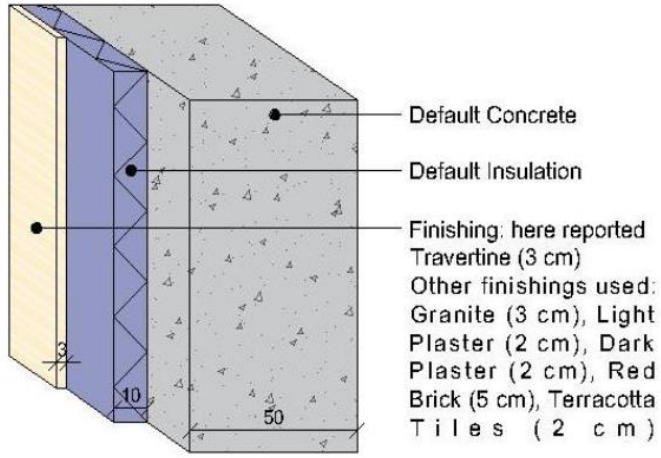




Wall Database setup

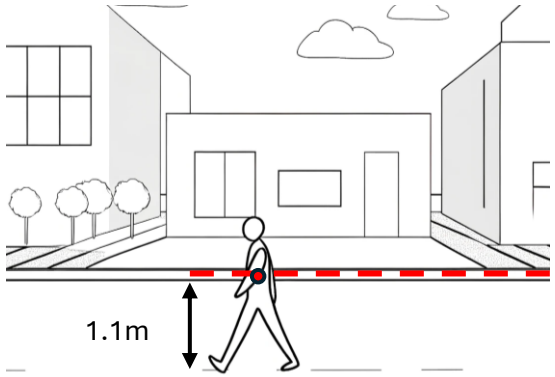
Database-ID: [0100C3]
Name: Concrete: hollow block
Color:

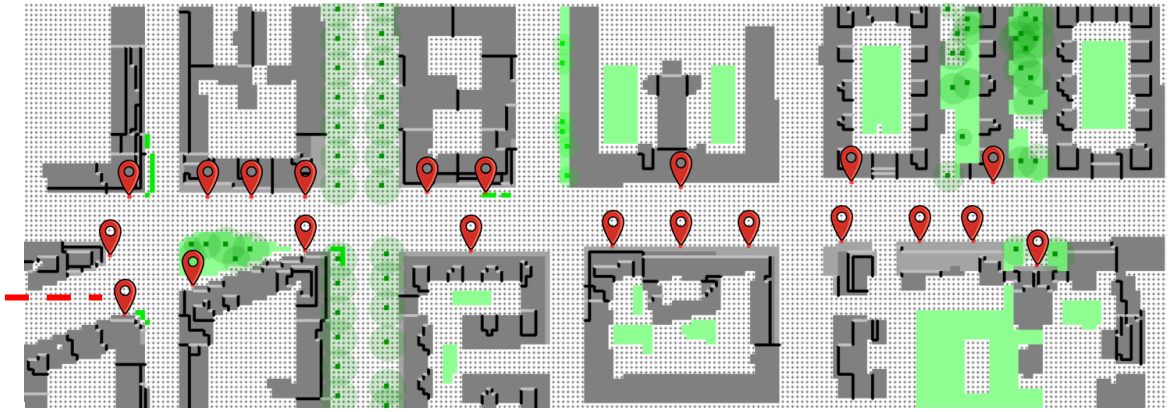
Parameter	Value
Default Thickness	0.30000
Absorption	0.70000
Transmission	0.00000
Reflection	0.30000
Emissivity	0.90000
Specific Heat	840.00000
Thermal Conductivity	0.86000
Density	930.00000
Extra ID	0

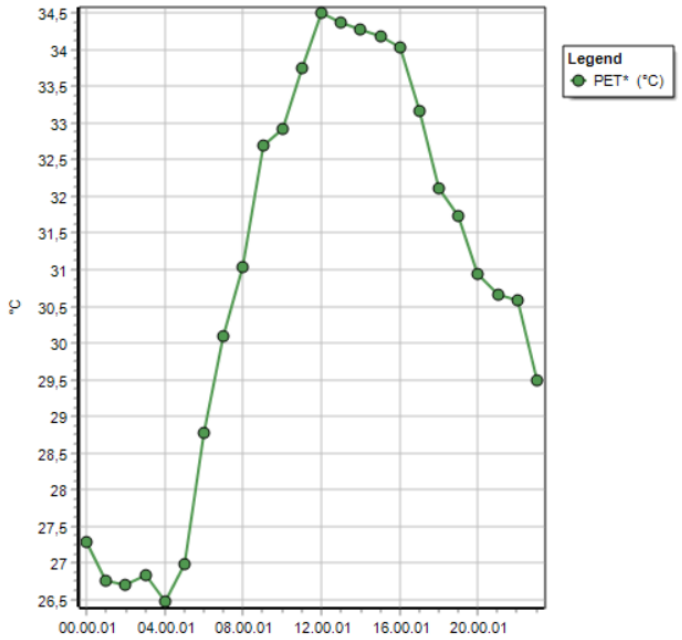


Material	Color	Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Specific Heat Capacity (J/(kg °C)	Albedo/ Reflectivity %	Density (kg/m3)	Absorption %	Emissivity
Stucco	Bright	0.8	850	66	2275	65	0.94
Limestone	Bright	1.5	900	25	2550	35	0.96
Brick	Red	2.0	750	30	1900	68	0.92
Plaster	Dark	1.0	1000	30	1070	45	0.86

Modeling in Envi-met



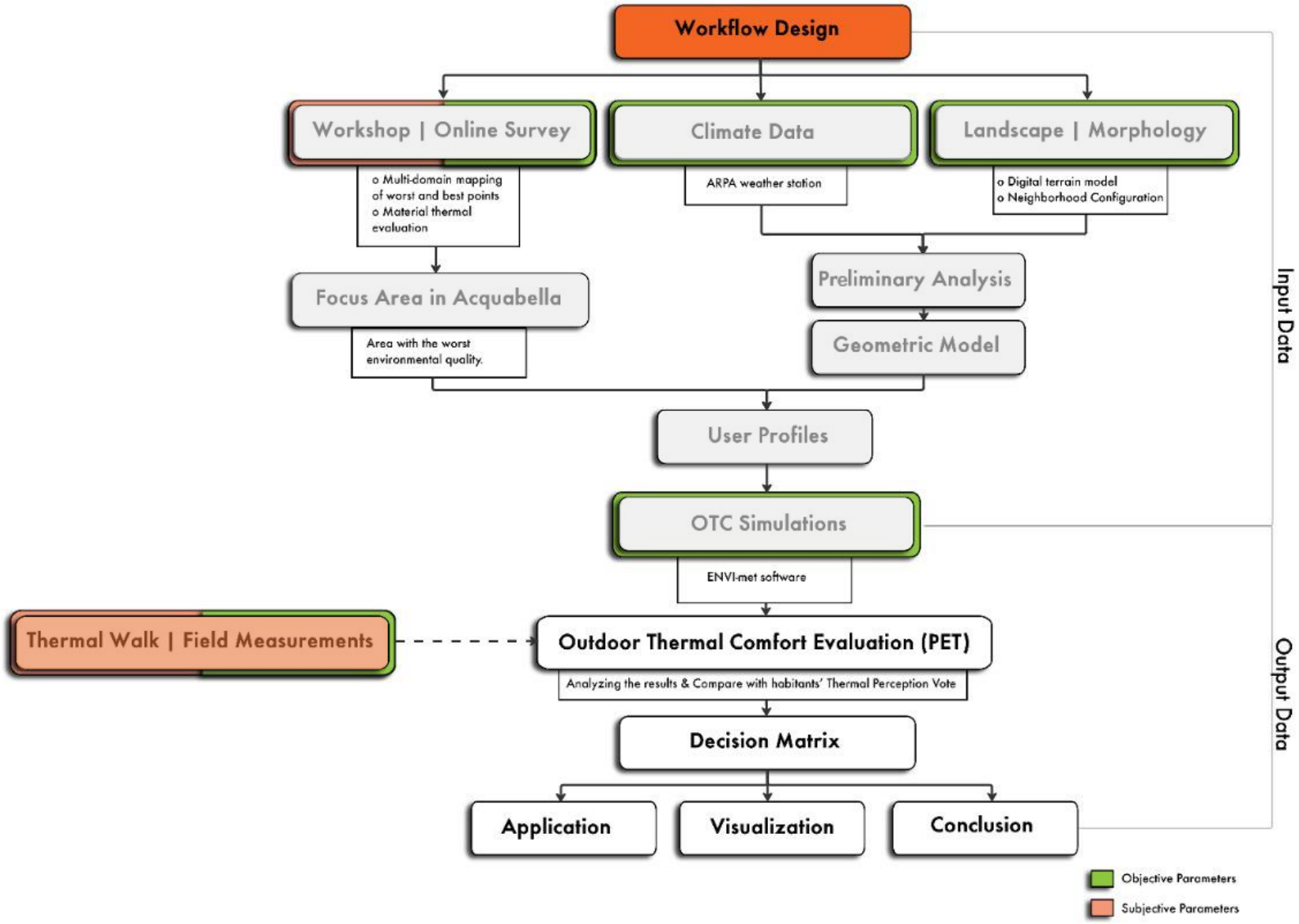




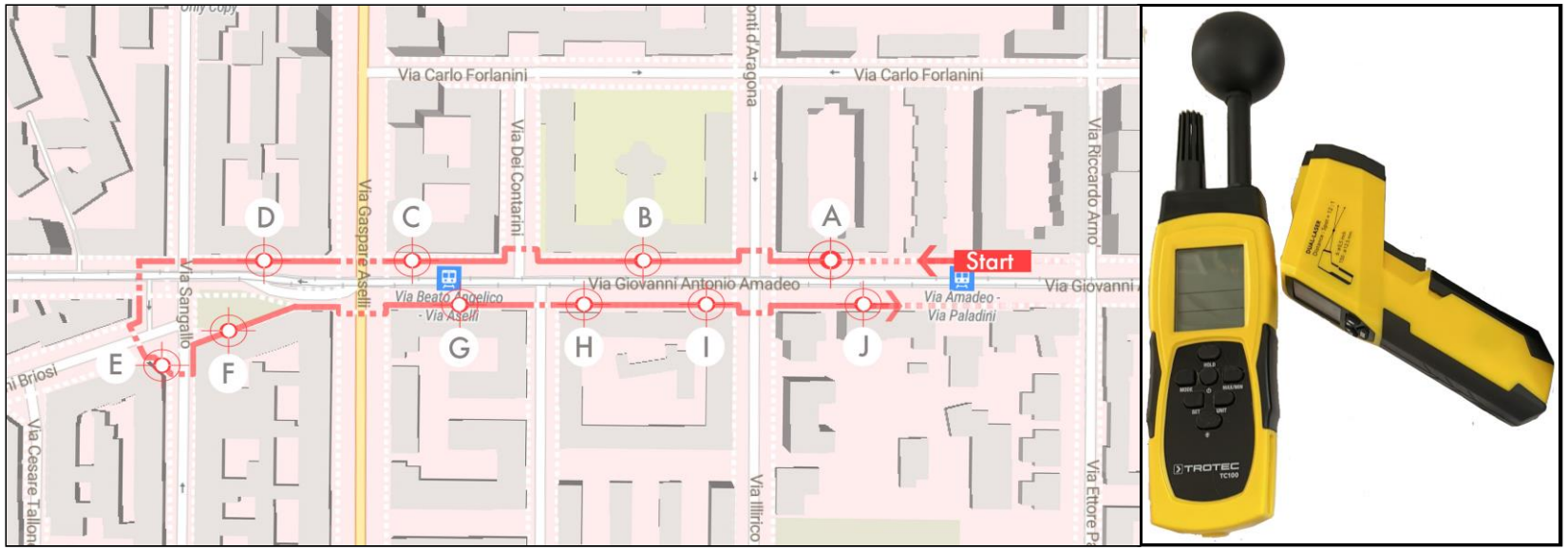
Receptors:

- Placed in 21 buildings' facades
- Measuring in average height of a standing person's center of gravity (1.1m)
- Measuring atmospheric, surface/flux, and soil data
- Data every 10 minutes of the simulation

OTC Workflow



Thermal walk - Steps



- **Participatory thermal walk:**
  - Members of the local community (Cista)
  - Portable sensors during the walk (field measurements)
  - 22 June
  - 10 stops

- **On-site survey distribution for PET assessment that will record:**
  - Personal characteristics of participants
  - Thermal perception of the facades
  - Participant's thermal comfort level
  - Participant's aesthetic perception


Research Framework
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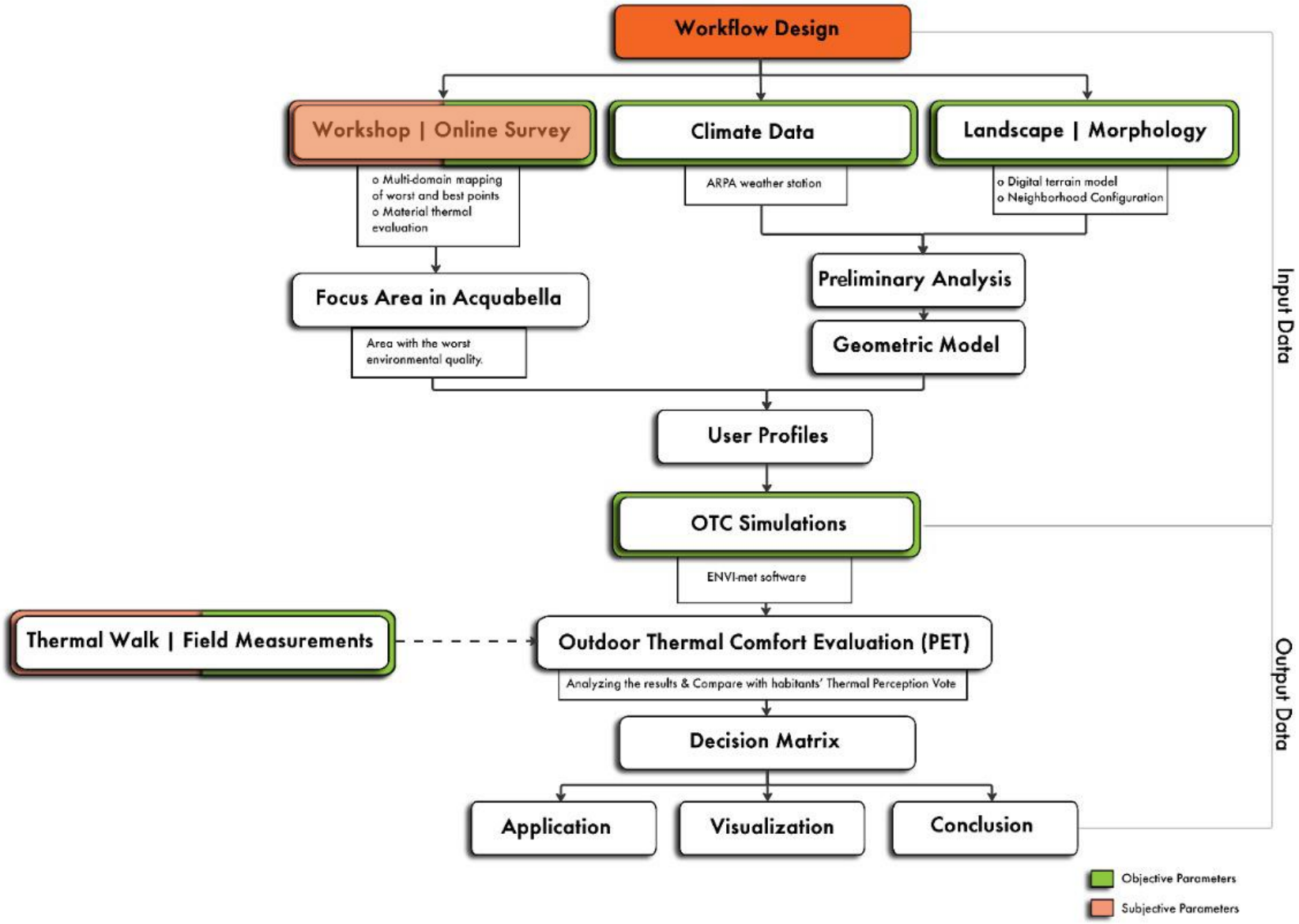
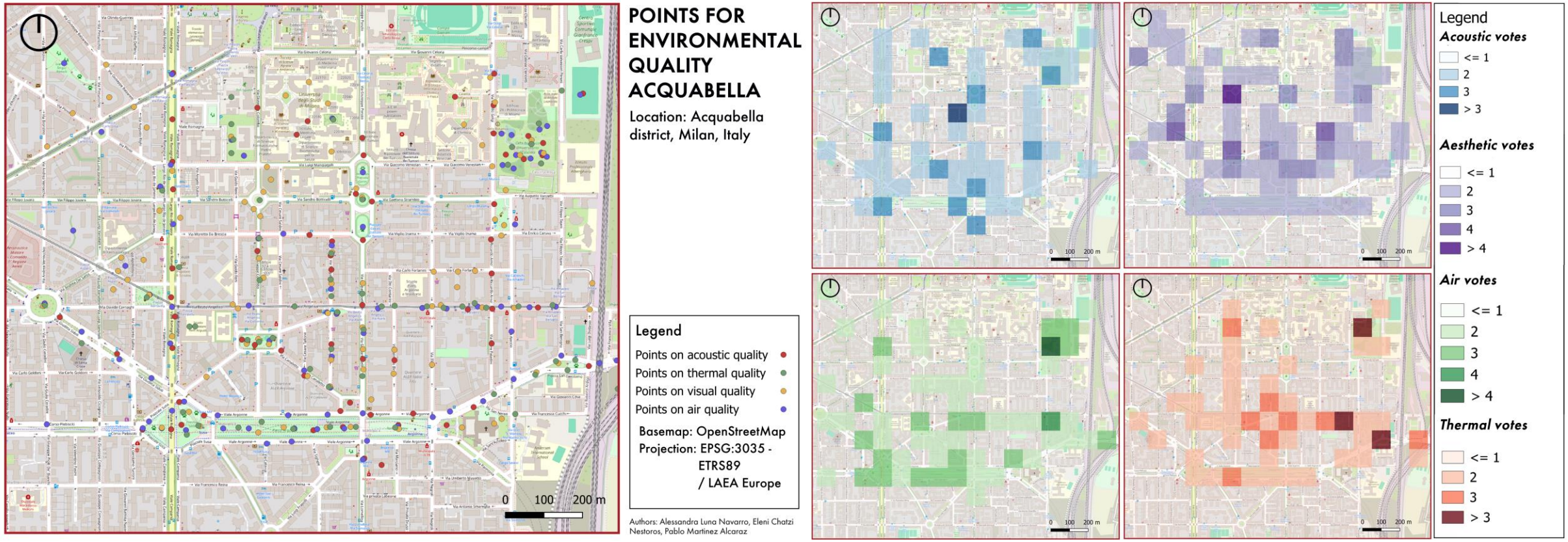
OTC Workflow



Workshop | Multi-domain analysis

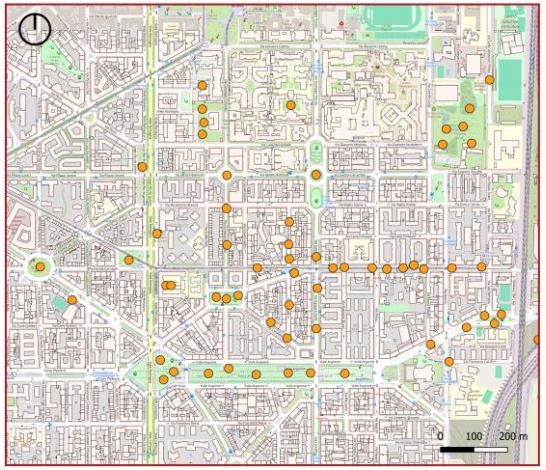
Votes in QGIS:



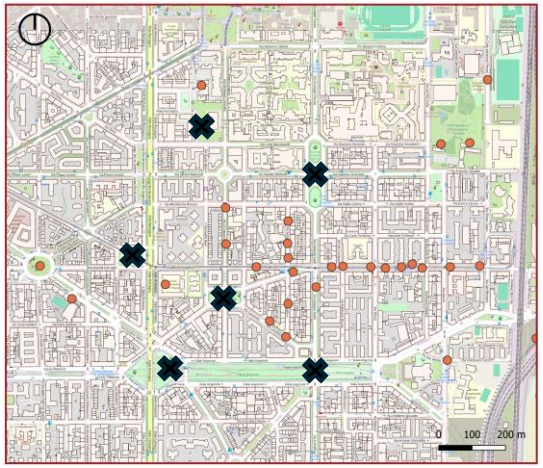
Workshop | Multi-domain analysis

Filtering by:

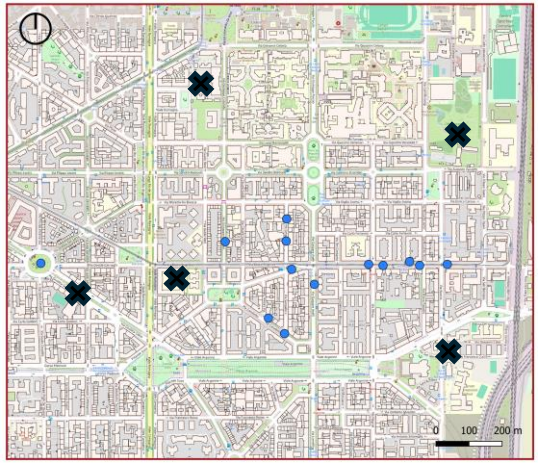
Thermal Votes



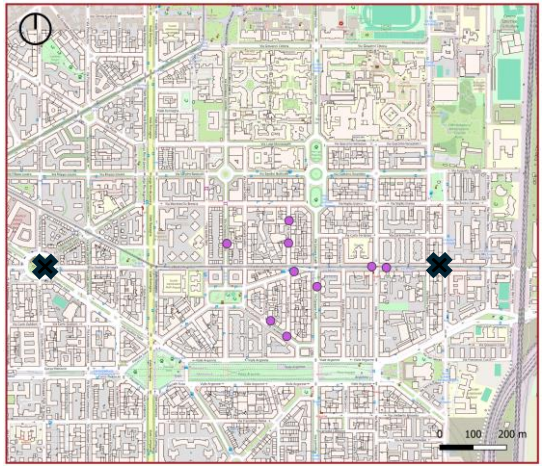
Building



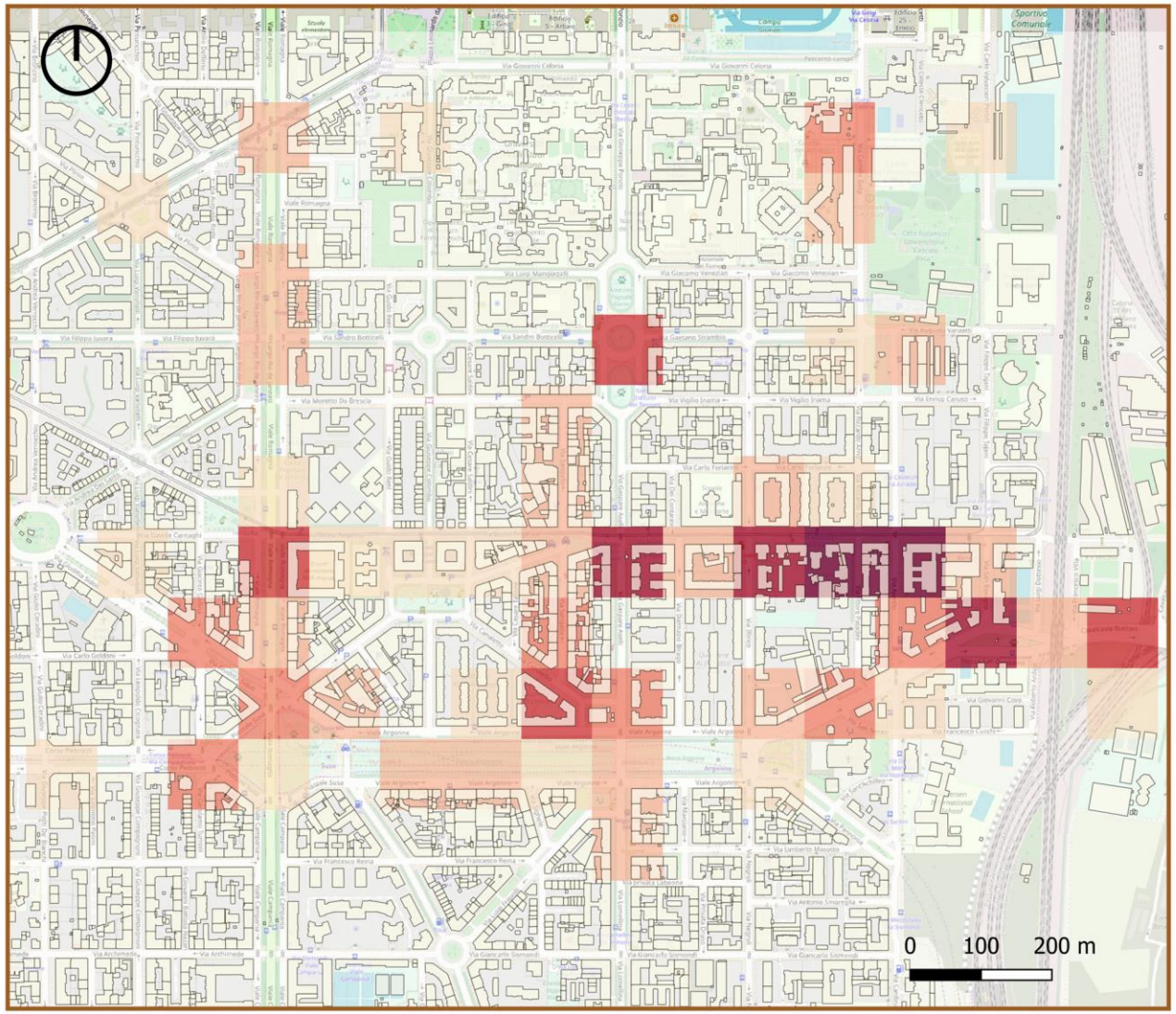
Aesthetic perception

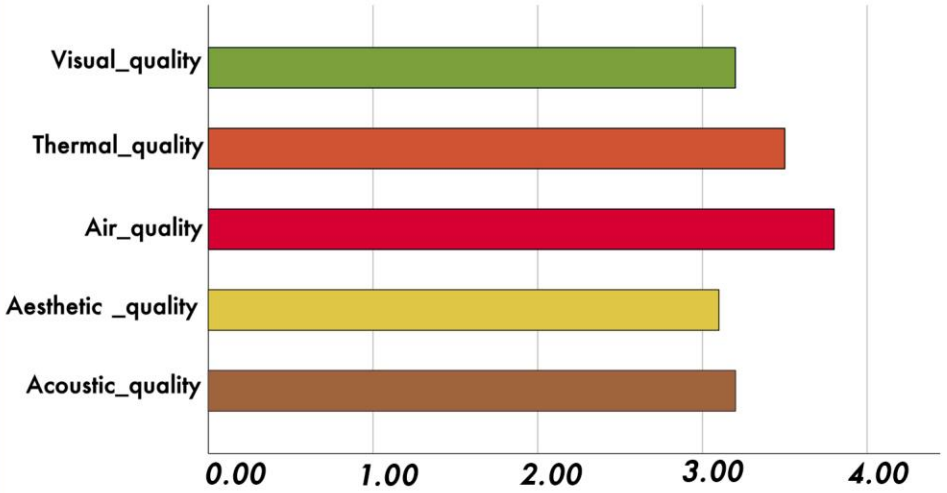


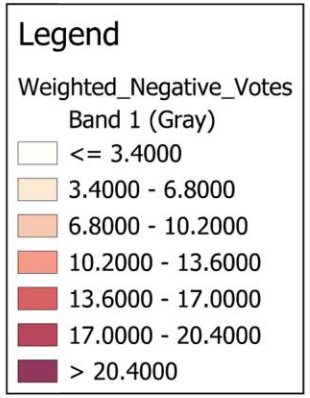
Frequency & importance



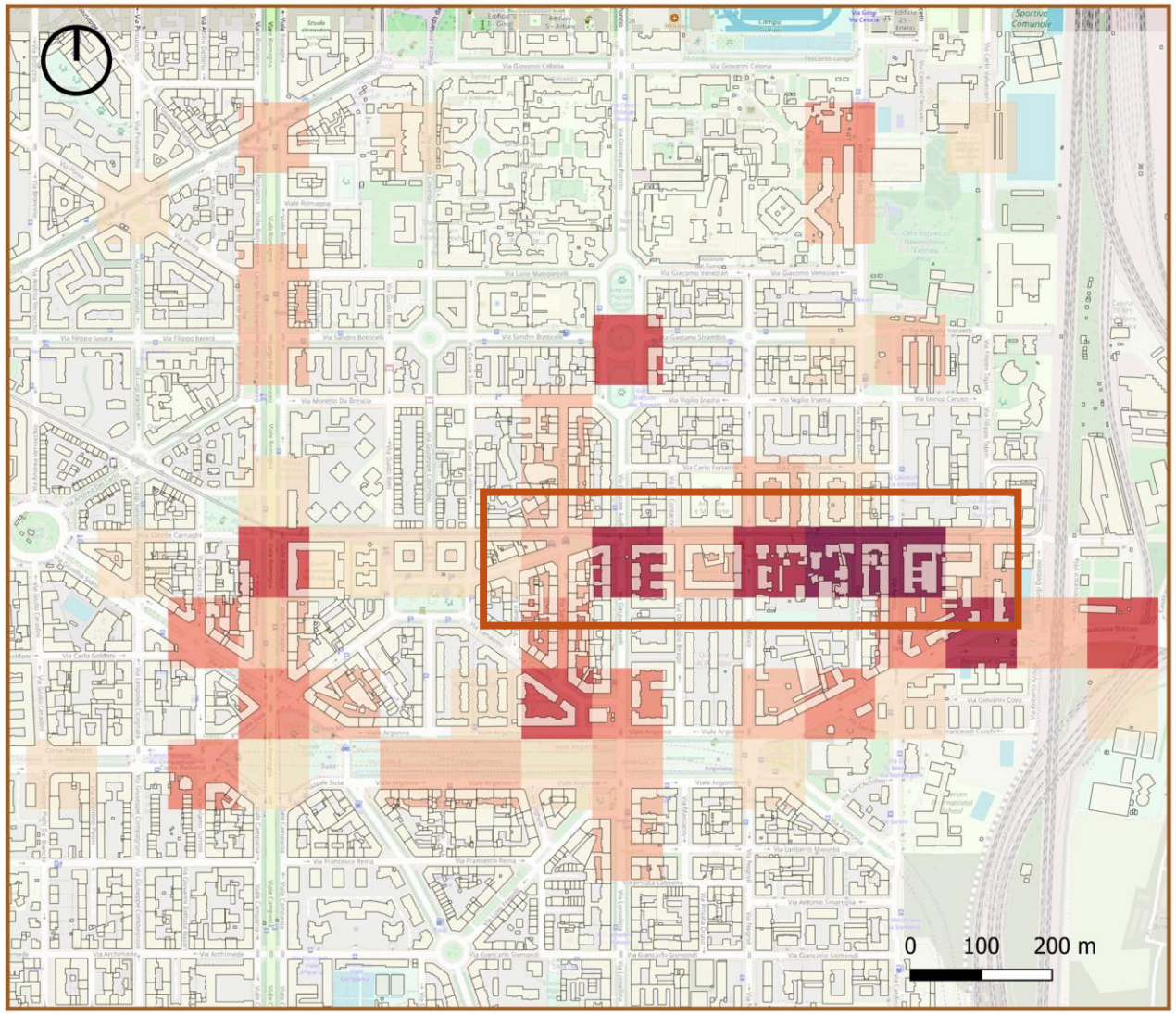
Workshop | Multi-domain analysis







Focus area



Via Beato Angelico:

- Bad environmental quality votes
- Concentrated thermal votes
- Wide street , uniform (AR) & orientation
- Few to none vegetation
- Variety in building Materials & heights
- Street high in traffic / pedestrians

Focus area

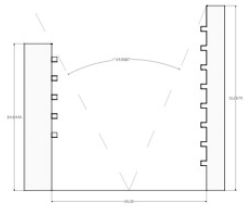
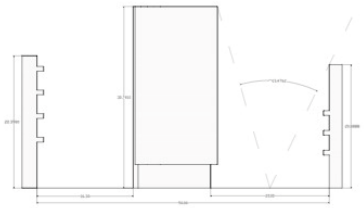
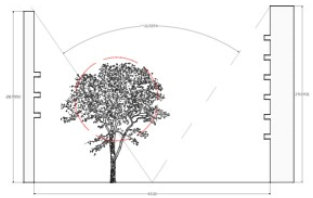
Independent variables

1. Building Height
2. Surface properties , age of building & roughness
3. ~~Shading devices from façade (explain later why balconies don't affect pedestrians)~~
4. ~~Width of the street (Aspect ratio)~~
5. ~~SVF (sky view factor)~~
6. ~~Neighborhood geometrical configuration~~
7. ~~Pavement material~~
8. ~~Orientation~~
9. ~~Shading devices external~~
10. ~~Traffic- heavy or not~~
11. ~~Ratio pavement over car pavement~~
12. Building type: residential, commercial (glass% in ground floor)
13. Aesthetic satisfaction
14. Perceived thermal sensation associated with the image

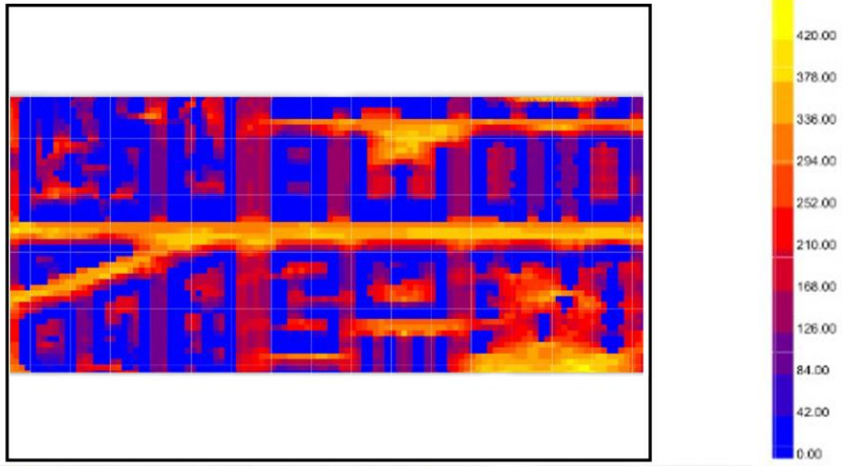
Dependent variables

1. Thermal perception: TSV
2. Thermal environment e.g. PET

Preliminary analysis :Neighborhood Configuration

Section of the street	Orientation	SVF %	Aspect ratio H/W
	E-W	33.30	Asymmetrical ~1.07
	E-W	30.30	Asymmetrical ~0.43
	E-W	45.60	Asymmetrical ~0.73

Study on balconies:

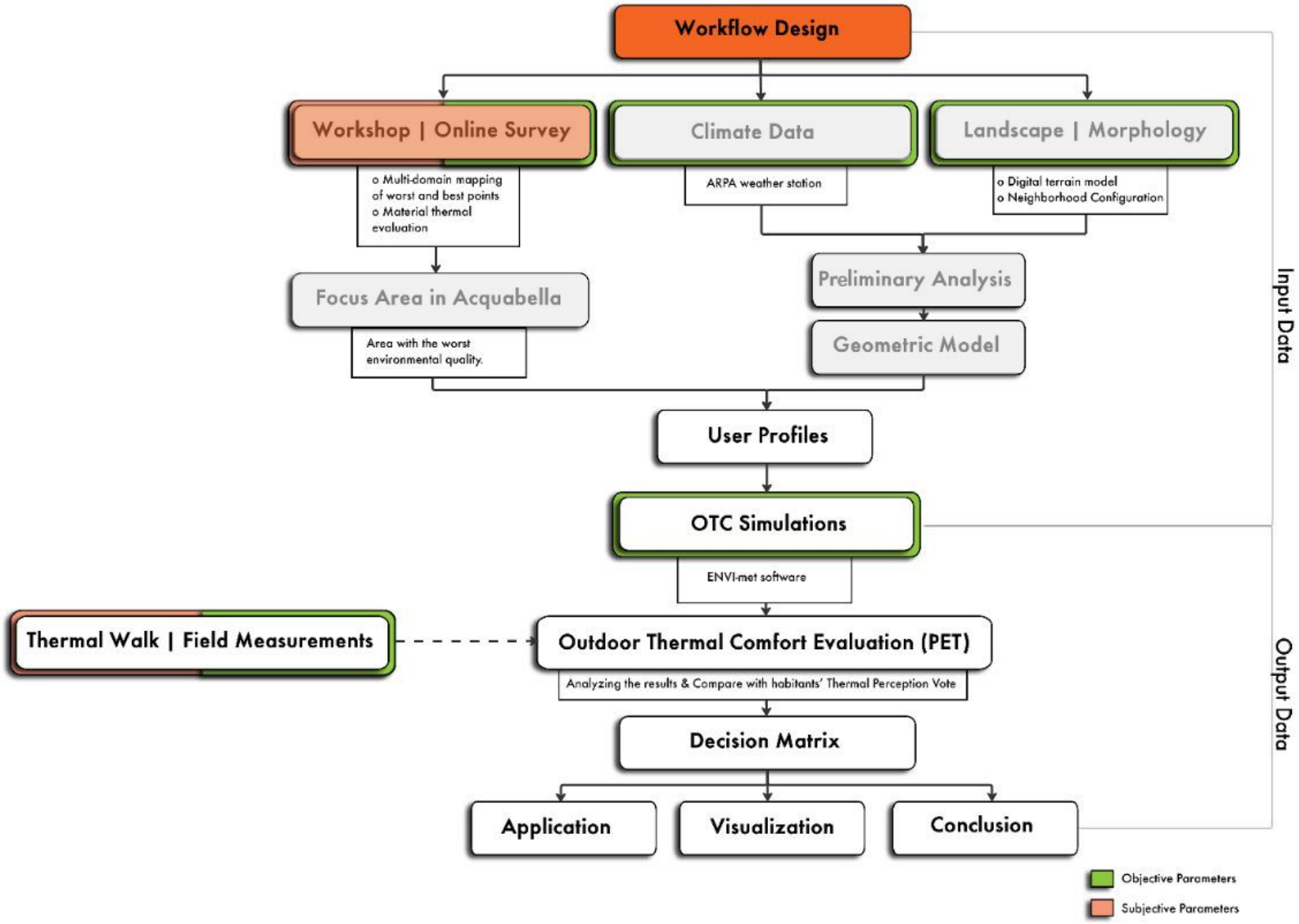


SVF:

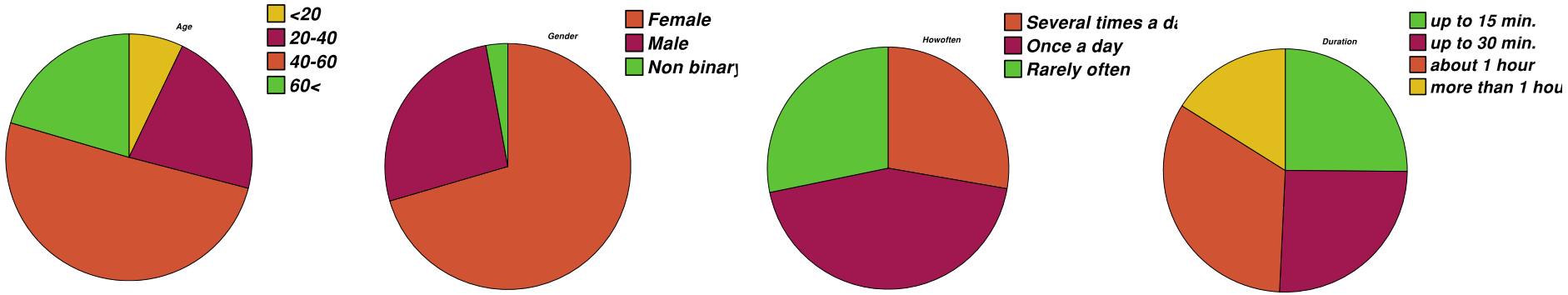
Preliminary analysis: Building Codes

Building ID	Height (m)	Class	Façade material	Construction type	Layers	U-Value (W/m^2K)	Building Type
A1	17.19	1921-1945	Stucco	Stone masonry striped with bricks		1.61	Non-Residential
F1	22.78	1876-1990	Brick	Hollow-case masonry with perforated bricks medium level of insulation		0.59	Residential
D2	31.40	1946-1960	Brick	Solid break masonry		1.48	Shop

OTC Workflow

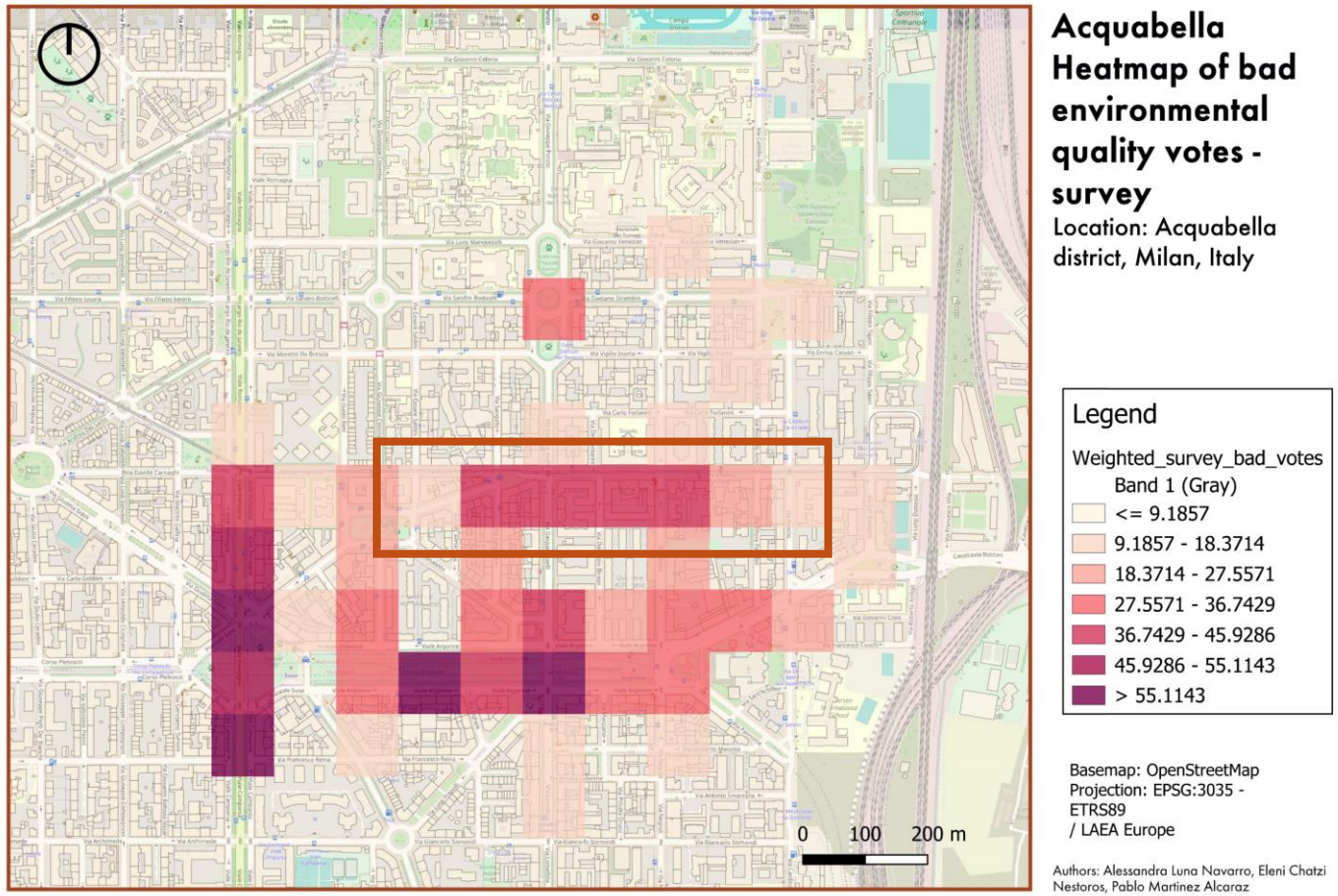


Survey – Demographics & user profiles

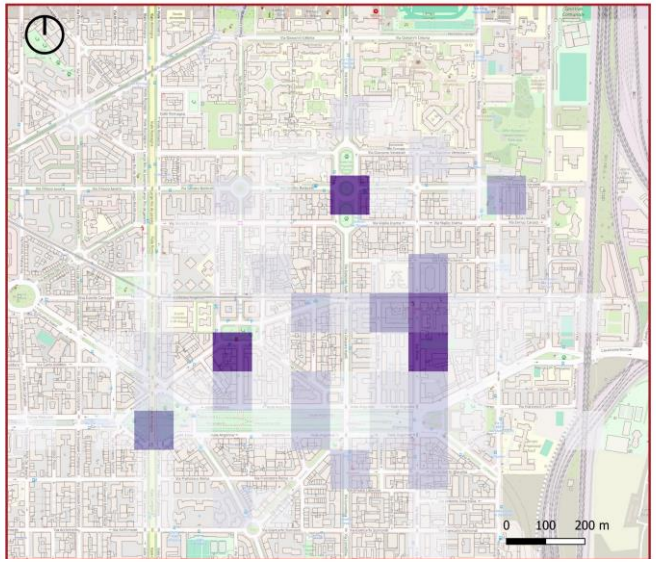


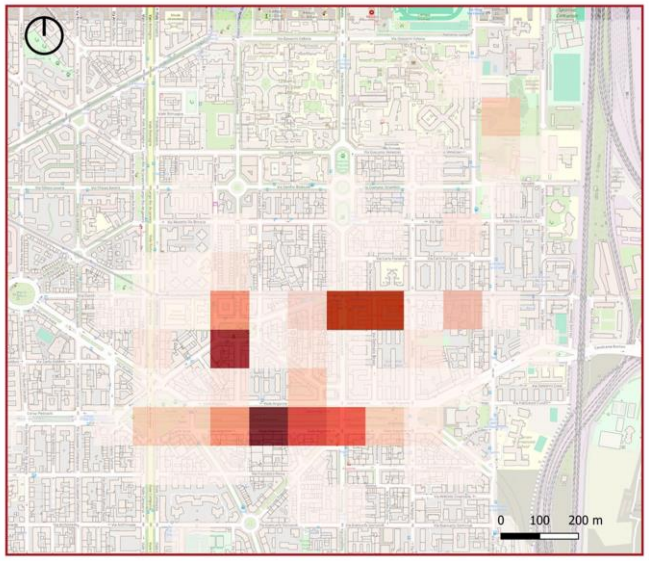
1. 2. 3. 4. 5. 6.

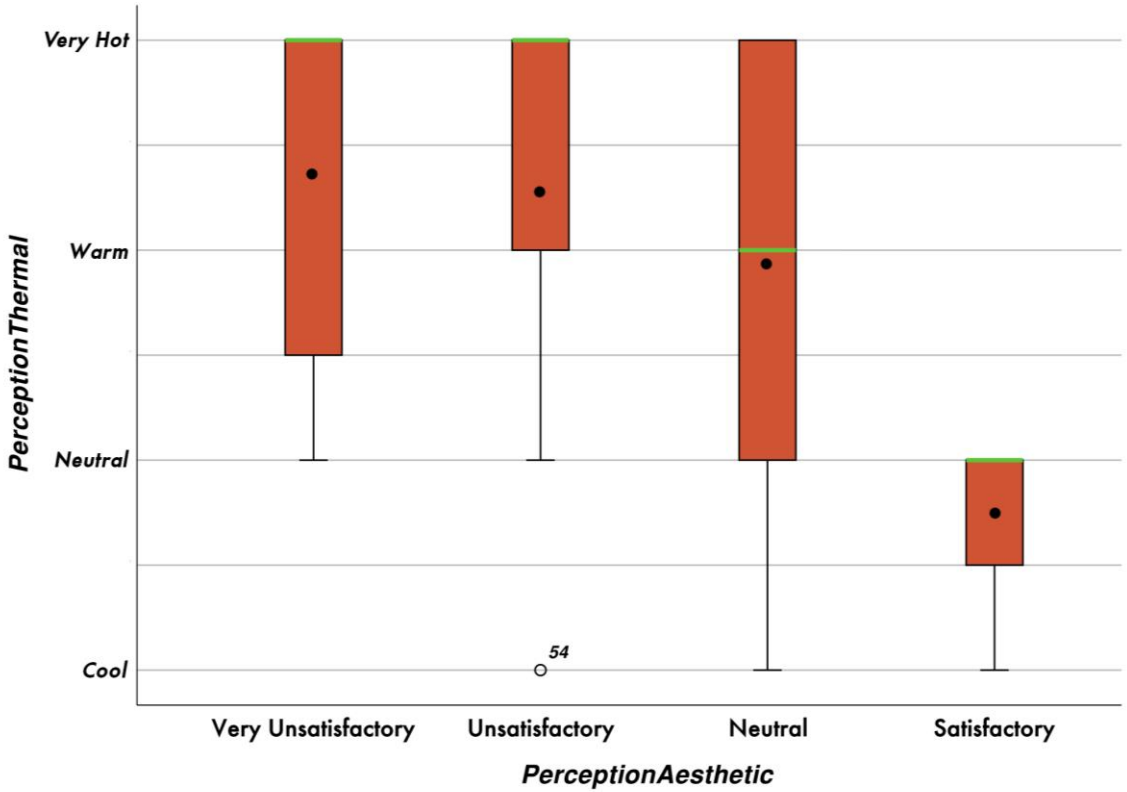
Survey - Clusters



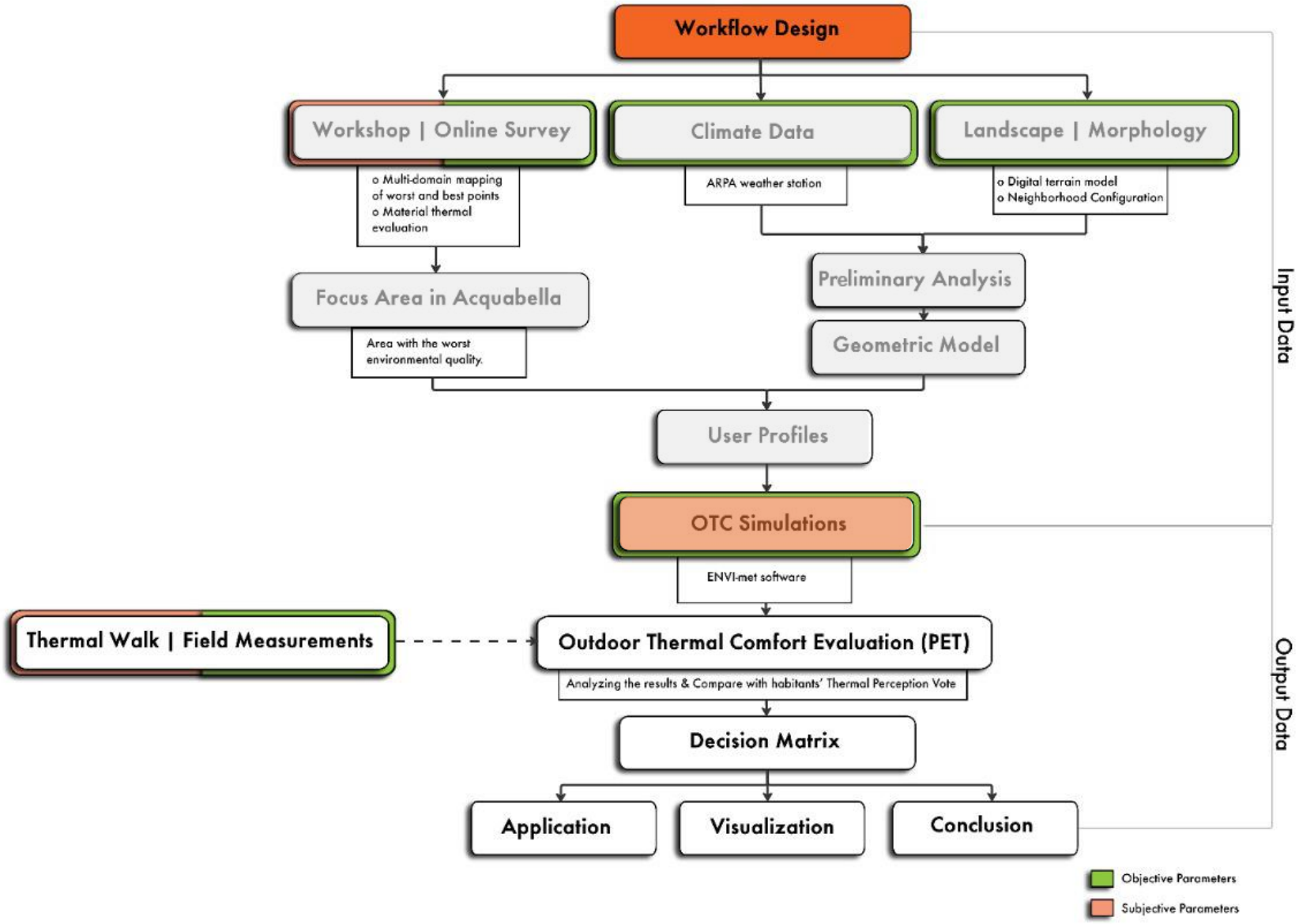
Survey - Clusters



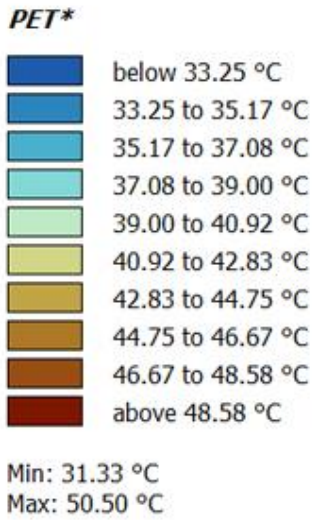




OTC Workflow



Simulations



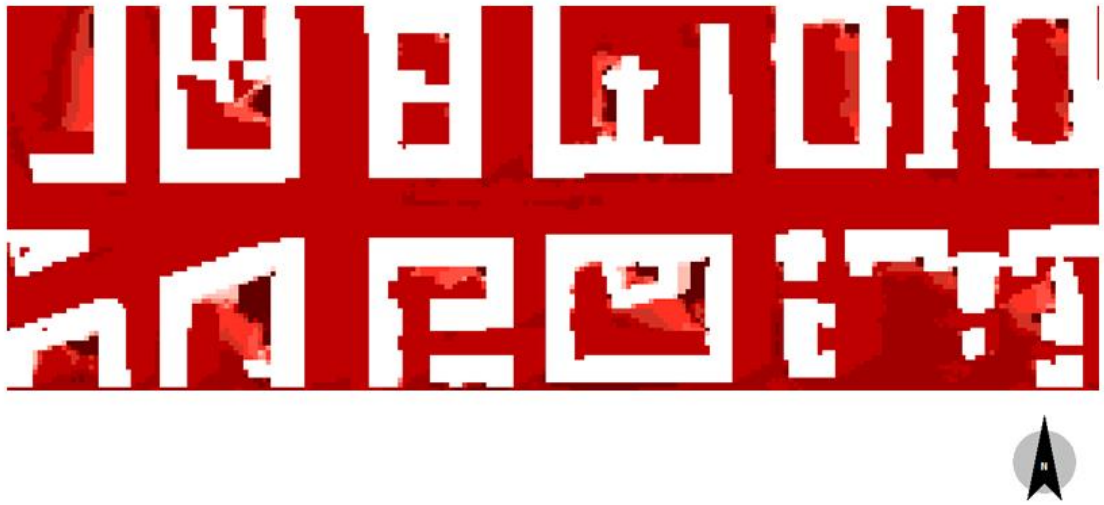
Simulations:

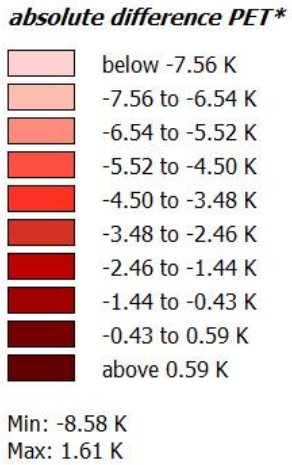
- PET Comfortable range in Mediterranean countries 24.6-29.2 °C
- 4.00 AM all users in comfortable ranges
- 15.00 PM most thermally uncomfortable hour
- 15.00 PM highest Tair and Tmrt

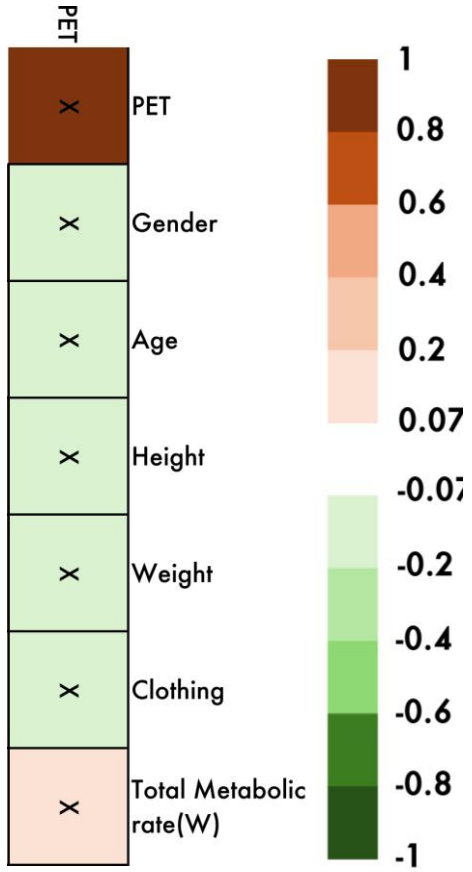
Effect of user characteristics

Spearman's rank correlation:

Date	User		Receptor		PET
Hours	Personal characteristics	Clothing	Environmental variables	Built environment variables	°C
...	..	..	..	..	..

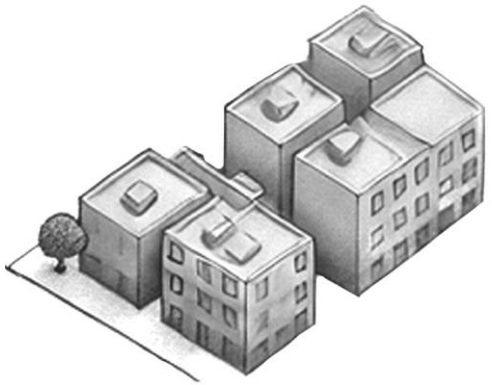


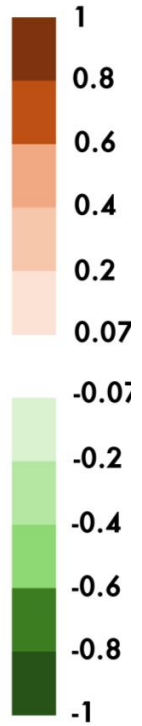




Impact of built environment parameters

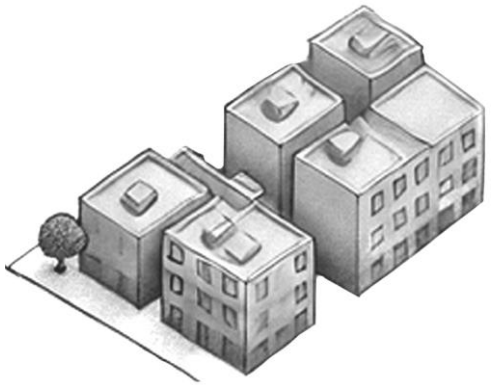
Neighborhood configuration



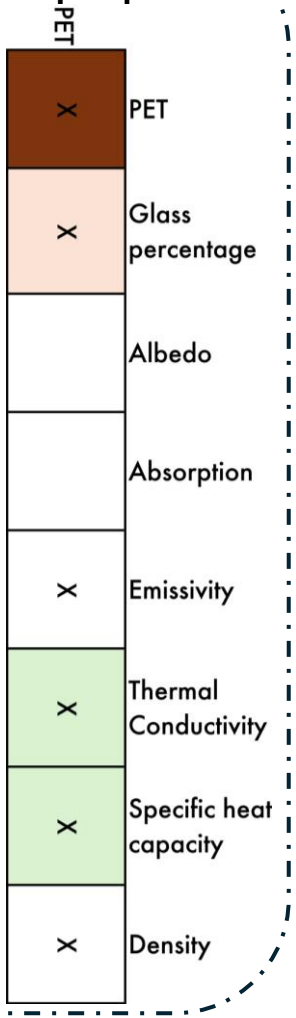


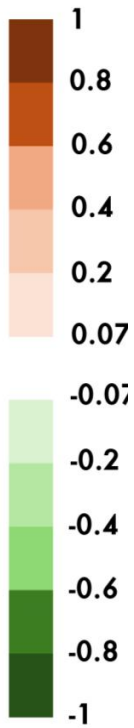
Impact of built environment parameters

Neighborhood configuration



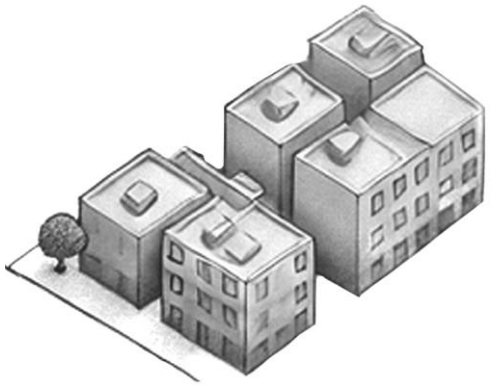
Ground floor façade properties



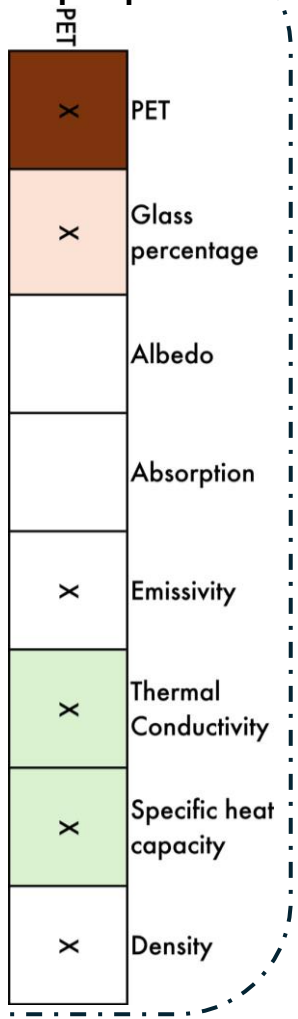


Impact of built environment parameters

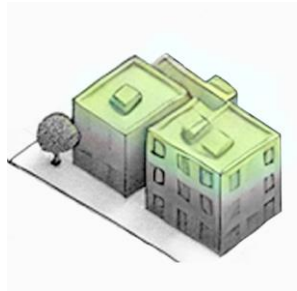
Neighborhood configuration

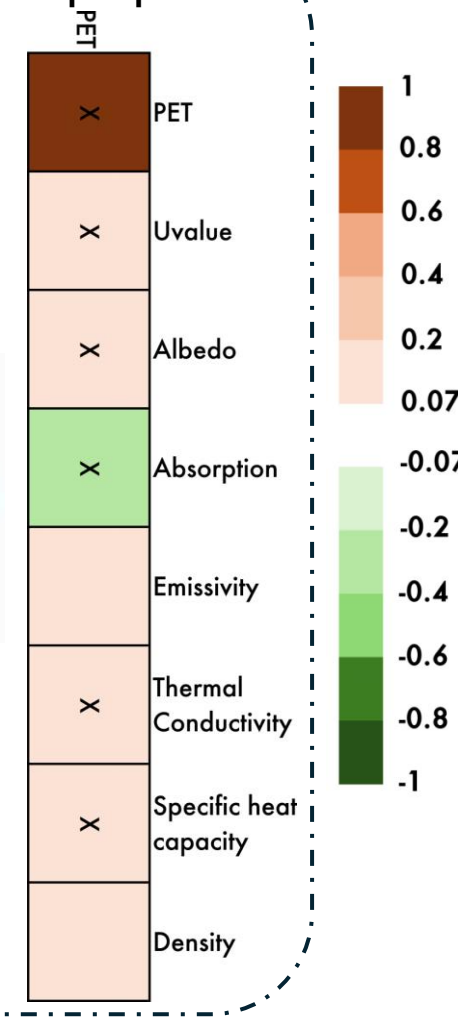


Ground floor façade properties

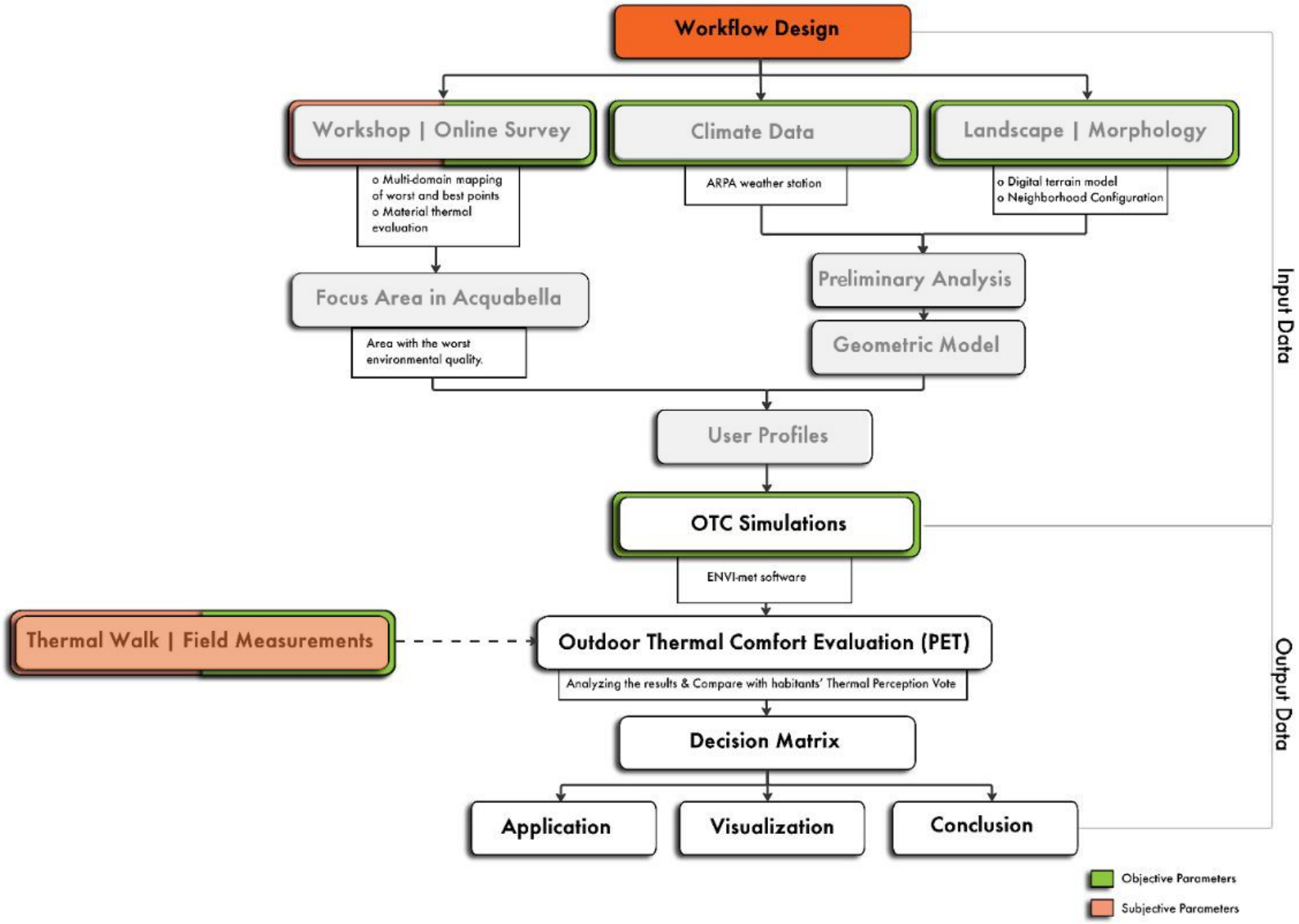


Upper façade properties

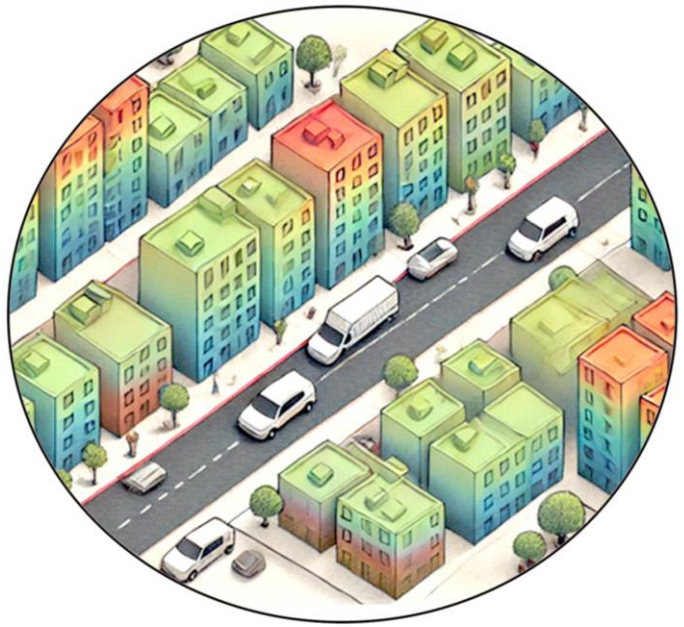




OTC Workflow



Thermal walk

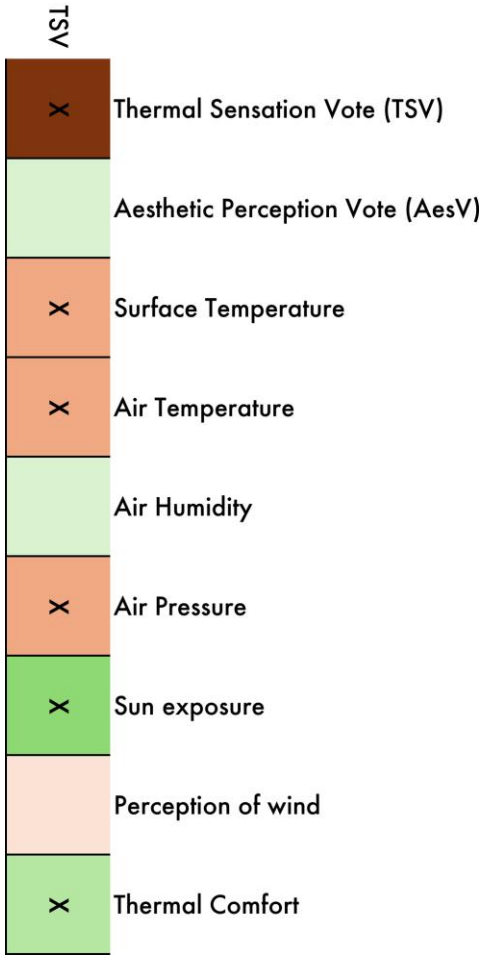


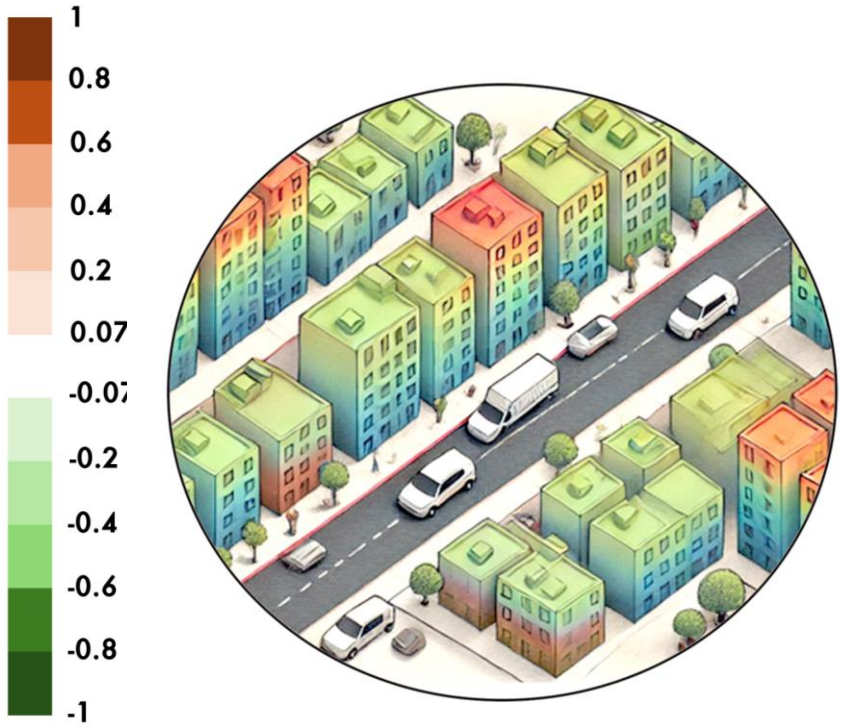
Thermal Sensation Vote (TSV):

- Very Cold (-3)
- Cold (-2)
- Cool (-1)
- Slightly Cool
- Comfortable (0)
- Slightly Warm
- Warm (+1)
- Hot (+2)
- Very Hot (+3)

Thermal walk

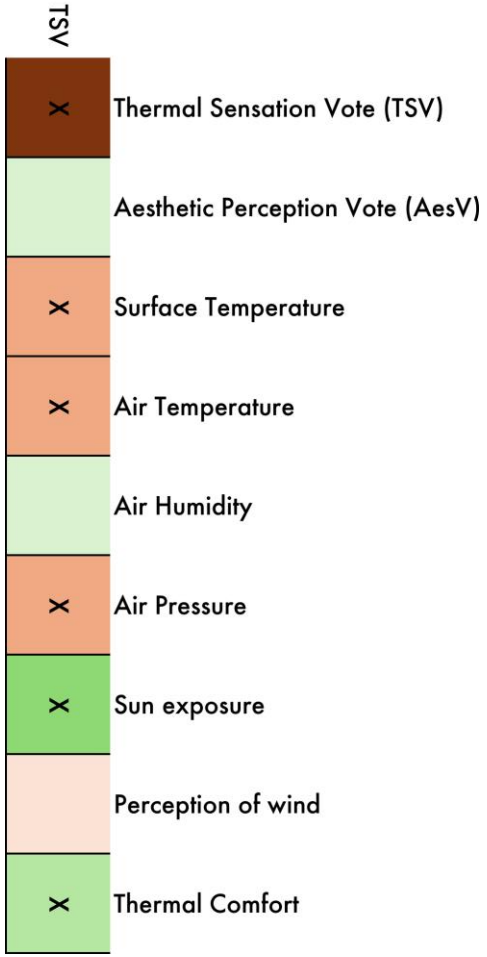
TSV & environmental conditions



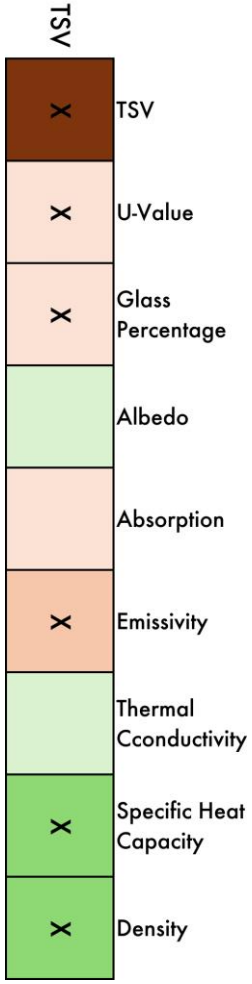


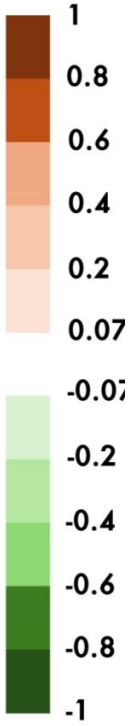
Thermal walk

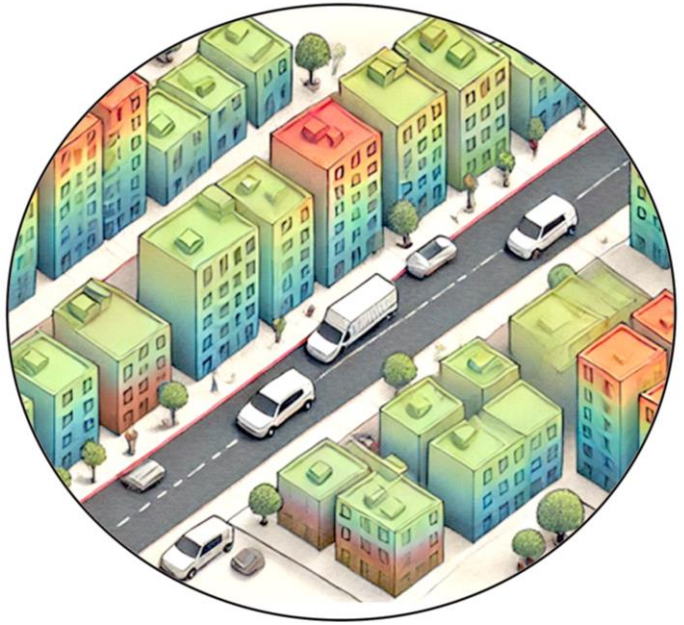
TSV & environmental conditions



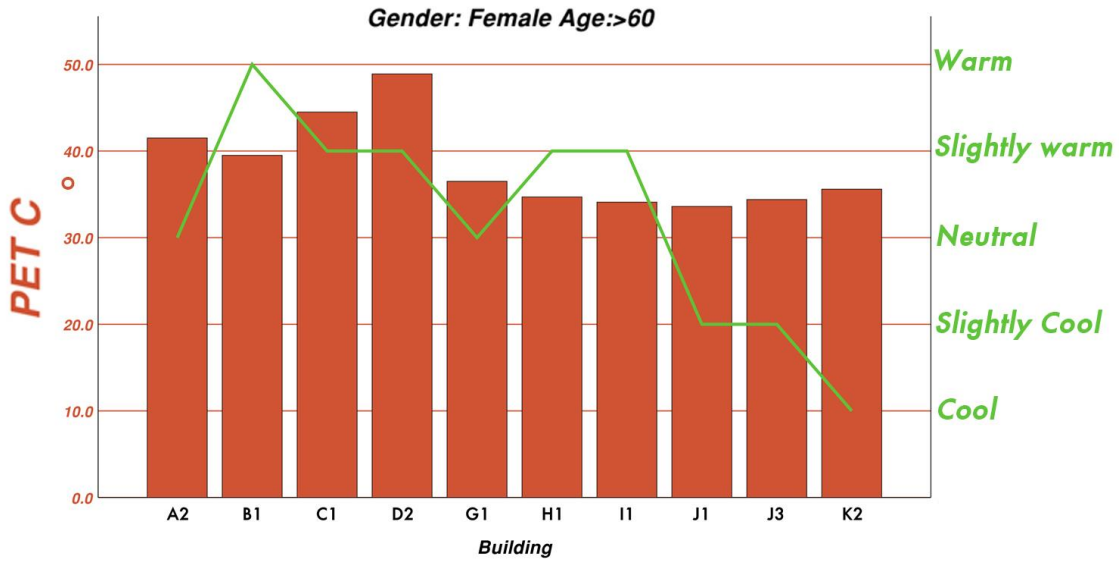
TSV & Ground Floor Materials:

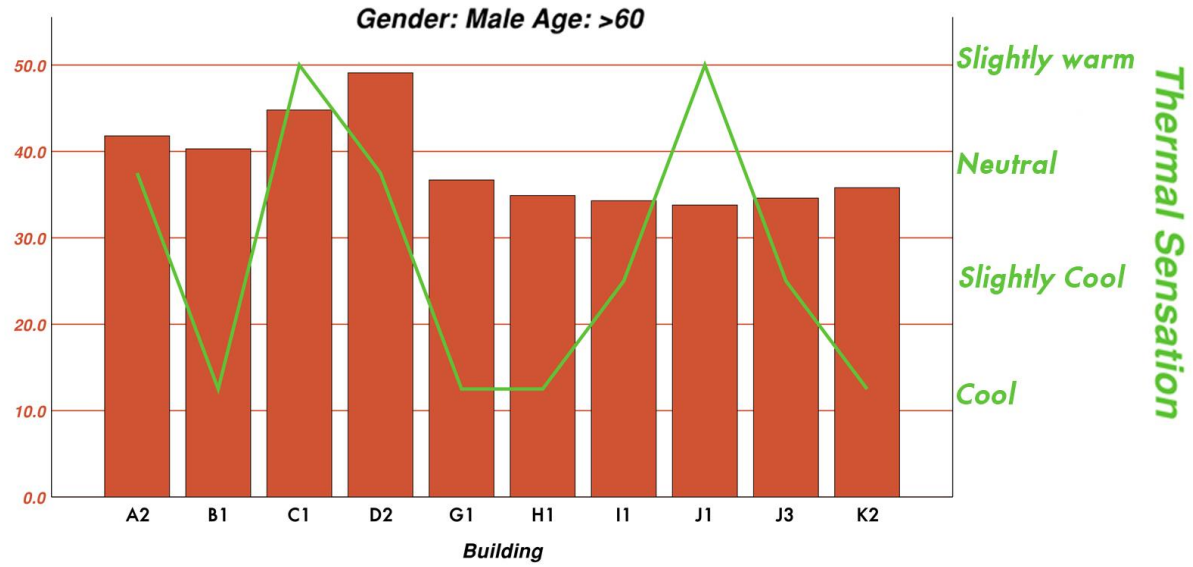




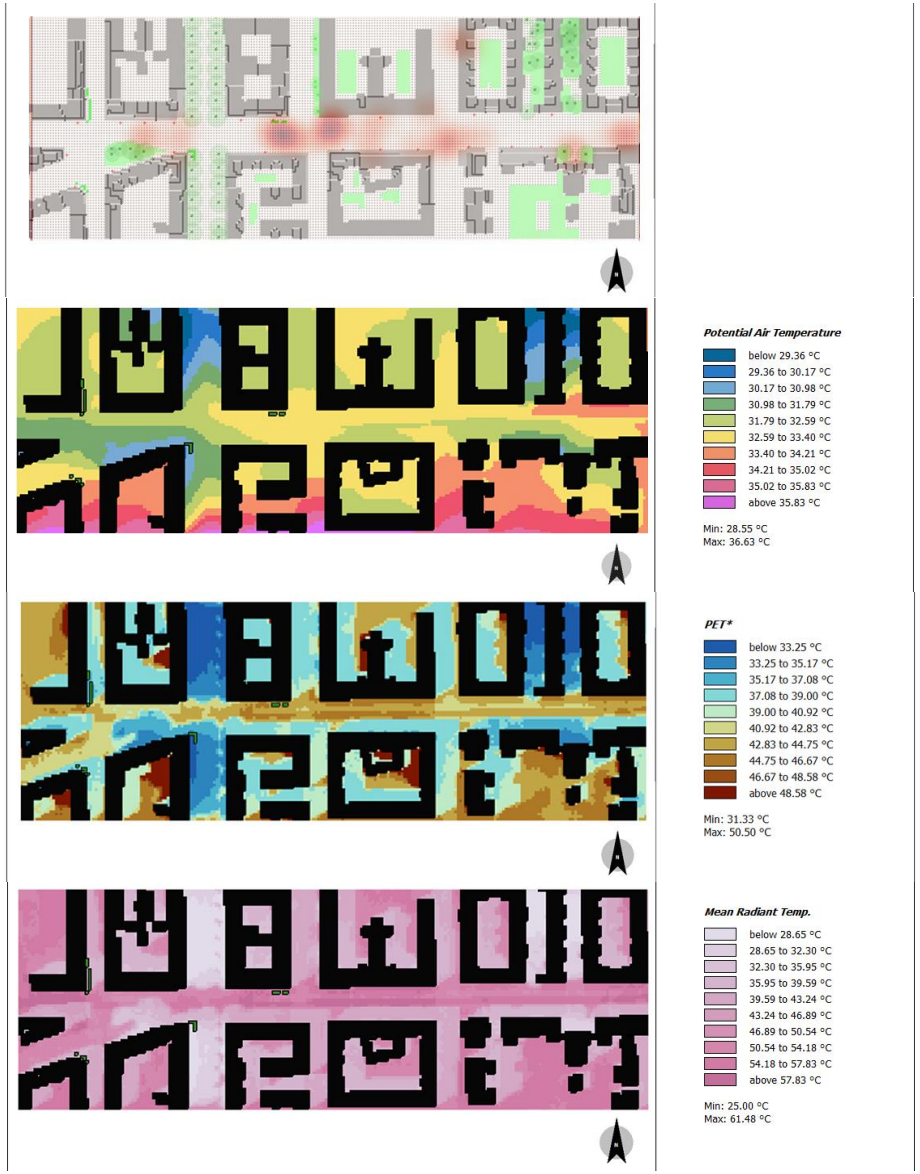


Thermal walk: PET





Objective & subjective data



Heatmap of negative thermal and visual votes (Acquabella clusters|survey):

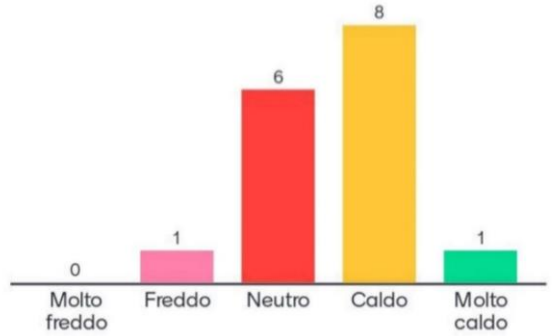
- Significant discomfort in Blocks B,C,I,J.
- Alignment with high Tair, Tmrt and PET zones from the simulations
- Compare with worst-rated buildings |Thermal walk

Building Facade	A2	B1	C1	D2	G1	H1	I1	J1	J3	K2	Std. Deviation
Thermal Comfort	3.38	2.87	3	3.25	4.38	5.13	4.38	4.57	3.63	4.57	1.559
Aesthetics	3.57	5.13	2.88	3.50	4.13	5.13	4.75	2.14	4.38	4.29	1.853
Total	6.95	8	5.88	6.75	8.51	10.26	9.13	6.71	8.01	8.86	

Perception of materials

Material	Rank Tair	Tair reduction by high radiative properties	Tair reduction by high thermal mass & moderate albedo	Rank PET	PET Index reduction by Tmrt	PET Index reduction by Tair	Rank TSV | Workshop	Rank TSV | Thermal walk
Stucco white	4		*	4	*		5	4
Stucco grey	3		*	5	*		6	2
Plaster white	10			10			3	7
Marble white	2		*	2	*		1	-
Marble cream	1		*	1	*		2	1
Concrete white	5	*		8			7	-
Concrete grey	6			3		*	4	5
Brick cream	8			8			8	3
Brick red	7			6			7	6

What thermal sensation do you associate with this material?



Decision matrix

Design for Via Beato Angelico

Building code	Upper Facade	GF Facade	Vegetation
A1 ..	↑ Albedo ↓ Absorption	~ Albedo ↓ Emissivity ↑ Specific Heat Capacity	Greenery on balconies More trees

- Survey & Thermal walk: Drastic changes in buildings voted as 'unattractive' and thermally 'uncomfortable', high thermal mass
- Simulations & Workshop : vivid and fresh colors, moderate albedo
- Simulations: moderate albedo, low emissivity paints
  Literature: Awnings & shading devices
- Workshop & Survey: more vegetation on balconies and street
- Survey: permeable layers for horizontal surfaces, replacement of parking-lot asphalt

Evaluation of New design

PET Simulation : Original

Min: 31.33 °C
Max: 50.50 °C

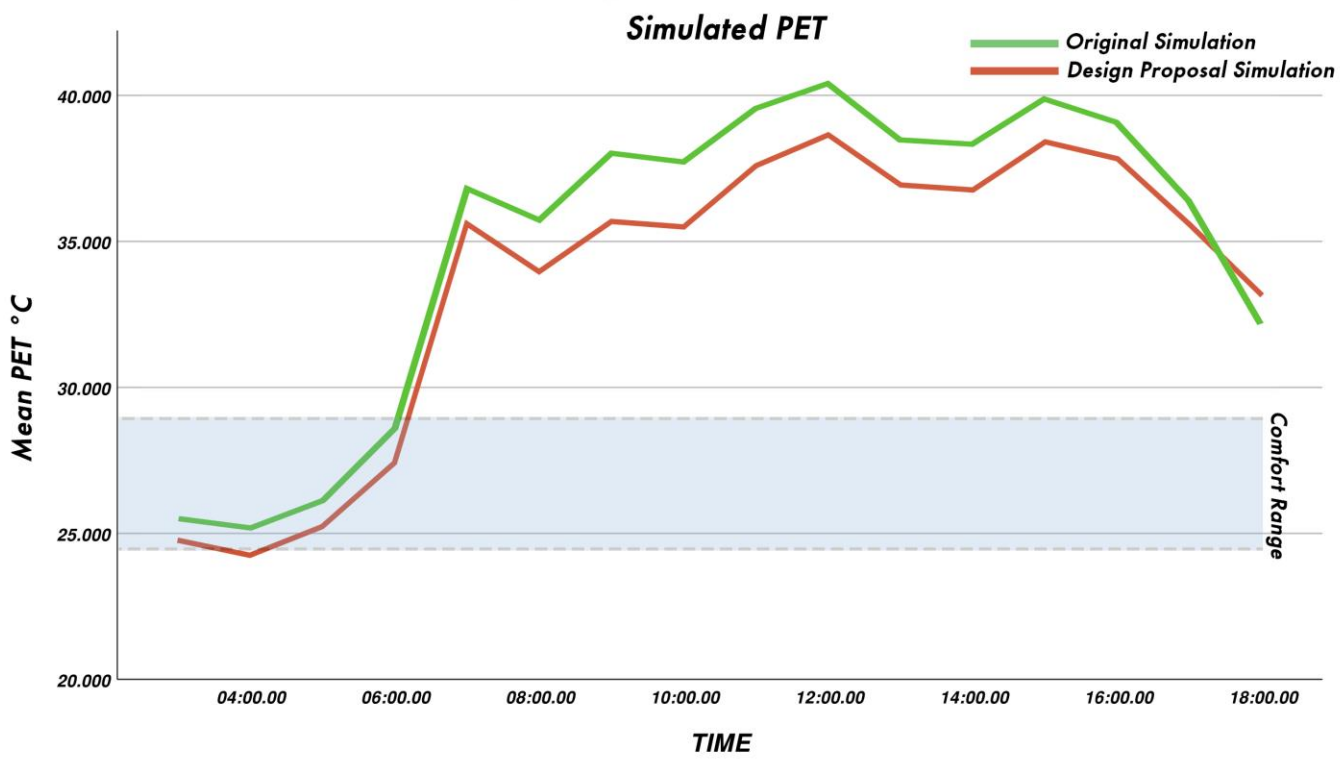
PET Simulation : Design Proposal

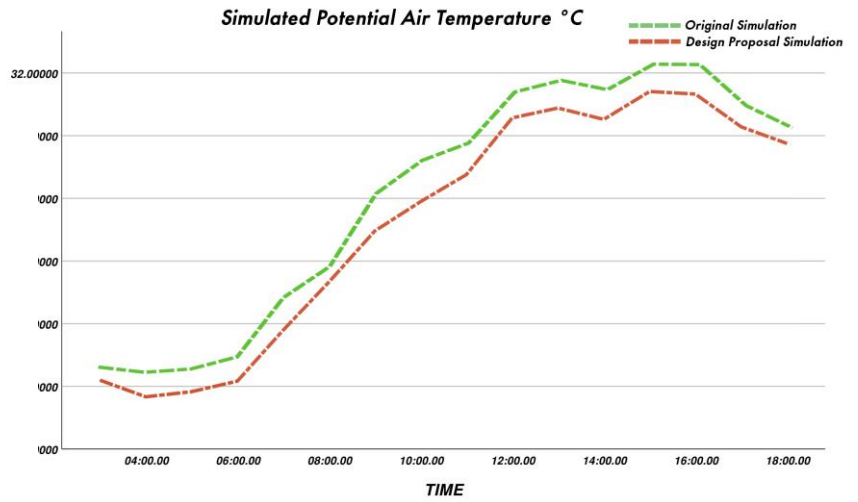
Min: 30.17 °C
Max: 50.32 °C

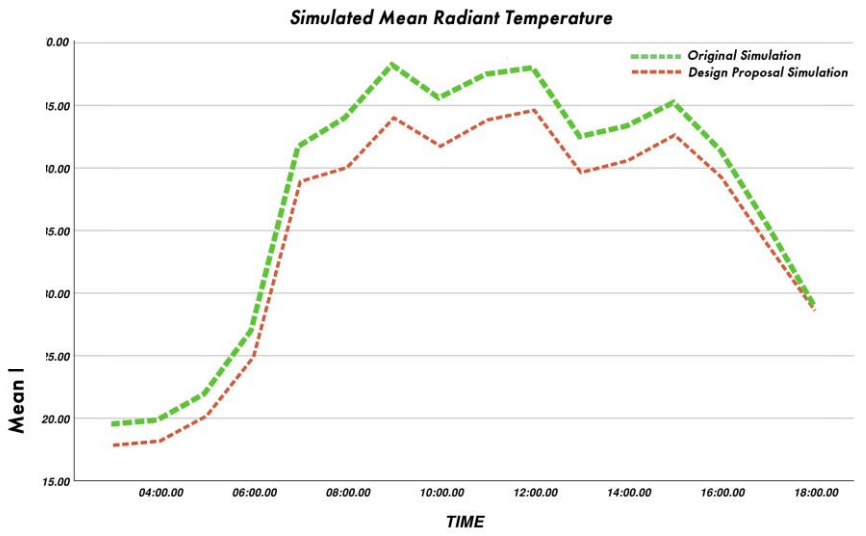
PET*

- below 33.25 °C
- 33.25 to 35.17 °C
- 35.17 to 37.08 °C
- 37.08 to 39.00 °C
- 39.00 to 40.92 °C
- 40.92 to 42.83 °C
- 42.83 to 44.75 °C
- 44.75 to 46.67 °C
- 46.67 to 48.58 °C
- above 48.58 °C

Evaluation of New design








Research Framework
Case Study
OTC Workflow
Results
Discussion

Conclusions

Workflow for OTC assessment

To whom:

- Citizens
- Policy makers
- Urban planners

What:

- Materiality of façade
- Neighborhood configuration
- Perceptual aesthetics
- Objective & subjective thermal sensation

How:

- Participatory workshop
- Online survey
- Simulations
- Statistical analysis
- Decision matrix
- Design proposal
- Thermal walk / Monitoring campaigns

Advantages:

- Holistic Assessment
- Community Engagement
- Data-Driven Design
- Replicability and Flexibility
- Validation and Accuracy

Limitations & Future research

Thank you

Questions?..

Workflow overview