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

## A case study of Milan.

**Eleni Chatzi Nestoros**
MSc Architecture, Urbanism and Building Sciences
Track Building Technology
Delft University of Technology

TU Delft

## MSc Graduation Thesis Report

Final report : 04.07.2024

Name : Eleni Chatzi Nestoros
Student Number : 5854067

Delft University of Technology (TU Delft)
Faculty of Architecture and the Built Environment
Department of Architectural Engineering + Technology
MSc Architecture, Urbanism and Building Sciences
Track Building Technology

First Mentor: Alessandra Luna Navarro — Façade Design and Engineering
Second Mentor: Michela Turrin — Computational Design
Supervisor: Alejandro Fuentes — Computational Design

## Acknowledgements

I would like to thank my TUDelft mentors Alessandra, Michela, and Alejandro for guiding me through the process and for their prompt responses to my inquiries. This thesis has been a long and unpredictable journey, but with their guidance and insights on problem-solving approaches, we managed to reach a personal goal together. The process was very demanding and touched multiple fields where my knowledge was limited, but they were always there to provide feedback and insightful suggestions.

I am also very grateful to Pablo, the fellow PhD student, whose presence not only added an element of fun but also provided invaluable help throughout the data management of the thesis.

A sincere thank you to Cista social district of Acquabella and particularly to Roberto, who helped in realizing the thermal walk on very short notice and coordinated the whole event. I also want to personally thank the other members of 'Cista': Analisa, Caterina, and Otho, for being so active and passionate, helping me gather data, organize events, and distribute the survey.

I extend my gratitude to the research fellow at Politecnico di Milano, Juan, who provided me with data on the urban environment of Milan and guided me on how to use the ENVI-met software.

My appreciation extends to the entire team, always open and willing to address questions and offer valuable input to enhance the quality of my thesis. Finally, I would like to express my gratitude to my family and friends for their support throughout this journey.

Thank you all,
Eleni

# Abstract

Urbanization and climate change have intensified urban heat island effects, significantly affecting outdoor thermal comfort (OTC) in cities. Traditional methods of assessing the influence of urban environments on OTC often rely heavily on computational simulations, neglecting the integration of user-centric data and comprehensive environmental monitoring. This research addresses the critical gap by employing a multi-domain, mixed-method approach to evaluate the influence of building facades on outdoor thermal comfort, specifically in the Acquabella district of Milan.

To address the gap, this study suggests a structured workflow beginning with a participatory workshop and a long-term survey to gather demographic data and user perceptions, identifying areas of significant thermal discomfort. These insights inform the simulations conducted using ENVI-met software, which model the Physiological Equivalent Temperature (PET) across different facade geometries and material properties. Real-time validation is achieved through a thermal walk, which includes field measurements and on-site evaluations to capture situational thermal perceptions.

The research findings underscore the substantial impact of facade materiality on thermal perception. The study also reveals that aesthetic preferences and psychological factors play a crucial role in thermal perception, highlighting the necessity of integrating these aspects into urban design strategies.

These findings are synthesized into a decision matrix that guides the design of retrofit strategies. Proposed solutions focus on modifying facade materials, increasing vegetation, and optimizing the built environment based on user feedback. Simulations of these design proposals using ENVI-met demonstrate significant improvements in thermal comfort, validating the effectiveness of the proposed interventions.

This thesis presents a comprehensive framework for assessing the multi-domain influence of facades on outdoor thermal comfort, advocating for the integration of user-centric data and participatory approaches in urban design. The methodology and findings offer valuable insights for policymakers, urban planners, and researchers aiming to enhance urban thermal environments and address the challenges posed by climate change and urbanization.

# Table of Contents

# 1 RESEARCH FRAMEWORK

## 1.1. Background

Urbanization brings about major alterations in land cover and structure, resulting in new urban climates characterized by increased air pollution, temperature, and flooding. As the cities expand, so do the challenges posed by (undesirable) urban climate effects, requiring a subtle understanding of global climate change, urban climates, and their intersections with the built environment (N. de Waard, 2021).

### 1.1.1 Overheating, Urban Heat Island, Climate Change

A significant rise in global air temperatures since the mid-20th century is caused by anthropogenic greenhouse gas emissions (N. de Waard, 2021). The effects of climate change, such as warming oceans, melting ice, and changing precipitation patterns, affect both rural and urban areas. However, the unique characteristics of cities, such as their geometry and increased footprint, make them more vulnerable to environmental hazards.

Urban areas face high risks of overheating and flood, impacting the health and safety of residents during extreme weather events. The expected increase in warm summer days and urban density highlights a growing heat challenge in urban areas, necessitating an understanding of how increased heat manifests itself (N. de

Waard, 2021). Urban population growth has notably expanded the urban environment, changing the surrounding environment and the urban microclimatic conditions(Pigliautile et al., 2021).

Urban areas systematically experience higher air and surface temperatures than rural areas, a phenomenon known as the Urban Heat Island (UHI) effect. The driving physics involve a reduction in latent heat flux and an increase in sensible heat flux. UHI has brought significant changes in environmental quality and comfort of the citizens, posing threats like increased, discomfort, air pollution, energy consumption, and greenhouse gas emissions. It is associated with global warming and amplifies heatwave impacts, decreasing the quality and endangering city livability (Kousis et al., 2021) . The phenomenon is caused by: (i) anthropogenic and other heat sources, (ii) heat stored and emitted by massive building constructions, and (iii) lack of urban green canopies. Negative effects include increased building cooling energy consumption, thermal discomfort, elevated ground-level ozone, and health problems (Rosso et al., 2018).

UHI dynamics depend on factors such as urban morphology, density, and land consumption with impervious materials like asphalt and concrete, changing the balance in the urban energy budget. Impervious materials increase solar radiation absorption and heat storage, contributing to higher temperatures and energy demand for cooling (Rosso et al., 2022).

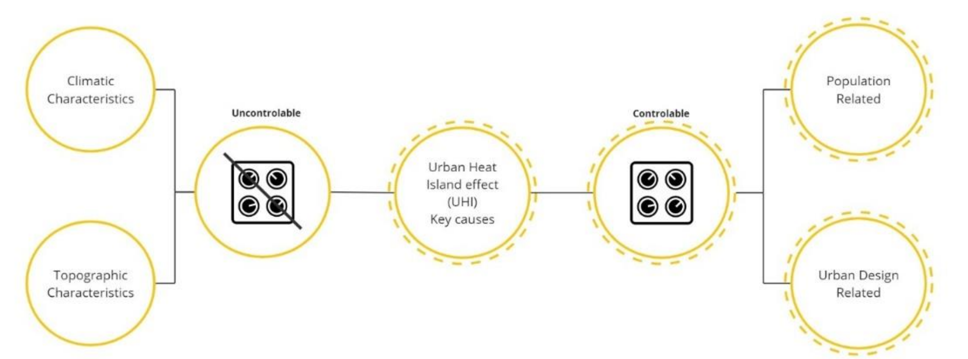



Figure 1. Urban Heat Island Effect - Controlable and Uncontrolable variables(Lama Idrees, 2021)

## 1.1.2 Microclimate

The term urban microclimate refers to the suite of climatic conditions measured in localized areas near the Earth's surface. To regulate this microclimate, a multitude of environmental variables such as SVF (sky view factor), Dr (direct radiation), Dfr(diffuse radiation), MRT (mean radiant temperature), St (surface temperature), Gt (ground temperature), Ba (building's albedo), Ga(ground albedo) are considered.

The complexity in morphology and heterogeneity that characterizes urban fabrics results in varied microclimate conditions, even in the same urban context and neighborhood. Recognizing this diversity, the analysis of local intra-urban microclimates plays a crucial role in identifying effective and feasible mitigation strategies to achieve better thermal comfort levels for the inhabitants (Rosso et al., 2022).

## Microclimate and built environment

Unlike controlled indoor environments, urban microclimates are dynamic, subject to the ever-changing sunlight, wind, and tree shading, making the outdoor environment unpredictable (Eslamirad et al., 2022). Microclimatic parameters at the local scale can be altered due to changes in the energy balance. As already mentioned, factors such as the replacement of green areas with impermeable surfaces, limited evapotranspiration, poor thermal and physical properties of construction surfaces, and the presence of anthropogenic heat sources contribute to this shift in the heat balance (Giridharan et al., 2007).

The spatial structure of a city, including block layouts, building geometries, and open public spaces, significantly influences the urban microclimate, impacting the cooling and heating loads of buildings and outdoor thermal comfort. As cities increasingly prioritize urban health and well-being, environmental analyses should extend beyond energy performance considerations to encompass broader aspects of environmental quality (Khraiwesh & Genovese, 2023).

Researchers have explored materials as significant factors influencing surface and air temperatures in urban street canyons and pedestrians' thermal comfort conditions. Green roofs, green envelopes, roof ponds, and cool materials have been considered, with the latter identified as more feasible solutions due to their easier maintenance and lower cost. Among mitigation strategies, the increase of highly reflective "cool" surfaces and green spaces emerges as the most effective in reducing built surfaces overheating, building cooling energy consumption, and $CO_2$ emissions (Rosso et al., 2018).

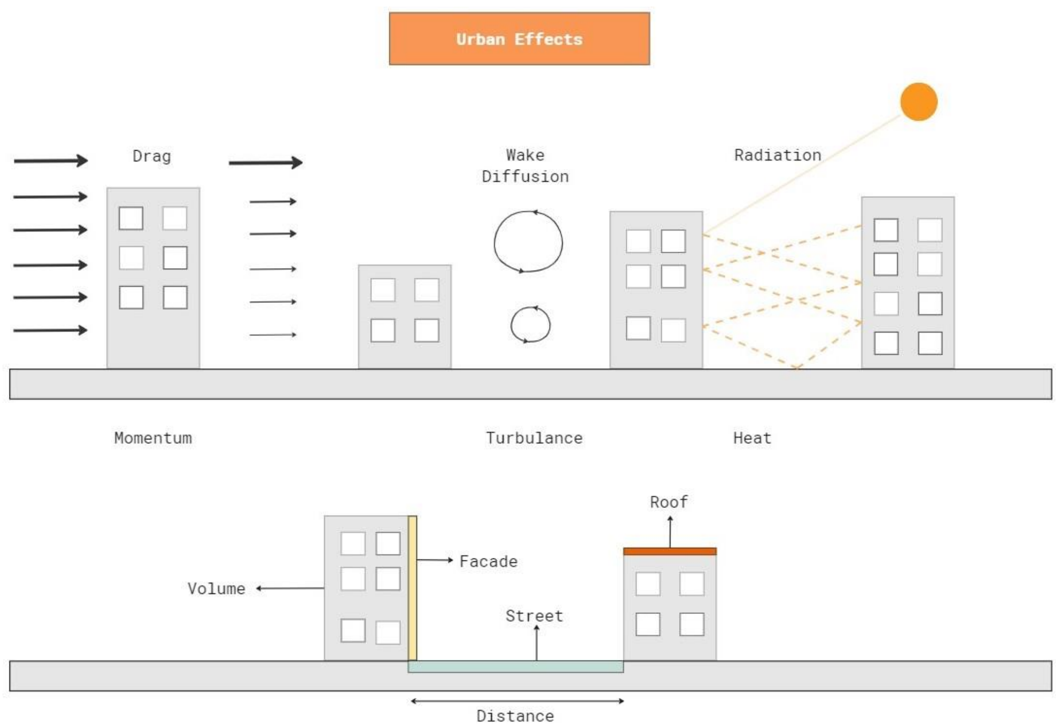



Figure 2. Effects caused by urban morphology.

### Microclimate and user

The quality of outdoor spaces is fundamentally determined by the outdoor microclimate, profoundly influencing people's perception of thermal comfort. Simulation methods can assess the intensity and extent of users' exposure to hazard-related stress and their following reactions, providing insights into behavioral patterns(Blanco Cadena et al., 2023).

Humans adapt to the thermal environment through three key approaches. Psychological adaptation involves altered perception and reaction to sensory information based on experience and expectations. Physiological adaptation, related to changes in physiological responses due to exposure to thermal parameters, aims to reduce strain. Physical or behavioral adaptation, involves active management of comfort levels through adjustments in posture, clothing, and activities, including reactions such as opening umbrellas, moving to shadow, or changing clothes (Kumar & Sharma, 2020). These adaptations are essential considerations in urban design to foster comfort and well-being (Coccolo et al., 2016) Mitigating discomfort in outdoor spaces not only enhances well-being but also attracts more people to use these modified areas (Kumar & Sharma, 2020).

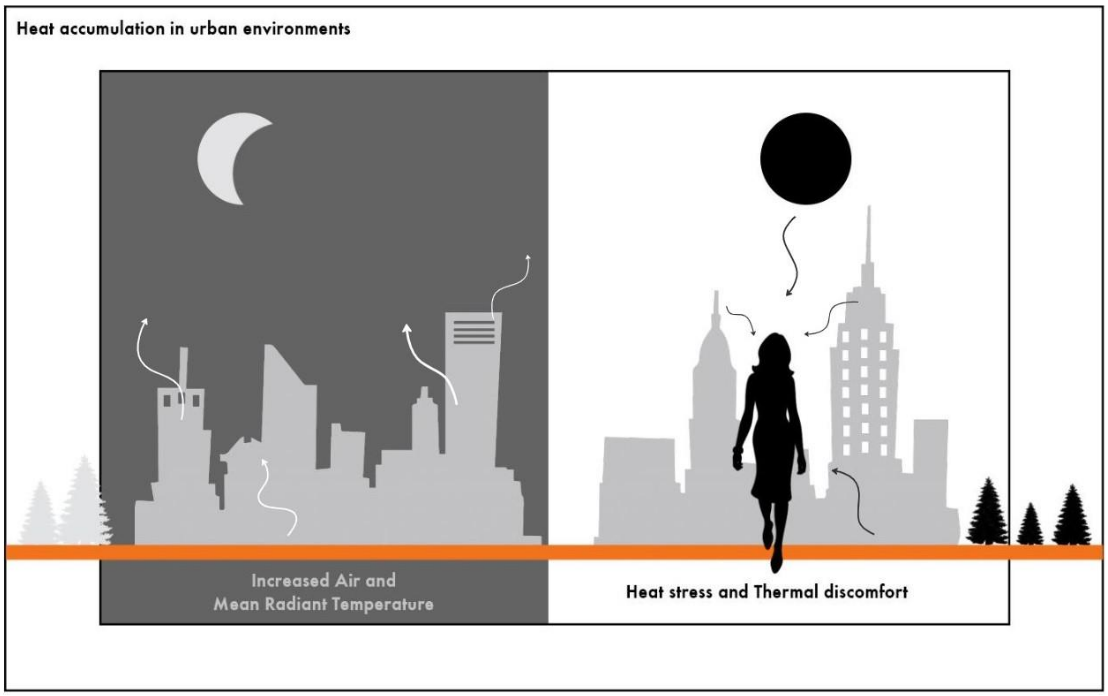



Figure 3. Heat accumulation in urban environments

## 1.2. Problem statement

As already mentioned, urban morphology, particularly the three-dimensional form of buildings and spaces, is one of the main causes of the phenomenon of overheating. Milan, being a metropolitan city, faces high temperatures and low outdoor thermal comfort mostly due to its compact urban tissues, which prevail over other characteristics of the city. This is linked directly to material properties, including low albedo, poor thermal conductivity, high emissivity, and other factors related to the urban fabric like vegetation degradation. More specifically, the influence of building facades on outdoor thermal comfort has been investigated in the latest years, considering facade geometry, materiality, greenery, orientation, and adaptability.

While existing studies offer valuable insights through simulations for assessing Outdoor Thermal Comfort (OTC), they primarily approach the issue computationally, lacking integration of objective monitoring, and user data (subjective). This prevents a thorough examination of the microclimatic and personal parameters that are affected by building facades. The multi-domain influence of facades emphasizes the need to include users in assessments beyond simulations, highlighting a lack of qualitative methods associated with facade impact. This gap, compounded by limited literature on participatory approaches, such as workshops and interviews, prevents effective assessment of outdoor thermal comfort and other environmental quality domains.

## 1.3. Objectives

The purpose of this study is to close the knowledge gaps mentioned in the previous section. Considering these gaps, the following research goals have been formulated.

### Research objectives:

- To study the influence of objective and subjective elements in defining outdoor comfort and the influence of facade in Acquabella district, Milan.

  This part of the research will include investigating the ways to evaluate thermal comfort, the methods to combine subjective thermal sensation and objective thermal perception, and the limitations and conditions that comfort should be assessed in this specific district of Milan.

- To design a workflow, following a systematic empirical investigation, that applies qualitative and quantitative research methods in defining and assessing comfort.

  This workflow incorporates a statistical analysis of the user responses that will first be used to develop profiles and provide input user data for simulations. The results of the simulations will be validated with comparisons with the stated objective perceptions of the users and further monitoring campaigns, testing the accuracy of the workflow.

- To provide measures for facade design that could be implemented to achieve better levels of pedestrians' thermal comfort without compromising the aesthetic and architectural integrity of the Acquabella district.

## 1.4. Research question

How can a multi-domain, mixed-method approach be implemented to support the assessment of facade influence 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 does facade influence urban inhabitants' thermal perception?
4. To what extent can the perceptual aesthetics of facades influence pedestrians' perception of the thermal environment?
5. How can qualitative and quantitative methods be combined to assess Outdoor Thermal Comfort (OTC)?

**Design Question:**

What facade design solutions can be used to effectively mitigate overheating and improve outdoor thermal comfort for pedestrians in Acquabella district?

## 1.5. Approach and methodology

The study is conducted in three phases:

In the first phase, research on the definition and methods of Outdoor Thermal Comfort (OTC) evaluation is conducted. This includes examining thermal indices and understanding their applications, considering the environmental and personal parameters crucial for assessing the thermal perception of pedestrians. Additionally, the research involves computational tools and existing method combinations for OTC assessment. This part also analyzes the impact of facades on outdoor environmental quality, focusing on thermal and visual comfort with an emphasis on perceptual aesthetics. The goal is to correlate the impact of facades on OTC with the subjective thermal sensations and perceptual aesthetics of pedestrians. Furthermore, an investigation into Milan's urban fabric regulations is carried out, along with the collection of climate and geometric data for the study area.

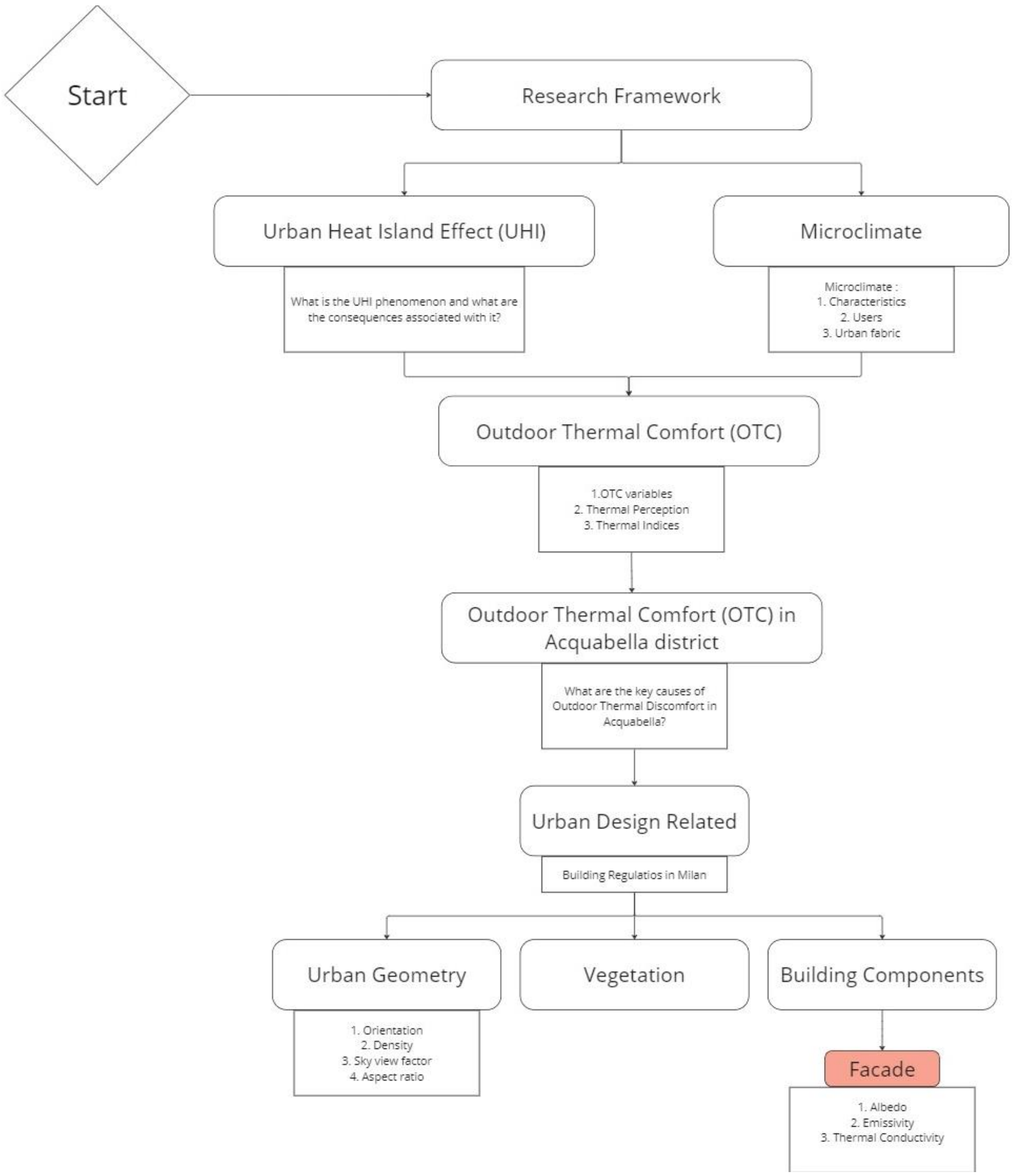



Figure 4. Flowchart of Literature Review

In the second phase, the design of the workflow is presented. Solely using computational methods for holistic OTC assessment has proven to be incomplete and inaccurate. Therefore, this workflow integrates both user preferences and computer simulations, incorporating qualitative and quantitative data as design inputs. This integration includes simulations, a participatory walk, online survey, and the development of a portable sensor system for field measurements. Initially, a participatory workshop is conducted in collaboration with the Cista social district and the community members of the Acquabella district to identify the most thermally uncomfortable areas for focused analysis. Following the workshop, a long-term survey is distributed to a larger sample to gather general satisfaction levels and evaluations of outdoor environmental quality in Acquabella. Another survey is distributed during monitoring campaigns to collect information on personal characteristics and individual thermal perceptions, which will be used to assign them to the user profiles created during the simulations, and compare for a more comprehensive assessment.

The third and final phase aims to provide the district's inhabitants with practical solutions to enhance comfort and attractiveness in the district's weak spots. This phase seeks to understand the factors influencing thermal sensation and identify the properties of the built environment that exacerbate the issue. The analysis helps formulate a decision matrix with feasible options, such as changing wall colors, altering the outer layer of a building's facade, modifying pavement tiles, or increasing greenery. These measures offer decision-makers the flexibility to allocate weights based on desired goals while accommodating the region's limitations and architectural barriers, resulting in a coherent and more visually appealing neighborhood.

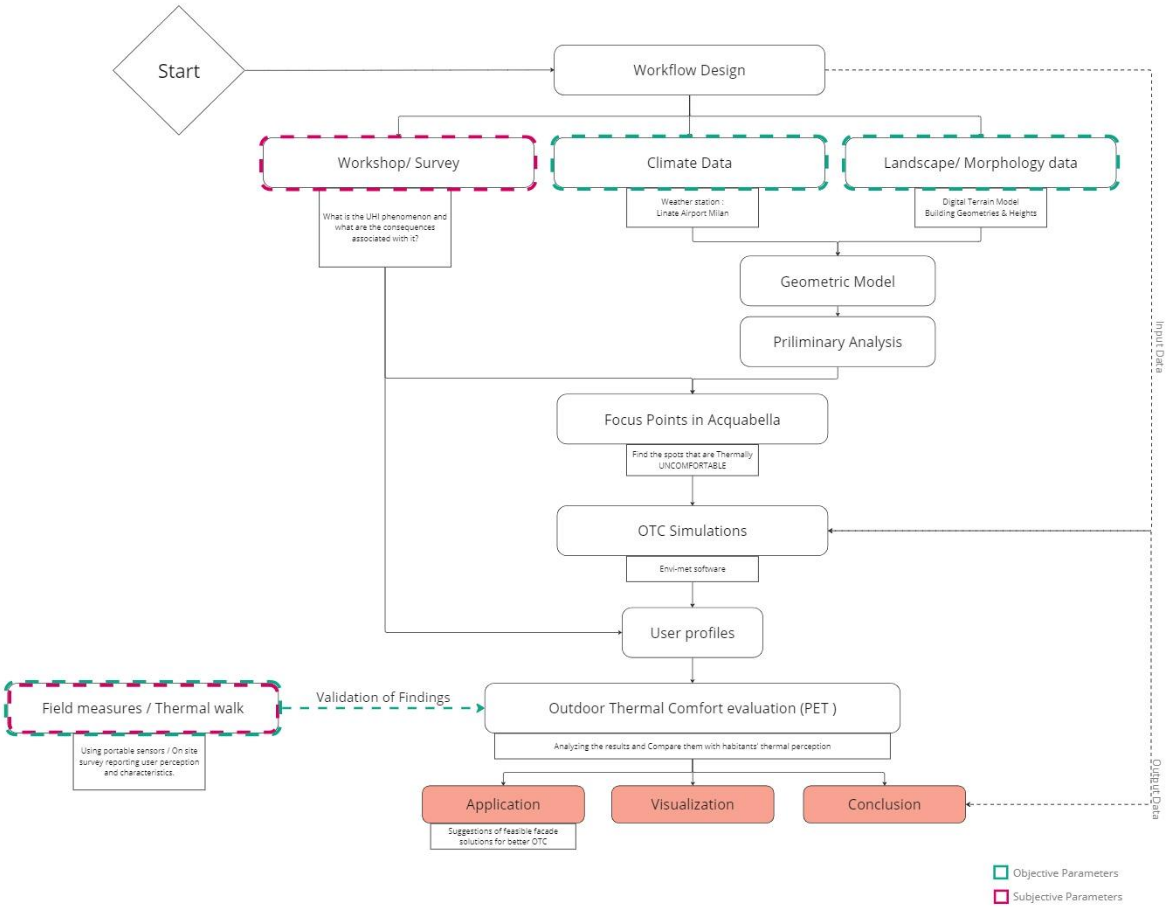



Figure 5. Steps of the Workflow

## 1.6. Planning and Organization

| WEEK No, GRADUATION | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DATE | 13 Nov. | 20 Nov. | 27 Nov. | 4 Dec. | 11 Dec. | 18 Dec. | 25 Dec. | 01 Jan. | 08 Jan. | 15 Jan. | 22 Jan. | 29 Jan. | 05 Feb. | 12 Feb. | 19 Feb. | 26 Feb. | 04 Mar. | 11 Mar. | 18 Mar. | 25 Mar. | 01 Apr. | 08 Apr. | 15 Apr. | 22 Apr. | 29 Apr. | 06 May. | 13 May. | 20 May. | 27 May. | 03 Jun. | 10 Jun. | 17 Jun. | 24 Jun. |
| Statistical Analysis of workshop's results | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Analysis of focus points | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Set-up of Geometrical Model | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Exploration and set-up of Envi-met model | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Statistical Analysis of long-term survey | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Simulation / PET assessment | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| P3 - Progress Review | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Design of short term survey | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Analysis of the simulation results | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Proposals on façade and paving measures | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Field measurements to validate model | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| User profiles to assess MOCI | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| P4 Preparation | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| P4 - green light | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Optimise based on feedback | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Comparison of PET & MOCI | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Prepare report | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| P5 Preparation | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| P5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

## 1.7. Relevance

### Relevance to the master track of Building Technology

My research " A multi-disciplinary approach to assessing the influence of facade on outdoor thermal comfort: A case study of Milan." is a multidisciplinary approach that aligns with the AUBS program's broad objectives. The MSc track "Building Technology" giving a particular focus on the technical elements of architecture, allowed me to integrate climate, computational, and facade design in the graduation project. The investigation of the facade's impact on outdoor environmental quality and the assessment of heat mitigation strategies fall under the umbrella of facade products and design. The study also emphasizes outdoor environmental quality—especially the growing concern of outdoor thermal comfort—closely aligning with the scopes of climate design. Computational design serves as the methodology for data extraction and analysis, but also in the formation of a workflow that supports data-driven and climate-responsive design solutions.

### Relevance to the social, professional, and scientific framework

This research significantly contributes to the field of urban climate design by addressing the increasing importance of outdoor thermal comfort, a critical issue in the context of climate change and urbanization. Focusing on improving the outdoor thermal quality of a specific district in Milan, this study offers feasible solutions for the community, impacting the built environment and building envelopes. Stakeholders and community members gain valuable insights into the possible implications of various design options, allowing them to make informed decisions. By incorporating personal preferences through a user-oriented approach, the workflow ensures that design solutions are not only effective but also align with users' needs and desires.

From a professional standpoint, the integration of computational design methods sets a precedent for future practices, highlighting the necessity of addressing user issues comprehensively and personally. The innovative methodologies introduced in this study, such as the multi-domain mixed-methods approach, are aligned with current trends in data-driven design solutions, enabling broader implementation and setting new standards in the field.

In the scientific framework, this thesis advances knowledge by bridging the gap between empirical data and subjective human experiences. The combination of participatory workshops, surveys, computational simulations using ENVI-met software, and real-time field measurements provides a holistic understanding of how facade materiality influences outdoor thermal comfort. This approach not only enriches the existing body of knowledge in urban climatology and environmental design but also offers practical guidelines for urban planners and policymakers. By demonstrating the effectiveness of integrating user feedback into design processes, the thesis promotes a more inclusive and responsive framework for sustainable and livable urban environments.

# 2 Outdoor Thermal Comfort (OTC)

## 2.1. Outdoor Thermal Comfort definition

Outdoor thermal comfort, a vital component of human well-being, refers to the state of mind where individuals feel satisfied within their thermal environment (ASHRAE 55, 2010). Climate change and urbanization, as noted, have led to a decline in the urban livability status for residents, emphasizing the urgency of addressing thermal comfort (Kumar & Sharma, 2020). The basis for understanding thermal comfort lies in the "two-node model," developed in 1936 based on thermodynamic principles (Gagge, 1937) and progressively modified. Givoni's Index of Thermal Stress (1963) and Fanger's Predicted Mean Vote (1970) represent significant advancements, with the second being now a well-recognized standard for assessing indoor human comfort (International Organization for Standardization, 2005).

## 2.2. OTC variables

In evaluating outdoor thermal comfort from a physiological standpoint (Fanger, 1970), the key factors include maintaining a heat flow balance of the human body (with core temperature between 36.5 and 37.5 °C), regulating sweat rate within comfort limits, and ensuring skin temperatures of 30 °C in extremities and 34-35 °C in the stem and head. These physiological variables interact with the following environmental parameters (IUPS, 2001; ASHRAE, 2010) (Coccolo et al., 2016):

• Air temperature (°C): average air temperature.

• Wind speed (m·s-1): air velocity.

• Relative humidity (%): ratio between the partial pressure of water vapor present in the air and the saturation pressure. Relative humidity is used to derive absolute humidity and water vapor pressure.

• Shortwave radiation (W·m-2): radiation received by the pedestrian from the sun, or reflected by the built environment.

• Longwave radiation (W·m-2): thermal radiation exchanged between the pedestrian and the environment.

• Human activity (met or W·m-2): rate of transformation of chemical energy into heat and mechanical work or so-called Metabolic rate.

• Clothing level (clo): resistance to sensible heat transfer provided by clothing or so-called clothing insulation.

• Mean Radiant Temperature (Tmrt)

Mean Radiant Temperature (Tmrt) is an artificial measure expressing the degree of exposure to environmental radiation, and is influenced by solar shortwave and terrestrial longwave radiation (Coccolo et al., 2016). Tmrt determination involves considerations of direct and diffuse solar radiation from the sun to the person, as well as radiation reflected from walls and ground, along with infrared radiation from walls, ground, and the sky (Dietrich, 2018). The mean radiant temperature is commonly determined using Equation (1), according to ISO 7726 Standard (Coccolo et al., 2016):

$$T_{mrt} = \left[ (T_{globe} + 273.15)^4 \left( \frac{1.1 \times 10^8 \times (W \times S)^{0.6}}{\varepsilon \times D^{0.4}} \right) \times (T_{globe} - T_a) \right]^{0.25} - 273.15$$

(1)

Where:

- *Tmrt* is the mean radiant temperature,
- *Tglobe* is the globe temperature,
- *W* is the wind speed,
- *S* is the solar radiation,
- *ε* is the emissivity of the surfaces,
- *D* is the diameter of the globe (m),
- *Ta* is the air temperature.

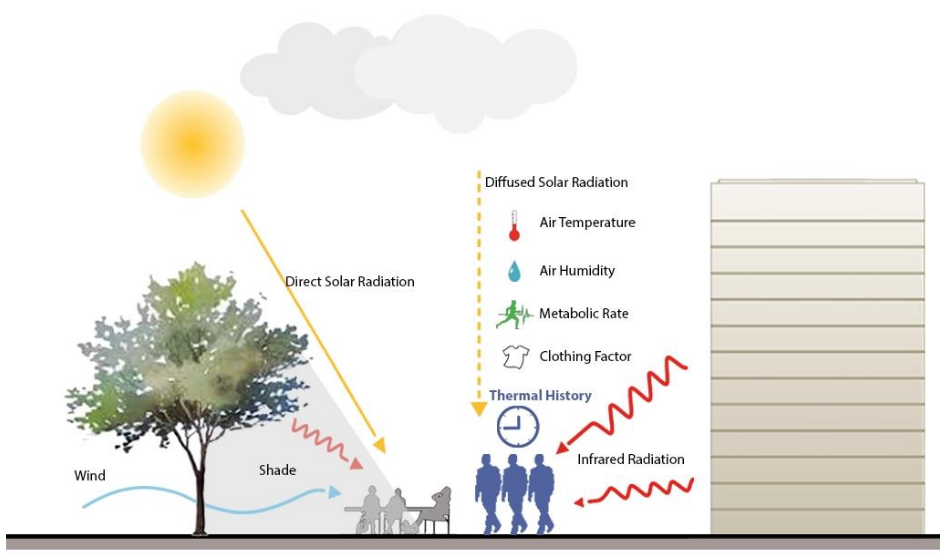



Figure 6. Environmental and user parameters (Pallavi Chidambaranath –India ¦ Transsolar ¦ KlimaEngineering, n.d.)

## 2.3. Thermal Perception

To ensure cities' resilience and environmental sustainability, it is imperative to adopt mitigation strategies prioritizing human-centered solutions in outdoor spaces (Rosso et al., 2022). Although assessing outdoor thermal comfort is essential, it remains a relatively recent area of research (Golasi et al., 2016). In previous chapters the human body's adaptation techniques were briefly mentioned. Beyond environmental variables, diverse thermal perceptions among individuals are influenced by factors such as personal characteristics (height, weight, age, gender), physiological acclimatization, behavioral and social adaptations, and personal expectations and preferences shaped by different climates (Golasi et al., 2016). Additionally, an individual's physical-behavioral adaptation, including factors like metabolic rate, activity, and clothing insulation, significantly shapes their thermal perception (Castaldo et al., 2017).

| Activity | Met units | W/m2 |
|---|---|---|
| Reclining | 0.8 | 39.0 |
| Seated | 1.0 | 48.8 |
| Standing | 1.2 | 58.6 |
| Walking (0.9m/s , 32km/h) | 2.0 | 97.6 |
| Walking (1.2m/s, 4.3km/h) | 2.6 | 126.9 |
| Exercising | 3.1 | 151.3 |

| Clothing | m2K/W | Icl |
|---|---|---|
| without Clothing | 0 | 0 |
| Slimmer doming (shorts, T-shirt, sandals) | 0.05 | 0.3 |
| Summer doming (trousers, shirt, shoes) | 0.08 | 0.5 |
| Spring clothing (trousers, shirt, jacket, shoes) | 0.11 | 0.7 |
| Winter clothing (trousers, sweeter, jacket, shoes) | 0.2 | 1.3 |

Figure 7. Values for Metabolic rate and Clothing Insulation

## 2.4. OTC Indices and applications

The 1980s witnessed a leap in research, cause by an improved knowledge of heat exchange physics and the development of computers, allowing the formulation of indices that were based in heat exchange of the human body (Coccolo et al., 2016). Thermal stress indices, categorized by their rationale, could be divided in three groups (Parsons 2003; NIOSH 1986). Firstly, there are rational indices based on heat balance equations, exemplified by the heat stress index (HSI) for warm weather and required clothing insulations (IREQ) for cold environments. The second group includes empirical indices founded on objective and subjective strain, such as the physiological strain index (PSI). Empirical indices, which are stated as linear regressions based on field research (on onsite monitoring and surveys) characterize human comfort for a given climate. These protocols are applied for the specificselect-ed locations, where they are defined and validated.(Coccolo et al., 2016) The third group involves direct indices measured from environmental variables, including apparent temperature (AT), operative temperature, and wet-bulb globe temperature (WBGT) (Blazejczyk et al., 2012).

Models for assessing human comfort and thermal stress are also distinguished in indoor and outdoor comfort models. While indoor comfort has been extensively studied and quantified due to the relative stability of indoor environments and the ability of the user to mechanically modify them, outdoor comfort creates challenges due to rapid environmental variability, especially in solar exposure and wind speed, but also, varying exposure times ranging from minutes to hours. The need for non-steady state models to quantify outdoor human comfort is emphasized, considering individual differences in thermal history, memory, and expectations, as well as the impact of metabolic rate variations on thermal sensation. Outdoor models are further classified into thermal indices, empirical indices, and indices based on linear equations (Coccolo et al., 2016).

1. In thermal comfort indices, there exist various thermal models, including the COMFA model, Universal Effective Temperature (ETU), Index of Thermal Stress (ITS), MENEX model, Physiologically Equivalent Temperature (PET), Predicted Mean Vote (PMV), Perceived Temperature (PT), New Standard Effective Temperature (SET*), and Outdoor Effective Temperature (OUT_SET*), as well as the Universal Thermal Climate Index (UTCI).
2. Empirical models include the Actual Sensation Vote (ASV), Thermal Sensation (TS), and Thermal Sensation Vote (TSV).
3. Indices based on linear equations, such as the Apparent Temperature (AT), Discomfort Index (DI) , Environmental Stress Index (ESI) and Physiological Strain Index (PSI), Effective Temperature (ET), Humidex (H), Heat Index (HI), Cooling power index (PE), Relative strain index (RSI), Wet Bulb Globe Temperature Index (WBGT), Wind Chill Index (WCI)

## Outdoor Comfort Indices

| Thermal Perception 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 |

Figure 8. Outdoor Thermal Comfort models¦ Adaptation to climate conditions

Outdoor Thermal Comfort (OTC) is evaluated through prominent indices such as PET, UTCI, PMV, and SET*. These indices were selected among all the OTC indices for their broad applicability and accuracy.

- Physiological Equivalent Temperature (PET) is designed to understand the impact of meteorological factors on perceptions of the person, signifies the air temperature without wind and solar influences. Recognizing PET's unsuitability for all hot and humid zones, mPET was developed to address limitations, incorporating adjustments for varied climates (Lin et al., 2018; Lin & Matzarakis, 2008; Hoppe, 1999).
- Universal Thermal Climate Index (UTCI), developed by the International Society of Biometeorology, adopts a Fiala multi-node model, encompassing 187 body nodes, to assess physiological responses across diverse outdoor thermal environments (Fiala et al., 2001).

- Standard Equivalent temperature (SET*), another widely used index, calculates the temperature in a hypothetical environment at 50% RH, suitable for moderate to hot climates, supported by 12 studies from 2001–19 (ASHRAE 55, 2010; Potchter et al., 2018).
- Predicted Mean Vote (PMV), originally an indoor quantification tool, transforms into an OTC index under the name "Klima-Michel-Modell." It adapts to outdoor conditions, accounting for weather data, radiation fluxes, and typical activity and clothing assumptions. The stationary nature of PMV, assuming constant climate conditions, leads to the calculation of more representative outdoor indices, such as PET and MOCI (Castaldo et al., 2017). PMV stands as the sole rational index lacking validation, while UTCI and PET have undergone comparisons against fully validated indices (de Freitas & Grigorieva, 2017).
- The prementioned indices have predominantly found application in temperate climate zones (Kumar & Sharma, 2020). The Mediterranean Outdoor Comfort Index (MOCI), introduced as an empirical tool, stems from an annual field survey in Rome. Using the ASHRAE 7-point scale and considering variables like air temperature, mean radiant temperature, relative humidity, wind speed, and thermal clothing insulation, MOCI predicts the mean value of thermal votes for outdoor environments in the Mediterranean region (Golasi et al., 2016).

| | | 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 |

Figure 9. Thermal Comfort models and climate, microclimate and human variables.

### Software

The computation of thermal comfort indices is a pivotal task for researchers seeking accurate results, and various indices have been developed based on heat balance and linear equations. Among the essential software tools, RayMan stands out, specifically designed for quantifying thermal comfort by calculating indices and Mean Radiant Temperature (MRT). This software integrates personal data, clothing choices, activities, and climate parameters to determine index ranges tailored to geographical locations (Matzarakis, Rutz, & Mayer, 2007). Notably, RayMan facilitates the calculation of widely used indices such as PMV, PET, UTCI, and SET*, with a particular emphasis on PET, which can also be computed using the heat balance equation (Kumar & Sharma, 2020)

| | PMV (-) | SET (°C) | UTCI (°C) | PET (°C) | MOCI(-) |
|---|---|---|---|---|---|
| ENVI-met and BioMet | X | | X | X | |
| RayMan | X | X | X | X | X |
| OTC model | | | X | X | |
| SOLWEIG | | | X | X | |
| UTCI Calculator | | | X | | |

Figure 10. OTC indices and softwares.

## 2.5. OTC Assessment Methods

Outdoor thermal comfort (OTC) studies have been explored through three main approaches. Initially, numerical simulations were used for OTC investigations. Subsequently, studies used a combination of subjective surveys and objective measurements, emphasizing the importance of both human perception and measurable data. Lastly, OTC assessment methods involved the evaluation of existing or prospective projects, contributing to the development of sustainable designs (Coccolo et al., 2016). In contemporary research, the combination of subjective surveys, objective measurements and user-centered participatory approaches remains should be a fundamental methodological tool for determining thermal comfort.

The assessment of OTC considers the impact of climate variables (global radiation, air temperature, relative humidity, and wind speed), microclimate factors (sky view factor, direct and diffuse radiation, mean radiant temperature, surface temperature, ground temperature, building's albedo, and ground albedo), as well as individual characteristics of pedestrians, including metabolic activity and clothing. Energy balance models, applicable to both outdoor and indoor environments, analyze pedestrian thermal sensations in complex urban settings. In contrast, simplified thermal indices focus on climate variables but overlook microclimate and pedestrian characteristics, offering a quicker but less detailed analysis of urban microclimates (Coccolo et al., 2016).

## 2.5.1 Qualitative Methods

The qualitative assessment of outdoor thermal comfort is approached through a constructivist methodology, recognizing the complexity of individuals' perceptions of outdoor areas and the need for a holistic understanding of their reality (Eslamirad et al., 2022). It has been recognized that theoretical thermoregulatory models developed for indoor environments are insufficient to describe outdoor thermal conditions, as outdoor environments are temporally and spatially variable. This recognition has led to an increased emphasis on empirical data obtained through field surveys on subjective human parameters in outdoor contexts (Nikolopoulou & Lykoudis, 2006).

Groundbreaking research by Nikolopoulou et al. in Cambridge, UK, involved large-scale interviews, considering subjective thermal sensations along with environmental and individual characteristics. The research highlighted the importance of the thermal environment while emphasizing the significance of psychological factors such as adaptation, environmental stimulation, thermal history, memory effect, and expectations (Eslamirad et al., 2022). Psychological adaptations were identified as having a greater impact than the thermal environment itself (Nikolopoulou & Lykoudis, 2006) .The influence of local microclimatic conditions on thermal sensation and comfort assessments is emphasized, and studies by Kenz et al. and Lenzholzer et al. highlight the dynamic and subjective nature of these assessments (Eliasson et al., 2007). Qualitative methods, like structured interviews, were used to design thermally comfortable urban public spaces, correlating thermal and spatial information to people's perceptions (Eslamirad et al., 2022). Additionally, research by Zacharias et al. explored the relationship between local microclimates and the level of use in urban spaces, while Auliciems argued for a comprehensive term, "thermal perception," to encompass physiological and psychological influences related to thermal conditions (Zacharias et al., 2001).

## 2.5.2. Quantitative Methods

Regarding quantitative methods for evaluating outdoor thermal comfort, there are several different approaches that include field measurements, surveys, and numerical simulations. Each of these methods offers a distinct perspective.

### Monitoring Campaigns

Field measurements, conducted through stable or portable sensors, are focused on the pedestrian-centric perspective within urban environments, dynamically measuring environmental parameters at individuals' height, particularly in areas inaccessible by car (Rosso et al., 2022). They are usually used to monitor the following urban microclimate variables:

Tair, air temperature [°C] ¦ RH, relative humidity [%] ¦ G, global solar radiation [W/m2] ¦ Ts, surface temperature [°C] ¦ illuminance [lux] ¦ $CO_2$ concentration [ppm] ¦ reflected radiation by pavements [W/m2] ¦ wind velocity [m/s] and direction [°]

### Survey

Surveys take various forms, including experimental questionnaires distributed on-site or available online. In their study, Eslamirad et al. (2022) structured survey questions along three main axes: Personal Background, Preferred Summer Weather Conditions, and Location Use. Other participatory surveys adopted categories such as Independent Variables, with participants' responses on thermal comfort, air pollution, and noise pollution serving as Dependent Variables. These surveys delved into the perception, comfort, and tolerability of traveling pedestrians concerning thermal conditions, air pollution, and acoustic pollution. Additionally, respondents were asked about their perspectives on potential design strategies to enhance the surrounding environment in passage areas (Piselli et al., 2018). Various approaches on-site included questions about individual characteristics, physical signs (such as sweating), and thermal perception to assess if respondents had a complete understanding of the thermal environment (Huang et al., 2021). Other studies incorporated factors like activity level and clothing to establish correlations between the results and the subjects' thermal perception (Ouis et al., 2023); (Stazi et al., 2017)).

## Statistical Analysis

Statistical analysis is a key strategy in understanding and interpreting data, using various mathematical techniques adjusted to the nature of the data and research objectives. In the context of outdoor thermal comfort determination, statistical analysis is essential to processing personal and thermal sensation data to measure the thermal environment. Kumar and Sharma (2020) emphasize the use of Kruskal–Wallis H test, Shapiro-Wilk test, and non-parametric Spearman correlation test to check data distribution and correlate thermal perception with meteorological data. Further analysis involves ANOVA, t-tests, and regression methods, facilitated by tools like SPSS software, to determine neutral temperature and assess the impact of microclimate parameters on thermal perceptions.

Several studies exemplify the application of these statistical methods. Eslamirad et al. (2022) utilize Pearson correlation to identify significant variables correlated with Predicted Mean Vote (PET), emphasizing its strength in revealing associations between factors like metabolic rate and clothing insulation. Palusci et al. (2023) employ Python scripts and GIS software, mapping cities and assessing validity through statistical metrics like R2 and RMSE. (Haeri et al., 2023) calculate R2 and RMSE to evaluate simulation accuracy and explore discrepancies, highlighting the significance of statistical metrics in validating models. (Chatzipoulka et al., 2016) utilize Pearson correlation and linear regression to unravel urban geometry relationships, demonstrating the aptness of these statistical tests in describing linear connections. (Ouis et al., 2023) showcase a comprehensive use of SPSS software, employing descriptive statistics, regression analysis, and the Kruskal-Wallis H test to understand the impact of microclimate parameters on thermal sensations.

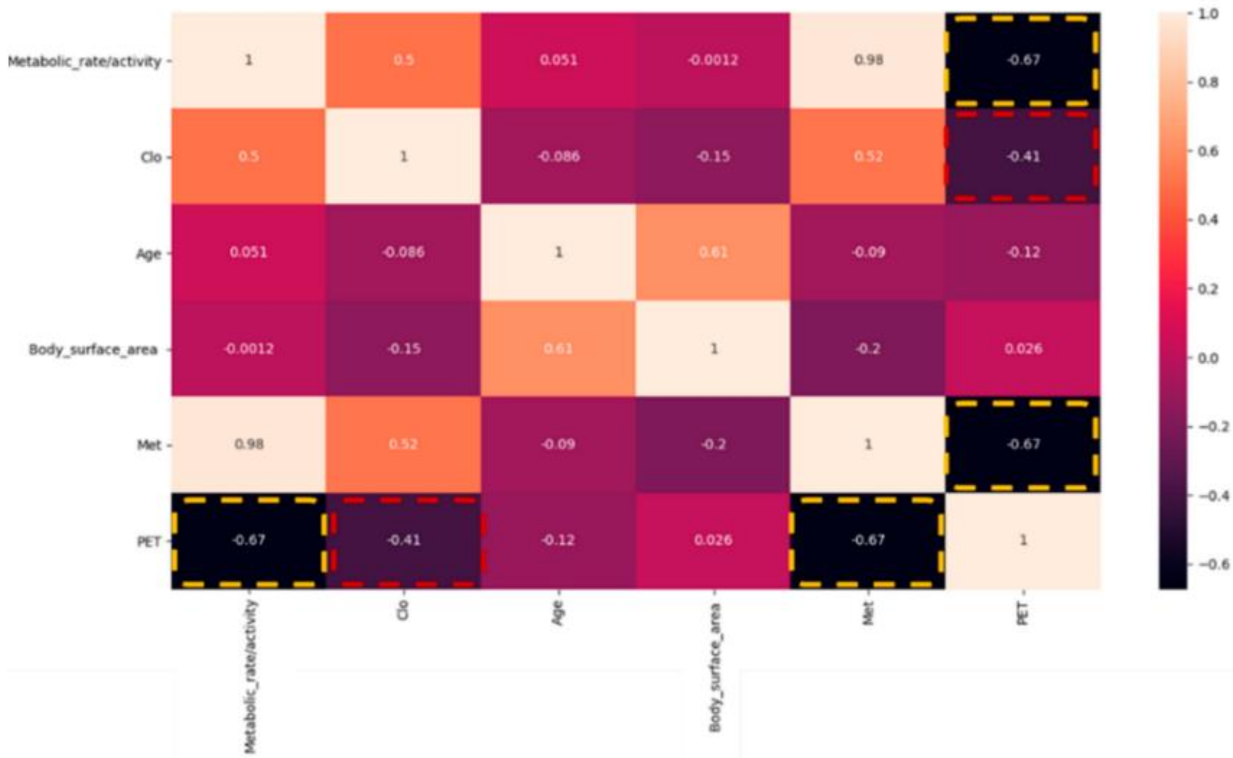



Figure 11.Dependency values between personal factors and PET (Eslamirad et al., 2022).

## Tools

Several models that target smaller scales have been developed to enhance fidelity, in the field of microscale modeling for pedestrians. RayMan, introduced in 2007, presented a tool achieving an RMSE of 12.6 °C against measurements. However, limitations were identified, particularly in handling long-wave radiation exchange, impacting accuracy at low sun angles(Dogan et al., 2021). Another model, TUF-3D, introduced in the same year, incorporated short-wave and long-wave radiative fluxes, reporting a wall-averaged surface temperature RMSE of 4.0 °C. SOLWEIG, introduced in 2010, considered both short- and long-wave radiant fluxes, achieving an RMSE of 4.8 °C for Tmrt. MUST, a voxel-based Model for Urban Surface Temperature, demonstrated daytime RMSE of about 26 W/m2 and nighttime RMSE of 20 W/m2. VTUF-3D, an extension of TUF-3D, integrated radiative fluxes from vegetation. Model comparisons revealed that ENVI-met systematically underestimated Tmrt in specific conditions.(Dogan et al., 2021)

Efforts to integrate long-wave radiation exchange models into building energy simulation packages were made by coupling EnergyPlus with ENVI-met and CitySim. These studies highlighted significant impacts on heating and cooling loads, with reported differences in external surface temperatures of 6 and 10 °C, respectively. In 2020, Luo et al. implemented a more detailed long-wave radiation exchange model directly into EnergyPlus, addressing the previously unaccounted long-wave heat exchange between buildings. This enhancement allowed users to estimate long-wave heat exchange with appropriate view factors, minimizing modeling complexity. For microclimatic simulations of POS environmental conditions, Rhinoceros V6 + Ladybug Tools 1.3.0 and ENVIMET v.5 are used by Blanco Cadena et al., 2023.

ENVI-met, a widely used 3D urban climate modeling tool, simulates microclimatic effects considering buildings, vegetation, façade materiality up to three layers and other objects in the built environment.Despite its limitations, ENVI-met is extensively employed for multifactorial analysis, as demonstrated by Ayyad and Sharples's study validating its suitability for relative parameter changes (Tabatabaei & Fayaz, 2023). Another extension ENVI-met V4.4-Science, is used to analyze External Air Temperature (Ta), Relative Humidity (RH), Mean Radiant Temperature (Tmrt), and Wind Speed (WS) at pedestrian level (1.5 m), offering a holistic approach (Lassandro & Di Turi, 2019).

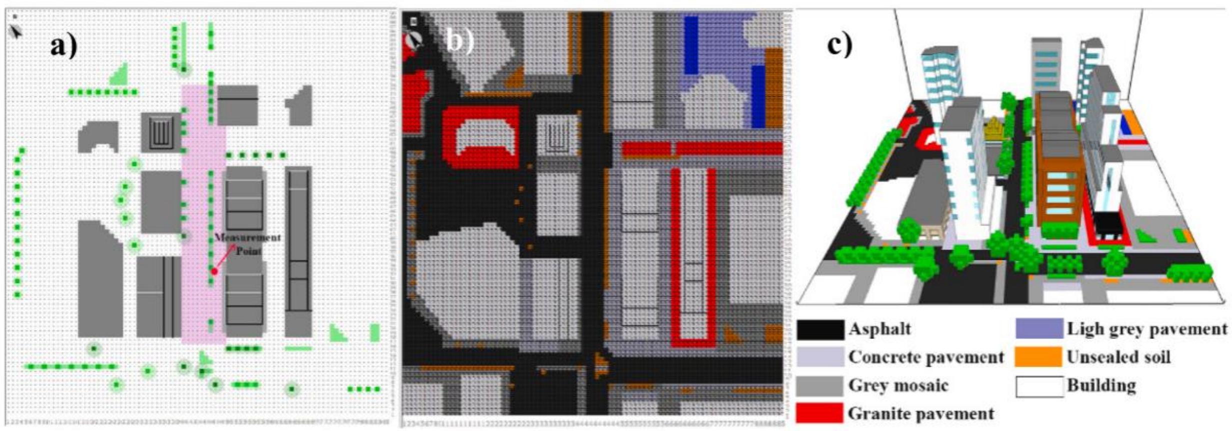



Figure 12.Modelled study area in Envi-met: a) plan view, b) plan view with soil profile, c) geometric model(Salata et al., 2015).

### Studies

Quantitative studies were conducted to explore various aspects of outdoor thermal comfort, using diverse methodologies and focusing on different parameters. In the first study conducted in Xi'an, China, four representative open spaces in a children's park were selected for investigation. The methods involved meteorological measurements and questionnaire surveys, emphasizing children's outdoor thermal comfort. Moreover, the results from studies on materials and built facilities provide practical implications. For instance, the identification of surface materials exceeding burn thresholds under sunlight suggests the potential application of high near-infrared paint to mitigate surface temperatures (Huang et al., 2021).

The second study used a comprehensive methodology combining microclimate monitoring with longitudinal survey campaigns in two pocket parks. This approach allowed for the assessment of both physical-objective and subjective parameters, revealing differences in microclimate and human perception between urban and pocket park environments. The results highlighted improved user perception within the park compared to immediate streets, emphasizing the significance of subjective assessment alongside microclimate analysis (Rosso et al., 2022).

In the third study, a multi-step approach was used to evaluate travelers' comfort levels, urban heat island intensity, and the effectiveness of mitigation techniques. The methodology included continuous in-situ monitoring, surveys, validated microclimate simulation, and comparative analysis of mitigation scenarios. Results indicated significant impacts of environmental variables on thermal perceptions and tolerability, with proposed strategies such as increased greenery and air purification systems (Piselli et al., 2018).

The fourth study, conducted in the Netherlands, involved five phases, including ENVI-met simulations and climate change impact analysis. The results recommended courtyard orientations based on climate considerations, with N-S orientation suitable for hot climates and E-W orientation favorable for colder regions. Heat mitigation strategies, such as higher albedo materials, water pools, and vegetation, were analyzed for their impact on mean radiant temperature and air temperature. The research suggested water pools and green areas as the most effective heat mitigation strategies for urban blocks in the Netherlands (Taleghani et al., 2014).

### 2.5.3. Mixed methods

In outdoor thermal comfort, the integration of both qualitative and quantitative methodologies is paramount to comprehensively understand the multifaceted nature of thermal perception. Introducing long-term perception through the dimensions of 'short-term' and 'memory' adds depth to the exploration of thermal influences (Eliasson et al., 2007). Examining people's perceptions through structured interviews, as demonstrated by Klemm et al. (2015), further refines the understanding of thermal perception in Dutch urban squares. The alignment between people's thermal perceptions and the results obtained from measurements and simulations reinforces the robustness of the employed methodology (Klemm et al., 2015). Insights into the contact time between interactive facilities and children in various environmental conditions offer guidance for designing well-shaded areas, ensuring the safety and well-being of children during outdoor activities (Huang et al., 2021).

Key findings of a particular mixed method approach, provide insights on critical aspects affecting outdoor thermal comfort. Notably, when activity levels are high, clothing plays a negligible role in influencing thermal comfort, emphasizing the multifaceted nature of comfort perception (Eslamirad et al., 2022). The consideration of visual aspects, including enjoyment, openness, enclosure, and green spaces, in the choice of a location adds a layer of complexity to the design and planning of urban spaces aiming for outdoor comfort (Eslamirad et al., 2022).

## 2.6. OTC and perceived aesthetic quality

When it comes to urban design, the perceived aesthetic dimension of the built environment should be an important factor to take into consideration, the biggest challenge of this being the presence of clashing conceptions of what we understand to be aesthetically pleasing (Prieto & Oldenhave, 2021).

The complexities of outdoor thermal comfort intertwine with microclimatic elements such as air temperature, humidity, wind velocity, mean radiant temperature (Tmrt), and thermal comfort indices, all influenced by urban geometry and greenery (Lau & Choi, 2021b). While microclimatic conditions account for a substantial portion of the variance in the relationship between objective and subjective thermal comfort, psychological adaptation emerges as a vital factor, incorporating aspects like naturalness, expectations, experience duration, perceived control, and environmental stimulation (Wu et al., 2020).

Lau and Choi's (2021a) innovative study diverges from conventional approaches, integrating perceived aesthetic quality into the complex interplay between human thermal perception and microclimatic conditions in outdoor settings. The findings underscore the pivotal role of aesthetic satisfaction in influencing thermal sensation, revealing higher Thermal Sensation Votes (TSVs) among respondents dissatisfied with aesthetic quality compared to those expressing neutral or positive sentiments (Lau & Choi, 2021b). This research contributes a holistic understanding of the aspects that shape human thermal perception, by revealing all the interrelationships between environmental conditions, aesthetics, and thermal comfort in outdoor spaces.

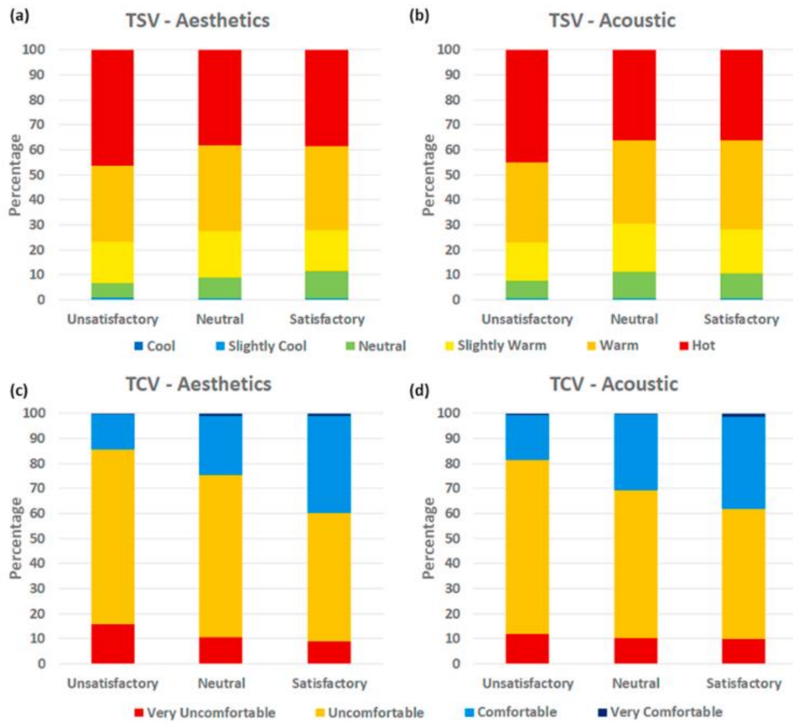



Figure 13.Distribution of the TSV according to satisfaction of (a) aesthetic and (b) acoustic quality. Distribution of the TCV according to satisfaction of (c) aesthetic and (d) acoustic quality **(Lau & Choi, 2021a)**.

## 2.7. Conclusions

In conclusion, the exploration of outdoor human thermal comfort has revealed notable gaps in outdoor thermal comfort assessment and the design practices.

Psychological Adaptation: Current outdoor human thermal comfort models lack consideration for psychological factors such as a person's "thermal history" and pedestrian expectations, which, if incorporated, could significantly enhance result validity (Coccolo et al., 2016).

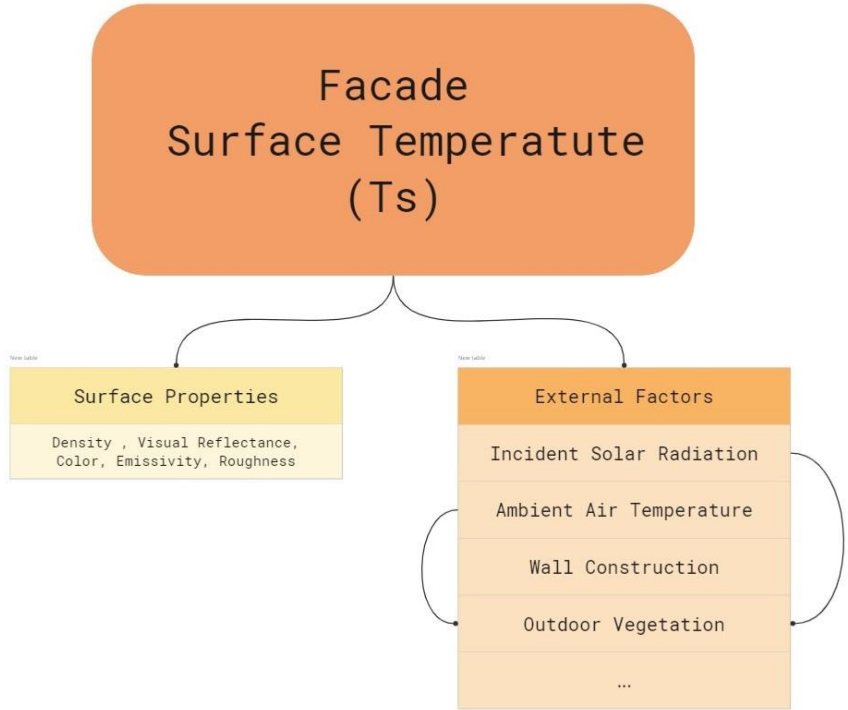
Bridge Between Energy Models and Empirical Models: While energy models offer a "universal" approach to quantify human comfort, empirical models are skilled at addressing thermal perception, including individual preferences and sensitivity to specific stimuli. Establishing a cohesive link between these two approaches is crucial for a comprehensive understanding (Coccolo et al., 2016).

Urban Climatic Maps vs. Architectural Practice: While urban climatic maps guide city planning, the integration of outdoor human comfort analysis into architectural practice remains limited. Bridging this gap requires further development and incorporation of comfort considerations into design practices (Ng and Ren, 2015).

Architecture and Aesthetic Satisfaction: Research emphasizing the connection between aesthetic satisfaction and subjective thermal comfort is essential for urban design aimed at fostering human adaptation to the built environment. Understanding the role of aesthetics contributes to creating comfortable and adaptive urban spaces (Lau & Choi, 2021).

# 3 OTC & Façade Influence

The surface temperature of building façades can be influenced by many factors, broadly categorized into 'external factors' and 'properties of façade's surface.' External factors include the environmental parameters (air temperature, relative humidity, mean radiant temperature, air velocity and direction, solar radiation), urban components (such as vegetation, water bodies, crowds, cars, paving), indoor conditions, the orientation of the building façade, the window to wall ratio of the façade, the properties and materials of the building. Simultaneously, properties of the façade surface, such as density, specific heat capacity, emissivity, color, albedo, absorptivity, transmittance, and roughness, play a crucial role. The way these elements interact, including their combinations, can lead to variations in the heat transfer mechanisms, namely conduction, convection, and radiation, ultimately determining the façade surface temperature. Certain external factors can strongly affect others, and the quantitative dynamics of these factors may change rapidly. For instance, building orientation affects solar irradiance, surrounding vegetation influences ambient air temperature and air velocity, and solar radiation incident on the façade can fluctuate swiftly due to cloud coverage, all contributing to the façade's surface temperature dynamics (Azarnejad & Mahdavi, 2018).




## 3.1. Existing studies on façade influence on OTC

The current trend in envelope design emphasizes the use of cool materials, characterized by high thermal emittance and solar reflectance, may effect on lowering surface temperature, particularly under peak solar radiation conditions (Santamouris, Synnefa, & Karlessi, 2011). This effect depends on various factors such as urban fabric, canyons, geometric characteristics, and land use (Wang et al., 2015). The materials' role extends to enhancing thermal behavior, minimizing energy consumption, and attenuating both internal and external temperatures in buildings (Lassandro & Di Turi, 2019). Conversely, the use of dark-colored and inappropriate façade materials, along with insufficient vegetation and urban planning choices, contributes to the urban heat island effect and elevates Land Surface Temperature over the long term (Tabatabaei & Fayaz, 2023). Studies on façade geometry involve simulations examining variables such as building orientation, height, distances between buildings, and street canyon dimensions, exploring their impact on thermal conditions (Salvati et al., 2022).

Material properties studies examine the impact of albedo, emissivity, absorption, and thermal performance of façade materials, considering diverse contexts such as road, pavement, roof, and walls (Fahed et al., 2020; Abrahem et al., 2020). The evaluation of solar reflectance index (SRI) for horizontal urban surfaces, when compared to vertical ones, suggests limited possibilities for improvement in thermal performance (Tabatabaei & Fayaz, 2023). Mitigation strategy studies explore the effectiveness of cool materials, green roofs, and green walls in enhancing reliability, adaptive capacity, and mitigation ability in the built environment (Lassandro & Di Turi, 2019). Additionally, research on historic sites examines the impact of both existing and new materials with different thermal properties, employing a combination of surveys, simulations, and measurements to assess thermal comfort parameters (Rosso et al., 2018). These studies collectively contribute valuable insights into the multifaceted influences of façade characteristics on outdoor thermal comfort.

## 3.2. Methods & Results

In this chapter, we analyze recent advancements in the field of outdoor thermal comfort (OTC) with a focus on the influence of facade characteristics. The chapter categorically presents a concise overview of studies based on three primary objectives: material properties, facade geometries, and mitigation strategies.

### Studies on Façade Material Properties:

1. Tabatabaei & Fayaz (2023) investigate facade materials' impact on the local microclimate, with the use of retro-reflective materials (cold color of reflective coatings) on facades and paving. Studying air temperature, relative humidity, wind speed, and mean radiant temperature for each material, they find that surface reflectivity influences both surface and air temperatures. Higher solar reflection and lower emissivity effectively reduce surface and air temperatures. Thermal mass also plays a role, with low-density materials exhibiting higher surface temperatures. Living walls, through permeability and evaporation, reduce air temperature. Simulation indicates that higher PET values occur when the mean radiant temperature is reaching its peak. (Tabatabaei & Fayaz, 2023).
2. Hassan et al.'s (2019) work on optimized building formations in Baghdad (linear pattern of low-rise buildings) is extended by Abrahem et al. (2020). Simulating low-rise and high-rise buildings with various facade materials, clay bricks, thermo-stone, glazed panels, and concrete blocks, they use ENVI-MET for analysis. The study analyzes factors like air temperature, specific humidity, wind speed, mean radiant temperature, and Predicted Mean Vote (PMV). Results indicate similar thermal comfort indexes for low-rise buildings, with glazed panels outperforming other materials in PMV values. On the contrary the brick façade had the highest PMV value, related to extreme thermal discomfort. Building height and facade material have negligible effects on wind speed (Abrahem et al., 2020).
3. Rosso et al. (2018) employ PMV and MOCI to assess outdoor thermal comfort, testing various materials' performances (Bianco Carrara marble and IR colored mortar, white, red and gray) and designing new cement-based materials aesthetically similar but with better thermal properties. The new materials should be tested in order to be suitable for applications in historical buildings. Results have showed that white mortar is the most reflective material. Recommendations include using cool materials like Bianco Carrara marble for ground surfaces. Albedo increase in building envelopes contributes to thermal comfort by reducing reflected radiation towards built elements (Rosso et al., 2018).

### Studies on Façade Geometry:

1. Lassandro & Di Turi (2019) present a novel method to evaluate retrofitting strategies for building opaque envelopes in response to rising summer temperatures. Their approach considers both building and urban dimensions, assessing the dynamic behavior of opaque envelope strategies. The study emphasizes adaptability to increasing temperatures at both levels (Lassandro & Di Turi, 2019).
2. Khraiwesh & Genovese (2023) integrate a detailed numerical and physical analysis on indoor and outdoor quality, analyzing design parameters' effects on OTC and energy use intensity (EUI). Their study of 59 residential urban block designs in Irbid, Jordan, reveals in what level street canyon orientation, width and length as rectangular and square, building orientation, block orientation, building combination, building height, facade length, built-up percentage (BUP), and setbacks influence thermal comfort. The study also considered the influence of various climatic factors under different weather conditions, including annual, summer, and winter scenarios, across distinct spatial zones. Wider street canyons exhibit lower wind speeds during the night. Factors such as building form, orientation, and setbacks play crucial roles in shaping the urban microclimate (Khraiwesh & Genovese, 2023).

3. Salvati et al. (2022) primary objectives, using a London urban area as a case study, were to: 1) Quantify Urban Canopy Air (UCA) through both experimental and numerical methods in real urban canyons. 2) Assess how the reflectance of materials on roads and façades, as well as their spatial distribution, influences UCA. 3) Understand the implications of high reflectance materials on the microclimate at street level and outdoor thermal comfort during heatwaves in urban canyons. 4) Evaluate the effects of high reflectance materials on indoor thermal conditions within buildings in urban canyons during the summer. Results indicate the complex interplay of reflectivity, canyon geometry, and solar availability. By lowering the reflectivity of the lower portion of façades better levels of outdoor thermal comfort could be achieved, diminishing solar reflections toward pedestrians and mean radiant temperature. High road reflectance increases albedo but worsens outdoor comfort, while façade reflectivity influences street-level thermal comfort during heatwaves (Salvati et al., 2022).

**Studies on Mitigation strategies:**

1. Fahed et al. (2020) explore multiple urban heat island (UHI) mitigation scenarios in a dense Lebanese district of Dora city. The study focuses on increasing green surfaces, replacing existing surfaces with high albedo materials, and implementing water sources. Statistical analysis reveals the relationship between sky view factor (SVF) and ambient/radiant temperatures. Results highlight the need to combine white variants with blue and green scenarios to counterbalance the external discomfort caused by high albedo materials (Fahed et al., 2020).
2. Dietrich (2018) developed a numerical model capable of simulating multiple urban heat mitigation measures simultaneously. It also took measurements from three different spots in a street canyon: one at pedestrian level near the south façade, one in the middle of the street, and one at the north façade. These measurements aimed to illustrate the variations in Mean Radiant Temperature (Tmrt) influenced by the surface temperatures of facades. It highlighted the dominance of solar reflection over material temperature for facade materials, providing insights into optimizing material choices for thermal comfort.

## 3.3. Conclusions

In summary, existing literature extensively explores the correlation between outdoor thermal comfort and building facades, emphasizing material characteristics, urban design and futureproof strategies. However, a critical gap persists as studies overlook the connection between facade influences and pedestrians' subjective thermal perception. While simulations and measurements offer valuable insights, a comprehensive understanding demands qualitative methods. The absence of such approaches limits our chance to holistically assess the impact of the built environment on thermal sensation. Future research should integrate qualitative methodologies to enrich our understanding, ensuring a more comprehensive exploration of how facades contribute to the thermal comfort of individuals in outdoor spaces.

| Author | Paper | Date | Location | Thermal Index | Methods | Software | Testing Variables |
|---|---|---|---|---|---|---|---|
| Tabatabaei Soha S,Tabatabaei Soha S | The effect of facade materials and coatings on urban heat island mitigation and outdoor thermal comfort in hot semi-arid climate | 2023 | Shiraz, Iran | PET | • Field Measurements<br>• Simulations | Envi-met | • Material properties<br>• Surface Temperature |
| Mohammad Taleghani, Martin Tenpierik , Andy van den Dobbelsteen , David J. Sailor | Heat in courtyards: A validated and calibrated parametric study of heat mitigation strategies for urban courtyards in the Netherlands | 2014 | Netherlands | * | • Field Measurements<br>• Simulations | Envi-met | • Orientation<br>• Albedo<br>• Vegetation<br>• Water Bodies |
| Nasim Eslamirad , Abel Sepúlveda , Francesco De Luca, Kimmo Sakari Lylykangas | Evaluating Outdoor Thermal Comfort Using a Mixed-Method to Improve the Environmental Quality of a University Campus | 2022 | Tallinn University | PET | • Field Measurements<br>• Simulations<br>• Interviews<br>• Online surveys | Envi-met | • Air temp.<br>• Wind Speed<br>• Relative Humidity<br>• Activity level<br>• Clothing Insulation<br>• Height<br>• Weight |
| Udo Dietrich | Urban street canyons - Impact of different materials and colours of facades and ground and different positions of persons on outdoor thermal comfort | 2018 | Bern, Switzerland | UTCI | Numerical analysis | * | • Material properties façade<br>• Material properties ground<br>• Sky view factor |
| Afef Ouis , Nassira Benhassine , Fatih Canan | Outdoor thermal perception in the semi-arid climate of Constantine, Algeria: A field survey during the post-COVID-19 | 2023 | Costantine, Algeria | PET<br>TSV | • Field Measurements<br>• Simulations<br>• On-site surveys | Envi-met | * |
| Boze Huang, Bo Hong, Yu Tian, Tingting Yuan, Meifang Su | Outdoor thermal benchmarks and thermal safety for children: A study in China's cold region | 2021 | Xi'an, China | UTCI<br>TSV<br>NUTCI | • Field Measurements<br>• Simulations<br>• On-site surveys | Rayman | • Physical characteristics<br>• Clothing Insulation<br>• Exposure time<br>• Sky view factor |
| Paola Lassandroa, Silvia Di Turi | Multi-criteria and multiscale assessment of building envelope response-ability to rising heat waves | 2019 | Bari, Italy<br>Tunis<br>Athens | HRI | Simulations | EnergyPlus and Envi-met | • Façade albedo (cool materials)<br>• Green Roof<br>• Green wall<br>• Tmrt<br>• Ts |
| C. Pisellia, V.L. Castaldo, I. Pigliautile, A.L. Piselloa, F. Cotana | Outdoor comfort conditions in urban areas: On citizens' perspective about microclimate mitigation of urban transit areas | 2018 | Perugia, Italy | PET | • Field Measurements<br>• Simulations<br>• On-site questionnaires<br>• Online surveys | Envi-met | • Vegetation<br>• High albedo surface (0.8)<br>• High albedo surface (0.7)<br>• Concrete surface<br>• PV asphalt<br>• PV trees |
| Federica Rosso , Iacopo Golasi, Veronica Lucia Castaldo, Cristina Piselli, Anna Laura Pisello, Ferdinando Salata, Marco Ferrero, Franco Cotana, Andrea de Lieto Vollaro | On the impact of innovative materials on outdoor thermal comfort of pedestrians in historical urban canyons | 2018 | Rome, Italy | MOCI<br>PMV | • Field Measurements<br>• Simulations | Envi-met | • Solar reflectance<br>• Emissivity<br>• Conductivity |
| Tara Haeri, Norhaslina Hassan , Amirhosein Ghaffarianhoseini | Evaluation of microclimate mitigation strategies in a heterogenous street canyon in Kuala Lumpur from outdoor thermal comfort perspective using Envi-met | 2023 | Kuala Lampur | PET | • Field Measurements<br>• Simulations | Envi-met | • Albedo on façade<br>• Albedo on ground<br>• Evaporative ground<br>• Green<br>• Mixed system<br>• Ts |

Figure 14. Main papers on OTC assessment and facade influence, methods and tools.

# 4 Case Study

## 4.1. Milan Analysis

### Population

Milan, a prominent city in Italy, has a population of approximately 1.4 million, while its metropolitan area is home to 3.22 million residents. The continuously built-up urban area, extending beyond administrative boundaries into Switzerland, stands as the fourth largest in the EU, accommodating 5.27 million inhabitants. The broader Milan metropolitan area, also known as Greater Milan, is estimated to have a population between 4.9 million and 7.4 million, solidifying its position as the largest metropolitan area in Italy and one of the largest in the EU. Functioning as the economic capital of Italy and a global financial center, Milan's influence resonates widely. The population growth from 3,506,838 in 1988 to 6,402,051 in 2013 underscores its dynamic development, with an average annual increase of 2.5% since 2003 (ATLAS OF URBAN EXPANSION, n.d.)

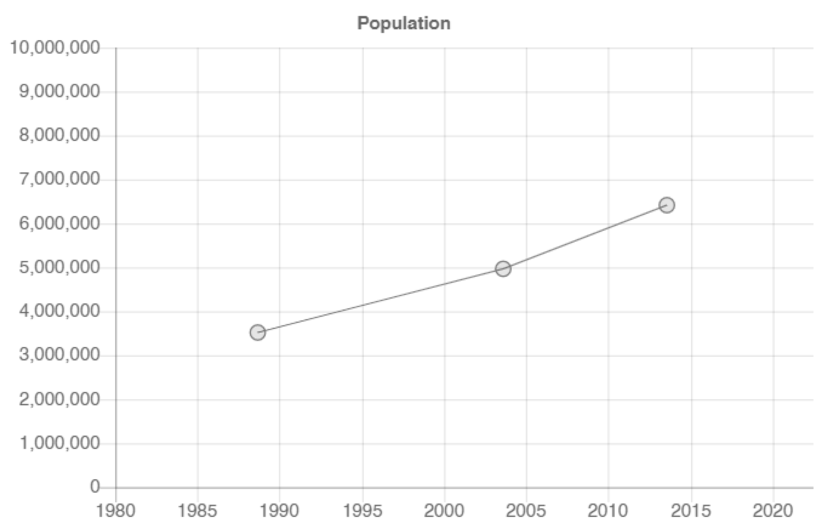



Figure 15. Milan's population(ATLAS OF URBAN EXPANSION, n.d.).

### Built Environment

Urban planning regulations in Milan are enforced through territorial and municipal master plans, along with regulations on building construction activities. The urban development history of Milan, marked by Beruto's plan in 1889, led to the destruction of Spanish walls and the creation of a new city expansion strip. The plan introduced a regular network of streets and squares, emphasizing large blocks, frontal facades alignment, and internal courtyards. The following urban plans reflected varying morphologies and neighborhood designs, showing the evolving urbanistic planning of Milan. The introduction of Beruto's plan brought a strategic linear grid street system with roundabouts, facilitating continuous connections between districts and enabling the city's expansion (*URBAN HISTORY FROM MEDIOLANUM TO MILAN – EVOLUTION OF MILAN'S URBAN PLANNING AND MORPHOLOGY - Issuu*, n.d.)

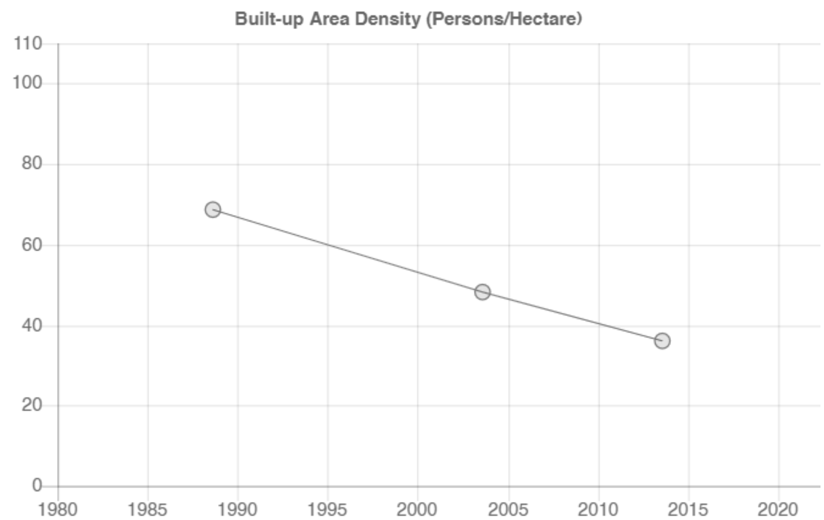



Figure 16. Milan Built-up Density (ATLAS OF URBAN EXPANSION, n.d.).

Analyzing Milan's expansion from 1990 to 2014, the average road width in the expansion area was 5.02 meters, contrasting with 8.36 meters in the pre-1990 area. The share of built-up area occupied by roads in the 1990-2014 expansion area was 18%, while it was 21% in the pre-1990 area. Additionally, the average block size in the 1990-2014 expansion area was 7.1 hectares, compared to 3.9 hectares in the pre-1990 area (ATLAS OF URBAN EXPANSION, n.d.). Examining the city's spatial characteristics, Milan presents a flat or contour-less terrain with a radial pattern, converging roads at the city center (*Milan, Italy - The Study of City Pattern _ PPT*, n.d.).

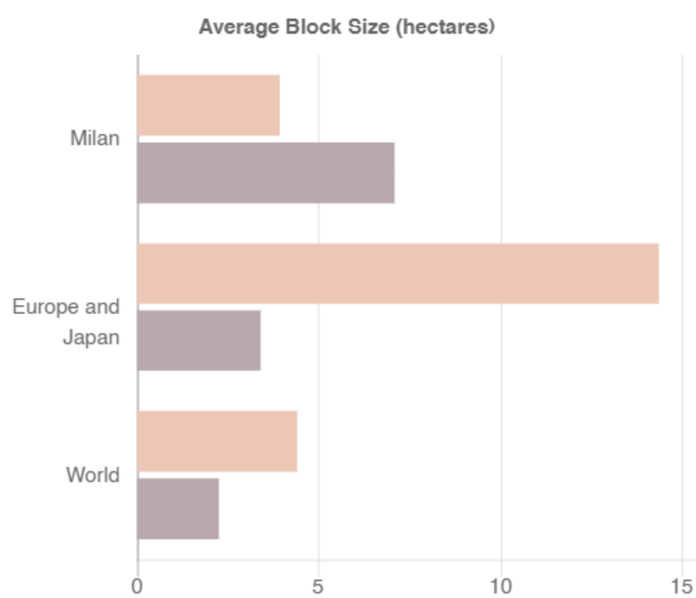



Figure 17. Milan's Average Block Size compared to Europe and world(ATLAS OF URBAN EXPANSION, n.d.).

## 4.1.1 Key causes of thermal Discomfort

The climatic analysis of Milan, Italy, reveals a Cfa - Köppen-Geiger climate type and falls under climate zone E, according to the Italian decree D.p.r 4124 (Beck et al., 2018). Milan is identified as an area susceptible to critical simultaneous Sustainable Local Overheating Densities (SLODs), ranking among the top three European countries at risk on an overheated planet (UNEP, 2021). This vulnerability is attributed to factors such as the high average population age, intense air pollutant concentrations, elevated summer temperatures, and high exposure as one of the most populated and densely populated municipalities in Italy (Blanco Cadena et al., 2023).

Stewart & Oke challenge traditional urban and rural area classifications, proposing the Local Climate Zones (LCZ) scheme, which includes 17 categories based on specific parameters for classifying urban areas (Palusci et al., 2023). The city of Milan falls under Level 2 in the Local Climate Zone (LCZ) map classification, characterized as a compact midrise area with buildings ranging from 3 to 9 stories. This zone features few or no trees, and the land cover is predominantly paved, with construction materials primarily consisting of stone, brick, tile, and concrete. In the context of Milan, the Urban Heat Island (UHI) phenomenon is prominent at every station, particularly during wintertime, with the compactness of urban tissues playing a significant role (Palusci et al., 2023).

A proposal to increase Milan's green canopy to mitigate urban heat and pollution emphasizes the current deficiency, standing at 7 percent of the urban area compared to northern European cities like Frankfurt and Amsterdam, where green coverage exceeds 20 percent (Barry, 2018). Milan's limited wind flow, compounded by its proximity to the Alps, hinders the dispersion of pollutants trapped by temperature inversions, where a layer of cool air is confined by a warmer layer (Barry, 2018).

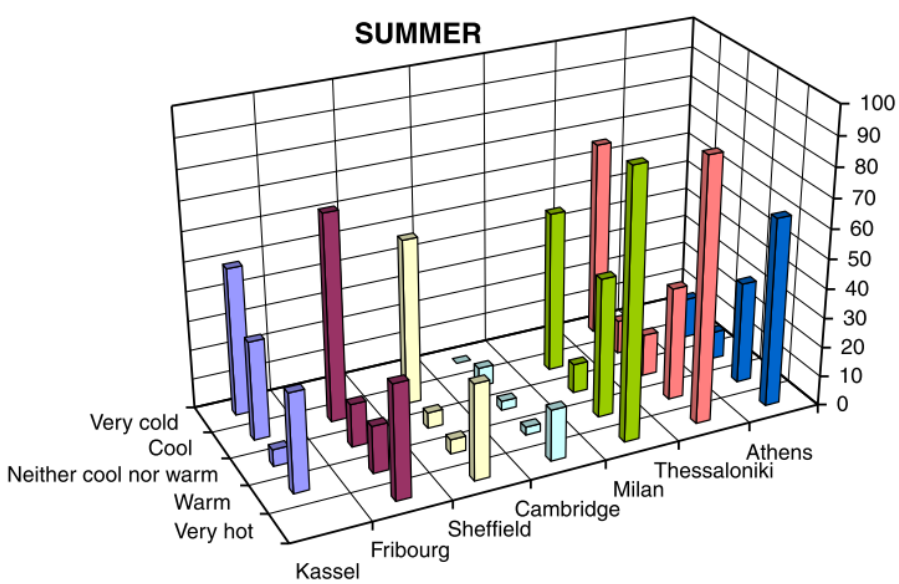



Figure 18.Percentage distribution of responses to overall discomfort, and evaluation of the thermal sensation, for the different cities **(Nikolopoulou & Lykoudis, 2006)**.

## 4.2. Current Standards and Regulations

In 1999, building regulations in Milan outlined specific criteria, including restrictions on the surface area covered by buildings, limiting it to 60% of the lot area, with occupancy not exceeding 90% in certain zones (Regolamento Edilizio Previgentetrans.It.En, n.d.).

The 2014 regulations introduced considerations for partition masonries, urban volume, building height, and other parameters for town planning purposes (Town Planning Scheme Regulatory Plan, n.d.).

### Urban Block:

1. Covered-occupied spaces must not exceed 60% of the relevant lot area (Regolamento Edilizio Previgentetrans.It.En, n.d.).
2. The occupied surface area should not exceed 90% in zones A and B, and 80% in other homogeneous zones. The surface must have a continuous and compact character (Regolamento Edilizio Previgentetrans.It.En, n.d.).

### Building Height, Orientation, Setback, Materials, Facade, and GFA:

1. Partition masonries between Ancillary Areas and Gross Floor Area will be considered up to the middle of the common wall.
2. Urban Volume (cbm) is obtained by multiplying Gross Floor Area by urban height for town planning purposes.
3. Building Height (m) is the maximum height among different fronts.
4. Urban Height (AU) is prearranged height per town planning scheme.
5. Height Line (LH) is the line formed by the intersection of the exterior of the structural ceiling of the last habitable floor and the external wall.
6. Building Projection Plane (IL) is the threshold within which construction is permitted, passing through the Height Line (LH) (Town Planning Scheme Regulatory Plan, n.d.).
7. Maximum height for certain buildings is understood as the existing height, increased if necessary for attic residential retrieval (Town Planning Scheme Regulatory Plan, n.d.).
8. In Unitary Front Urban Fabric, construction must align with the lowest adjacent building's height line. The bonus can be used for increased Gross Floor Area Ratio (Town Planning Scheme Regulatory Plan, n.d.).
9. Construction within courtyards in Consolidated Urban Fabric (TUC) should be shorter or equal to pre-existing buildings (Town Planning Scheme Regulatory Plan, n.d.).
10. New construction setback requirements and usage of resulting setback area for greenery, pedestrian paths, or bicycle parking (Comune di Milano, 2014).
11. Minimum distances between buildings and property boundaries, with exceptions for window fronts (Comune di Milano, 2014).
12. Courtyards defined for ventilation and lighting purposes, with setback checks for walls (Comune di Milano, 2014).
13. Setback areas must be mainly intended for greenery or pedestrian use (Comune di Milano, 2014).

### Courtyards and Greenery:

1. Courtyard defined as an area within blocks instrumental to lighting and ventilation (Town Planning Scheme Regulatory Plan, n.d.).

2. Courtyard construction in TUC must be shorter or equal to pre-existing buildings (Town Planning Scheme Regulatory Plan, n.d.).
3. Greenery, pedestrian paths, or bicycle parking required for setback areas in new construction (Comune di Milano, 2014).
4. Minimum distances between buildings and contiguous property boundaries (Comune di Milano, 2014).
5. Specific setback rules for courtyards and checks for surface area ratios (*Regolamento Edilizio Previgentetrans.It.En*, n.d.).

Energy Performance on Buildings:

1. Thermal requirements for top floor coverings, opaque walls, and reflectivity coefficients (Comune di Milano, 2014).
2. Use of materials to control thermal gains and reduce heat island effect (Comune di Milano, 2014).
3. Phase shift (S) and attenuation factor (fa) requirements (Comune di Milano, 2014).
4. Vertical and hanging greenery encouraged for facades, terraces, and roofing surfaces (Comune di Milano, 2014).

## 4.3. Acquabella Site Analysis

The expansion of Milan in the 20th century, following the Beruto plan, exhibits a 'donut' mode with a ring-like radiation from the city center. While respecting historical layouts, the expansion areas tend to be regular, featuring a grid form influenced by internationalism and modernism, reflecting efficiency and cost-effectiveness (Pierre-Alain, n.d.).

The Acquabella neighborhood in Milan, located between Municipality 3 and Municipality 4, derives its name from an ancient farmhouse constructed in the 15th century called Cascina Acquabella. This farmhouse, named after the artificial canal present in the area, survived urbanization and industrialization until its demolition in the 1950s due to abandonment and increasing demand for buildings. The IFACP Fabio Filzi neighborhood, designed by architects Franco Albini, Renato Camus, and Giancarlo Palanti in via Birago, represents a significant rationalist example in Milan, characterized by four or five-story buildings with a north-south orientation (Wikipedia contributors, 2024).

Analyzing the number of floors in the buildings, it is observed that 17% have 2 floors, 50% have 3-5 floors, and 24% have more than 5 floors (OERCO2, n.d.).

Regarding construction materials, commonly used in the district for new and refurbishment activities include concrete, structural or reinforcement steel, fired clay products, insulating materials, ceramic tiles, wood, cementitious materials, and paintings. Notably, concrete, the most used material, accounts for 90% of energy consumption in primary raw materials production, prompting efforts to minimize environmental impact and explore sustainable alternatives. For the building envelope, bricks are extensively used in Acquabella. Despite being considered sustainable, their extraction and production stages have notable environmental impacts and high energy consumption, ranging from 490 kWh/m3 to 1730 kWh/m3 for the production of 1 m3 of product (OERCO2, n.d.).Also widely used material in the Acquabella neighborhood, called with the term "clinker", is a type of brick obtained through high-temperature cooking, imparting a shiny appearance and enhancing material resilience. (Pierre-Alain, n.d.).

Figure 19. Different materials in Acquabella(Pierre-Alain, n.d.).

The following part constitutes a preliminary simulation of Acquabella district. The geometrical model was developed using QGIS software, incorporating a geopackage of Italy's buildings and a Digital Terrain Model (DTM) specific to the Lombardy region. Daily meteorological data from the Linate weather station were used for the simulations. The Laydy_bug plugin in Grasshopper was then used for Annual Direct Sun Hour analysis. It is crucial to note that this analysis did not consider vegetation or materiality, resulting in inaccuracies. However, it serves as an initial exploration to offer insights into the thermal comfort conditions of the district, before the on-site investigations.

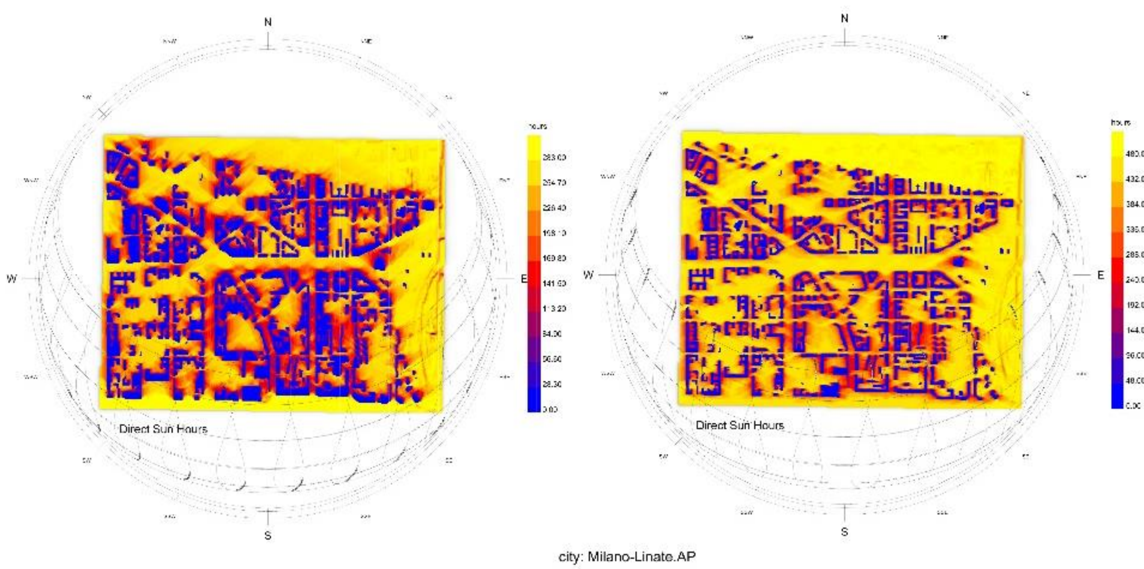



Figure 20. Direct sun hours for January and July in Acquabella.

# 5 Methodology

## 5.1 Overall workflow

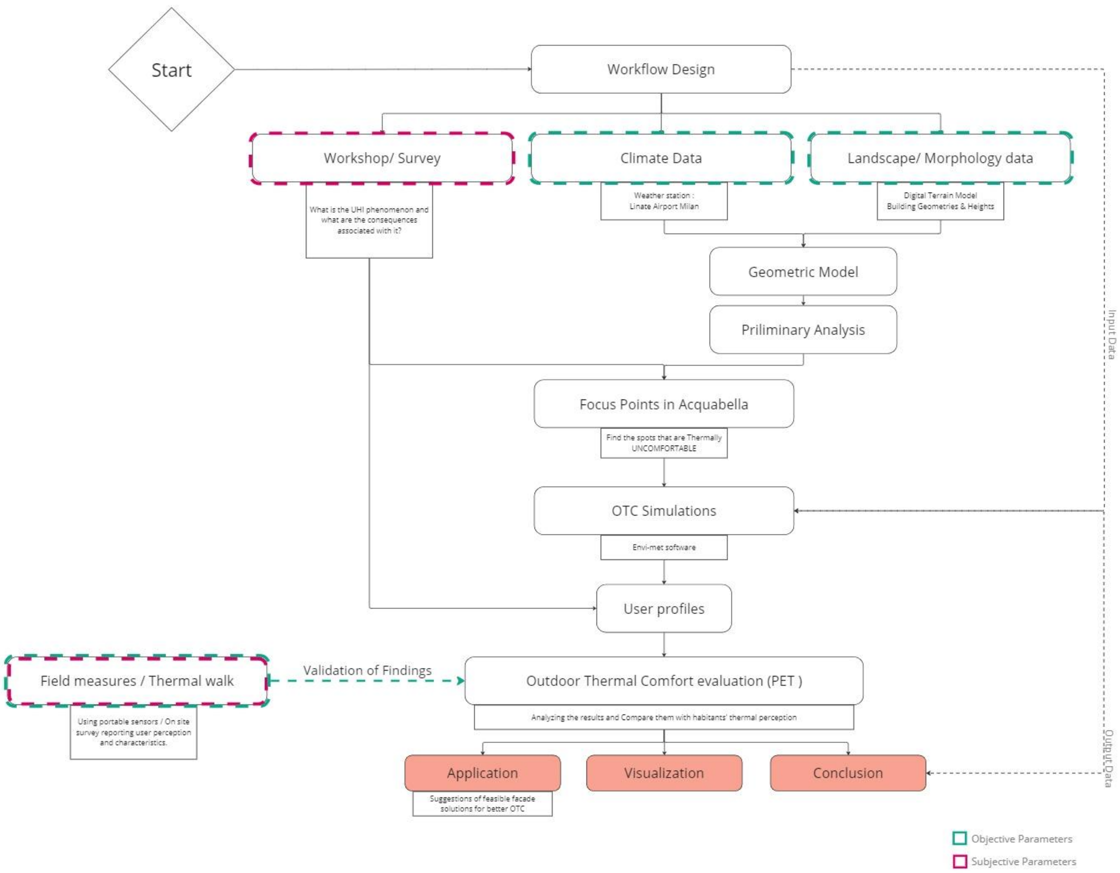



Figure 21. Overall workflow of the thesis

The study uses a mixed-method approach to evaluate the multi-domain influence of facades on thermal perception. The methodology is structured to systematically address each research objective, providing a comprehensive understanding of the factors affecting thermal comfort and proposing effective retrofit strategies.

The initial step involves conducting a workshop and a long-term survey aimed at identifying the most critical areas of study. These areas are selected based on the perceived thermal problems and the overall importance of the region under investigation. The workshop facilitates interactive discussions among citizens and users of the district, enabling the identification of specific zones that experience significant thermal discomfort. The long-term survey complements this by providing empirical data on thermal perceptions over an extended period. The desired outcome of this step is to pinpoint the areas in Acquabella district that warrant detailed examination due to their notable thermal issues and their importance and frequence of use, within the broader context of the study area.

Next, demographic data along with long-term survey are used to identify the physiological profiles of district residents. This information is crucial for simulating the Physiological Equivalent Temperature (PET) of representative groups within the district, with a particular focus on more vulnerable populations. The goal is to understand how different user groups experience thermal conditions and to ensure that simulations accurately reflect these variations.

Using the data gathered from the previous steps, simulations of the study area are conducted. This involves identifying factors within the neighborhood, such as geometrical and façade properties of buildings, that might affect PET. The aim is to evaluate PET and compare it with the thermal sensation votes collected from the survey participants. This comparison helps to validate the simulations and provides insights into the relationship between built environment characteristics and thermal perception.

The thermal walk is a participatory event involving citizens of the district in the area identified as problematic in previous steps. It includes field measurements and on-site evaluation of the area. The walk is designed to validate the findings of the workflow and identify different or even new parameters that might affect a pedestrian in real-time.

The final step focuses on identifying priority façades for intervention, particularly those associated with the worst aesthetic perceptions and areas of thermal discomfort. Based on this analysis, retrofit strategies are proposed to address both aesthetic and thermal demands, ensuring that the solutions meet the PET standards identified in the simulations. The objective is to develop practical, effective and feasible interventions that improve both the aesthetic and thermal experience of the urban environment.

## 5.2 Qualitative Methods

### 5.2.1 Workshop Design

The workshop was conducted on the 17th of January as part of the larger CoSMoPolis project, a collaboration between TU Delft and Cista. The project aims to develop a novel crowd-sourcing mobile-sensing platform for urban communities, capturing integrated multi-domain information on objective and subjective perceived environmental quality. The workshop focused on evaluating outdoor comfort in the Acquabella district, consisting of three stages designed to engage participants and gather valuable data.

**Workshop Schedule:**

**1.Informative Session:**

- Objective: Educate participants on outdoor comfort, its variables, and pedestrian perception.
- Activities: Presentations on the meaning of outdoor comfort, factors affecting it, and implications for pedestrians. Project goals and findings on the neighborhood were also shared. This session ensured participants had a foundational understanding of the topic. The procedure was anonymous.

**2.Interactive Mapping:**

- Objective: Gather data on environmental quality perceptions in Acquabella.
- Activities: Participants rated the district on maps based on frequency of visits and importance, and evaluated four environmental aspects: aesthetics, thermal, acoustic, and air quality. For this study, the

focus was on thermal and aesthetic votes. This session provided spatial data on perceived environmental quality.

**3.Material Evaluation and Feedback:**

- Objective: Assess thermal perception of common facade and pavement materials.
- Activities: Using the Mentimeter application, participants scanned a QR code to evaluate thermal sensations associated with different materials. They also voted on the most important environmental parameters for their well-being and suggested changes to improve the neighborhood's aesthetic quality. This session allowed for direct feedback on material preferences and environmental priorities.

The workshop attracted over 40 active community members. It aimed not only to collect data but also to raise awareness, educate participants about district issues, and set the stage for implementing research findings.

**Importance of Qualitative Human Data:**

- Multi-domain comfort and how the neighborhood understands the space.
- Building community resilience through access to information.
- Informing behavior and better use of public space.

### 5.2.2 Data processing and analysis

The methodology for evaluating outdoor comfort in the Acquabella district involves a structured process designed to gather and analyze comprehensive data on environmental perceptions and material thermal properties.

The analysis of the workshop results uses QGIS to identify the most problematic areas in the district for further investigation. Data collection focuses on thermal votes, using buffers to ensure relevance to facade influence, and highlights areas of high pedestrian activity and significance. Density mapping and heatmap creation in QGIS visualize the spatial distribution of environmental quality perceptions, refining the analysis to identify specific areas with high concentrations of positive and negative perceptions. Problematic areas are filtered by importance and frequency of visits, as well as proximity to buildings, excluding large parks to mitigate confounding variables, such as vegetation.

Further investigation of materials is conducted using SPSS, using the thermal sensation votes from the material evaluation session. Material radiative, thermal, and physical properties are assigned to the materials in the pictures. A one-way ANOVA test is used to determine whether thermal sensation is significantly influenced by certain material properties. ANOVA, or Analysis of Variance, is a statistical method used to compare the means of three or more groups to see if there is a significant difference among them. It helps to determine whether the observed differences among group means are statistically significant or if they occurred by chance.

### 5.2.3 Area of focus

The first step in selecting the simulation spots involves defining the independent and dependent variables. The goal is to choose an environment where most of the independent variables are fixed or controlled, ensuring that any changes observed are due to the variables of interest rather than other confounding factors. This approach allows for a controlled analysis of the impact of facade materials on thermal comfort.

Independent variables in an urban environment that may affect thermal comfort include (Johansson, 2006):

- Height of Buildings: Variations in building heights affect shading and wind patterns.
- Width of the Street: The street width influences the urban heat island effect and ventilation.
- Presence of Trees: Vegetation impacts both thermal comfort and perceived aesthetics but is kept minimal in this study to isolate facade effects.
- Surface Properties (Age and Roughness of Buildings): These factors influence heat retention and emission characteristics.
- Specific Heat of Surface Materials: This affects how materials store and release heat.
- Reflectance of Surfaces (Glass vs. Matte Surfaces): Reflective surfaces can reduce heat absorption, affecting thermal comfort.
- Pavement Material: Different materials have varying thermal properties.
- Orientation: Fixed to East-West to ensure consistent solar exposure.
- Shading Devices on Facades: External shading elements can significantly impact solar gain.
- Traffic Density: Variations in traffic affect heat generation and air quality.
- Ratio of Pavement to Car Pavement: This ratio impacts the urban heat island effect.
- Type of Building (Commercial vs. Residential): Different building uses affect heat generation and pedestrian traffic.
- Aesthetic Satisfaction: Visual appeal can influence perceived comfort.
- People's Perception of Air Quality and Noise: These perceptions also influence overall comfort.

The dependent variables for this study focus on the thermal perception, including sensation and satisfaction, and the thermal environment, measured using metrics like the Physiologically Equivalent Temperature (PET). These variables help gauge the subjective thermal comfort experienced by pedestrians and provide objective measures of thermal conditions.

Several constraints are applied to ensure controlled and accurate simulations. These include fixed orientation, fixed ratios of pavement and parking spots, fixed street width, consistent materials on streets and pavements, minimal vegetation to reduce the impact on thermal and aesthetic perception, and no changes in traffic to maintain consistent thermal conditions.

The simulations will test various variables, including the material on the base and upper parts of the facade, the age of the building (which affects thermal properties), the height of the building, and the type of shading devices on the facade. These variables are chosen to understand how different facade treatments can influence thermal comfort.

### 5.2.4 Urban Geometry and Properties

Key parameters affecting canyon geometry include(Jamei et al., 2016):

1.aspect ratio,

2.street orientation,

3.sky view factor,

4.neighborhood geometry complexity,

5.vegetation.

- Aspect Ratio and Urban Canyon Geometry

Air temperature is significantly influenced by the aspect ratio, which is the ratio between the average height of the canyon buildings (h) to the width (w) of the canyon. A higher aspect ratio results in higher night-time temperatures and lower day-time temperatures (Perini & Magliocco, 2014)(Jamei et al., 2016). Narrow streets in deep canyons (AR>2) provide better shading for pedestrians on sidewalks compared to wide streets. In shallow canyons (AR<0.5), it is necessary to promote shading on pedestrian areas and facades to improve outdoor thermal comfort. Urban canyons also channel wind, increasing its speed and helping dissipate excess heat. However, in deep canyons, variations in wind speed can reduce temperatures by up to 5°C within the canyon. Other studies indicate that tall buildings and narrow streets, termed deep canyons, trap warm air and reduce wind flow, negatively affecting thermal comfort(Jamei et al., 2016).

- Street Orientation

Street orientation greatly affects solar access and wind speed, thereby influencing outdoor thermal comfort. Studies offer varied results: some indicate that, with the same aspect ratio, E-W orientation is the least favorable, suggesting the need for tall buildings to mitigate air temperature through shading at the pedestrian level (Taleghani et al., 2014). In hot dry climates, a compact urban design with deep canyons is preferable. However, if there is a cold season, the design should include wider streets or open spaces to provide solar access. For instance, in Adelaide, E-W oriented canyons are thermally preferable in both seasons (Elnahas, 2003)(Jamei et al., 2016). Therefore, the optimal orientation and canyon shape depend on the site's climatic conditions, the need for sun or shade, and wind direction.

- Sky View Factor (SVF)

The sky view factor characterizes the geometry, density, and thermal balance of an urban area. It is defined as "the ratio of the amount of the sky visible from a given point on a surface to that potentially available"(Ali-Toudert & Mayer, 2006). A lower SVF is associated with cooler day-time temperatures and warmer night-time temperatures. This is due to reduced incoming solar radiation penetrating the canyon, affecting both air and mean radiant temperatures, thus enhancing outdoor comfort during the day. Conversely, a higher SVF increases wind speed at the pedestrian level by 8% for every 10% increase in SVF (Yang et al., 2013).

- Neighborhood Configuration

The neighborhood's configuration significantly impacts the formation of the Urban Heat Island (UHI) effect. Studies show that air temperature and relative humidity are consistent across different urban tissues, while wind speed and mean radiant temperature vary significantly (Johansson et al., 2013). This variation occurs because different urban layouts absorb solar energy at different rates, affecting outdoor thermal comfort levels. For instance, complex shapes with numerous cavities trap more radiation, reducing pedestrian-level comfort(Jamei et al., 2016). A compact urban form is recommended to mitigate UHI, though it may not be beneficial in winter. Therefore, the best urban layouts depend on the local context and geographical characteristics of the area (Milano Leonardo et al., n.d.).

- Vegetation

## 5.3 Quantitative methods

### 5.3.1 Long-term Survey

#### 5.3.1.1 Design of the Survey

The long-term survey begins on April 17th, made available initially via a QR code in both Italian and English, using Qualtrics XM software. On May 1st, it is officially distributed using posters and flyers placed in stores and on public walls in the neighborhood after obtaining permission from the municipality. The survey is designed to ensure anonymity, avoiding the collection of any identifiable information from respondents. It aims to serve both the research project and the local community organization, Cista, by gathering demographic data and identifying potential issues within the district. The questionnaire is structured into three main parts.

Part 1: Personal Information

This section collects basic demographic information from respondents, including:

- Gender
- Age
- Relationship to the Acquabella district
- Frequency of using public spaces in the district

Part 2: Thermal and Aesthetic Perception

This section aims to gather detailed information about respondents' thermal and aesthetic perceptions throughout the district. Respondents are asked to pinpoint specific locations on a map for various scenarios using Google Maps, where they can freely choose any location within the district. For thermal perception, respondents are asked to mark 1 to 2 public places where they feel uncomfortable during hot summer days in terms of temperature, and 1 to 2 public places where they feel comfortable during hot summer days in terms of temperature, by placing pins on the locations. Following these map-based questions, respondents evaluate their thermal sensation at the chosen spots using a 5-point ASHRAE scale (*ANSI/ASHRAE Addendum h to ANSI/ASHRAE Standard 55-2012*, 2013):(-2) Very cold, (-1) Cool, (0) Neutral, (1) Hot, (2) Very hot. The ASHRAE scale is selected to correlate thermal sensation with the PET (Physiological Equivalent Temperature) results from simulations, and to explore the relationship between thermal sensation and perceptual aesthetics. It is important to note that the survey does not collect personal characteristics such as BMI or clothing level, and it does not refer to a specific hot day. Therefore, the main objective is to validate workshop findings with a larger sample and to confirm the selection of the simulated region based on its poor environmental quality and user satisfaction ratings.

For aesthetic perception, respondents are asked to mark 1 to 2 public places in the Acquabella district that are the least attractive to spend time in and 1 to 2 public places in the Acquabella district that are the most attractive to spend time in. Respondents then evaluate their aesthetic perception at these spots using a 5-point Likert scale(Lau & Choi, 2021a): (-2) Very unsatisfactory, (-1) Unsatisfactory, (0) Neutral, (1) Satisfactory, (2) Very satisfactory.

Both thermal and aesthetics domains are assessed with questions on positive and negative perceptions to identify clear patterns in behavior and urban characteristics that influence these perceptions.

Part 3: Usage and Behavior

This section focuses on the frequency and nature of respondents' visits to the locations identified in Part 2. It includes questions on:

- Regularity: How often do respondents visit these places?
- Duration: How long do they usually spend there?
- Purpose: What activities do they engage in at these spots (e.g., sport, work, leisure, or other activities)?
- Reaction: How do they react when feeling thermally uncomfortable at these spots?

Finally, respondents are given an open-ended question to suggest changes that could make the district more comfortable during warm days.

### 5.3.1.2 Data Processing and Analysis

**Clustering of Points in QGIS**

To analyze the environmental quality votes, the first step involves clustering the data points using QGIS. The Atlas of Urban Expansion is referenced to determine the average block size for Milan, which is 3.9 hectares (39,000 $m^2$) with an average block dimension of 621 $m^2$. Based on these standards, the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm is implemented to create clusters of points within a standard distance from each other.

The rationale behind clustering is to categorize the concentrated points and analyze the results at a smaller scale, while accounting for potential errors or inaccuracies that may arise from the placement of pins on the map during the survey. The minimum number of points required to form a cluster is set to 2, ensuring each cluster includes at least one thermal and one aesthetic vote. The maximum distance for clustering objects is set to 30 meters, considering the average plot size of 30x30 meters. Points not within 30 meters of at least two other points are considered outliers.

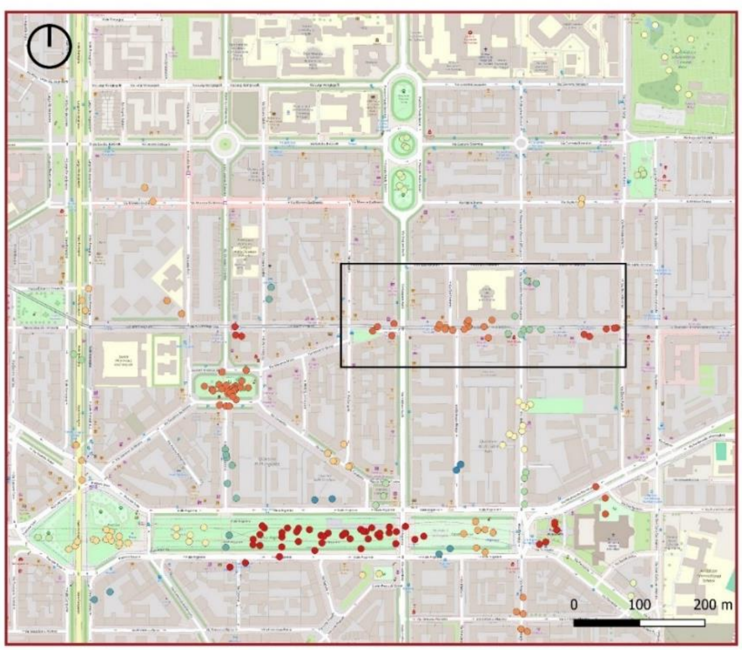



Figure 22. Clustered thermal and aesthetics votes from survey

#### Mean Values for Clusters

Once the clusters are formed, the data is analyzed using SPSS (Statistical Package for the Social Sciences) software. The responses regarding thermal perception are related to the corresponding Physiological Equivalent Temperature (PET) values.

For each cluster, the mean thermal sensation votes and aesthetic perception votes are calculated. This aggregation allows for the computation of average thermal and aesthetic perceptions for each cluster, providing a clear picture of the environmental quality in different areas.

#### Statistical Analysis

Statistical methods are employed to assess the collected data. One way ANOVA is used to detect statistical significance and  Spearman's Rank Correlation to compute the correlations between variables. This method is ideal for ordinal data where variables are ranked, but the exact distance between ranks is not necessarily consistent or known (*Spearman's Rank Order Correlation Using SPSS Statistics - a How-To Statistical Guide by Laerd Statistics*, n.d.). Spearman's correlation does not assume a normal distribution of variables, making it suitable for survey data. It detects monotonic relationships (either increasing or decreasing) rather than only linear relationships, which is particularly useful for data that may not exhibit a linear relationship but tend to increase or decrease together. The value of the coefficient ranges from -1 to 1, where 1 indicates a perfect positive correlation, -1 indicates a perfect negative correlation, and 0 indicates no correlation. Later on, the data are examined to identify trends in thermal perception as aesthetic perception changes, and vice versa. Additionally, significant correlations between perception and demographic factors such as age groups and genders, as well as the duration and frequency of visits to the clustered areas, are explored.

### 5.3.1.3 Conclusions

Conducted anonymously through Qualtrics XM software, the survey is structured into three parts: personal information, thermal and aesthetic perception, and usage and behavior of public spaces. The personal information section collects demographic data, while the thermal and aesthetic perception section asks respondents to evaluate specific locations within the district based on their comfort levels during hot summer days. The final section focuses on the frequency, duration, and nature of visits to these locations, with an open-ended question for suggestions to improve comfort during warm days.

Data processing involves clustering points using QGIS and analyzing the responses with SPSS software. The clustering method, DBSCAN, categorizes concentrated points to facilitate small-scale analysis and account for potential inaccuracies in map pin placements. The mean values for thermal and aesthetic perceptions within each cluster are computed to provide a clear picture of environmental quality. Spearman's Rank Correlation assesses the relationships between variables, detecting monotonic relationships suitable for the ordinal survey data. This analysis explores trends in thermal and aesthetic perceptions, correlations with demographic factors, and the impact of visit frequency and duration on perceived comfort. The results inform strategies to enhance outdoor thermal comfort and visual appeal in the district.

## 5.3.2 ENVI-MET Software and Modelling Setup

The numerical simulations in this study are conducted using ENVI-met V5.5.1, a three-dimensional computational fluid dynamics (CFD) microclimate modeling system. ENVI-met simulates urban climates, assessing the effects of atmosphere, vegetation, architecture, and materials. It offers high-resolution analysis of heat and energy fluxes, determining air temperature, radiant temperature, relative humidity, and air movement around buildings. The software calculates heat and humidity transfers through façades and assesses the impact of vertical greening, while its vegetation model simulates evapotranspiration, $CO_2$ uptake, and leaf temperature (Milano Leonardo et al., n.d.)

ENVI-met also allows for the examination of façade materials by simulating up to three layers in the building's façade. Wind patterns and speeds around buildings and trees are integrated into the ENVI-met module (ENVI-met, 2024). Model validation in urban-greening thermal-comfort-impact studies often presents diverse challenges. Although PET (Physiological Equivalent Temperature) is commonly used in urban-comfort studies, it is rarely used for model validation(Liu et al., 2021). This research attempts to validate ENVI-met simulations through user-subjective thermal perception in the district.

The ENVI-met methodology involves three stages: field survey, input data, and analysis (Barnstorf et al., 2023).In the field survey stage, the site is observed and systematically characterized onto a plan-referenced database. The input data stage involves setting up the model with detailed environmental data and specifying simulation parameters. The analysis stage processes and interprets the simulation results to understand heat and energy fluxes, the impact of surfaces and vegetation on thermal comfort, and the overall microclimate of the study area.

### 5.3.2.1 Field survey ENVI-met

The setup of the ENVI-met model begins with a field survey and updating of the plan. Comparing the urban geometry data exported from the Milano Geoportale geopackages to the Open Street Map using QGIS reveals that some plots in the district have changed. However, the elements in the area of interest are correctly placed and shaped. Most buildings in the plan lack detailed features such as roof-ridge lines, which are updated using 'Google Earth' extrapolation and measurements to estimate heights and elevations.

The model domain is set up in the ENVI-met Spaces section, focusing on a street canyon's public space. The dimensions of the model domain are 480x165m, based on the overall analysis in QGIS. The model is aligned with the prevailing street orientation and the limits are determined by the "model inspector" in "Spaces" to ensure smooth simulation of environmental conditions.

ENVI-met is designed for micro-scale simulations with a typical horizontal resolution ranging from 0.5 to 10 m. The chosen resolution for this simulation is 2m along the x, y, and z axes, balancing simulation time and output detail. This results in a grid of 240 x 83 x 25 cells, totaling 498,000 delta volumes. Potential errors can arise from low vertical model dimensions affecting wind flow or from buildings placed too close to the model (Milano Leonardo et al., n.d.).To mitigate this, empty cells are added at the borders to create space between buildings and the model boundary, ensuring proper infiltration of weather phenomena.

The final model dimensions are x: 264, y: 107, z: 25, with empty cells added to account for the maximum building height at the borders (25m), requiring 12 cells on each side. To minimize processing time, the height of grid cells can be varied using telescoping—where grid cells' heights increase at an editable rate from a certain height—and splitting the lowest grid cell's height into five sub-cells(Barnstorf et al., 2023). This approach allows finer data processing of air volume closest to the ground, which is crucial for simulating the height-dependent impacts of longwave and diffused shortwave radiation from the ground and the effects of environmental and urban parameters on pedestrian thermal comfort when simulating PET.

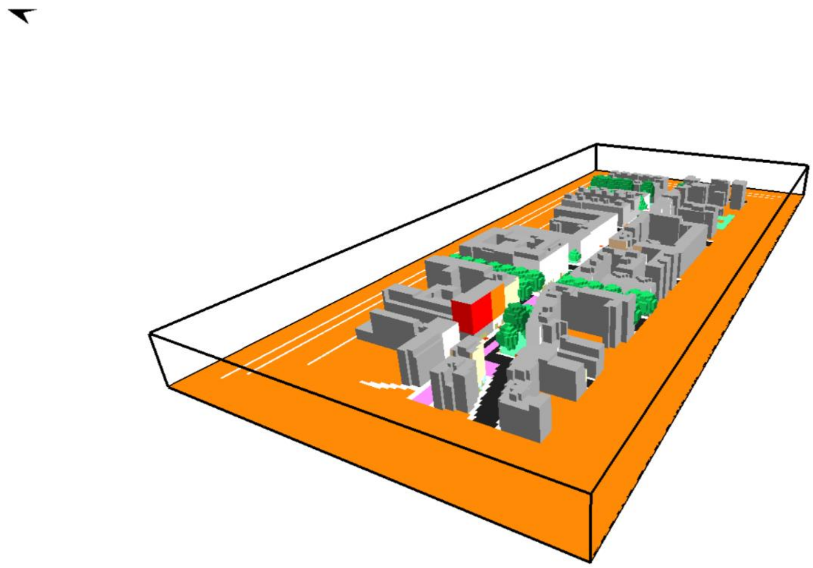


Figure 23.3D model visualization in ENVI-met

Table 1. 'Model area' in Spaces

| | |
|---|---|
| **'Model Location'** | |
| Latitude (deg, +N, -S) | 45.46 |
| Longitude (deg, -W,+E) | 9.19 |
| **Reference time zone** | |
| name | Central European Standard Time |
| **Model geometry** | |
| Size of grid cell (in meters) | 2 x 2 x 2 |
| Model dimensions (in grid cells) | 294 x 137 x 25 |
| Model rotation out of grid North | 0 |
| Number of nesting cells | 0 |
| **Method of vertical grid generation** | |
| Dz of the lowest grid box is split into 5 sub cells | Yes |
| Telescoping | Yes |
| Telescoping factor(%) | 30 |
| Start telescoping after height (m) | 30.00 |
| **Geometric check** | |
| Min.distance between buildings and model border | 24 |
| Height of 3D model top | 56 |
| Highest point building | 32 |
| **Georeference** | |
| Co-ordinate of lower left grid | x:4260573.2 / y: 2484542.9 |

## 5.3.2.2 Building Setup in ENVI-MET

The setup of building models in ENVI-met Spaces involves several steps to accurately represent the built environment and its impact on microclimate.

### Planimetry and 3D Model Creation

To initiate the modeling process, the AutoCAD project file is converted to a *.bmp format, making it readable by the ENVI-met software. Roofs with inclinations are translated into contour lines to approximate their real forms, considering the voxel-based nature of ENVI-met (in this case, using 2x2x2 voxels). Pavement borders, yards, and tram lanes are also included in the 2D AutoCAD plan to accurately assign soil materials in ENVI-met. From this two-dimensional image, a three-dimensional model of the neighborhood is constructed, with each building assigned its corresponding height.

### Building Identification and Material Assignment

Each building is labeled with a unique identifier, consisting of a letter and a number, indicating its block and specific location. The next step involves creating the materials characterizing the building facades and using them to construct the wall stratigraphy in the "Database Manager" section of ENVI-met. The internal parts of the walls are modeled using predefined construction types and their respective thicknesses, as discussed in the previous chapter. Due to ENVI-met's limitation of modeling only up to three layers in wall composition, some construction details, such as air cavities, are simplified, which may slightly affect the façade performance.

Table 2. Facade materials and properties

| Material | Color | Thermal properties | | Optical properties | | | | Physical properties |
|---|---|---|---|---|---|---|---|---|
| | | Thermal Conductivity W/(m·°C) | Specific Heat Capacity J/(kg·°C) | Absorption | Albedo | Emissivity | LRF (%) | Density (kg/m^3) |
| **Stucco** | Bright | 0.8 | 850 | 0.65 | 0.66 | 0.94 | 75 | 2275 |
| | Grey | 0.8 | 850 | 0.65 | 0.3 | 0.94 | 35 | 2275 |
| **Plaster** | Bright | 1.5 | 1000 | 0.35 | 0.45 | 0.86 | 45 | 1500 |
| | Dark | 1.5 | 1000 | 0.5 | 0.25 | 0.86 | 25 | 1500 |
| **Marble** | Bright | 2.28 | 890 | 0.44 | 0.59 | 0.95 | 60 | 2750 |
| | Grey | 2.28 | 890 | 0.65 | 0.4 | 0.83 | 60 | 2750 |
| **Concrete** | Bright | 0.86 | 880 | 0.6 | 0.7 | 0.92 | 25 | 930 |
| | Grey | 0.86 | 840 | 0.7 | 0.3 | 0.9 | 20 | 930 |
| **Brick** | Red | 0.3 | 840 | 0.68 | 0.39 | 0.92 | 10 | 1000 |
| | Bright | 0.3 | 840 | 0.55 | 0.7 | 0.75 | 15 | 1000 |
| **Ceramic** | Bright | 0.84 | 800 | 0.5 | 0.7 | 0.97 | 40 | 2158 |
| **Granite** | Dark | 4,61 | 790 | 0.55 | 0.47 | 0.96 | 25 | 1700 |
| **Limestone** | Bright | 1.5 | 900 | 0.35 | 0.4 | 0.96 | 0.55 | 2550 |
| | Dark | 1.5 | 900 | 0.5 | 0.25 | 0.96 | 0.35 | 2550 |

### Glass Specifications

The glass used for the ground floor level of facades is standardized as "floating glass" due to the lack of specific information for each building. The properties of the floating glass are as follows:

Table 3. 'Floating glass' properties in ENVI-met

| Property | Value |
|---|---|
| Thickness | 1.5 cm |
| Roughness | 0.02 |
| Layers | 3 layers clear float glass |
| Absorption | 0.05 |
| Transmission | 0.9 |
| Reflection | 0.05 |
| Emissivity | 0.9 |
| Specific heat capacity | 750 J/(kg·°C) |
| Thermal conductivity | 1.050 W/(m·°C) |
| Density | 2500 kg/m$^3$ |

The surrounding buildings are modeled using default materials in ENVI-met, such as brick walls with moderate insulation, and a standardized roofing material for all buildings.

### Considerations and Simplifications

The ENVI-met model imposes limitations on the shape of buildings, preventing the modeling of curved or diagonal geometries. Therefore, the geometrical configuration of buildings in the neighborhood, which are mostly squared, is simplified in the model. Balconies are also excluded from the simulation due to their negligible effect on pedestrian-level sunlight.

### Urban greening

Urban greening, though limited in the modeled area, is a critical parameter due to its significant impact on microclimate heat fluxes and its ability to create shadows on building facades and roads (Milano Leonardo et al., n.d.). Two types of vegetation are considered in the ENVI-met model: ‘Simple plants’ and ‘3D Plants’.

Simple plants include grass and bushes that do not overhang canopies. These plants are characterized by nine parameters, including albedo, transmittance, plant height, CO2 fixation type, and leaf type (grass, deciduous, or conifers) (Barnstorf et al., 2023). In this model, ‘Grass 25cm aver, dense’ is used to simulate the effect of vegetation in courtyards, small parks, and some ‘hedges dense,2cm’ placed on the pavement.

In contrast, 3D plants have a more complex canopy and include trees. These plants are represented by clusters of cells with a Leaf Area Density (LAD) that provides a three-dimensional shape. The "Albero" section in ENVI-met includes deciduous trees, conifers, and palm trees, with options for high or low LAD and various volumetric shapes (conic, cylindrical, spherical, or heart-shaped). Trunk sizes can range from small to large(Milano Leonardo et al., n.d.). The list of trees used in the model includes species identified in the area analysis, such as Acer Platanoides, Acer Pseudoplatanus, Platanus A- Acerifolia, Quercus Robur, Acer Negundo, Tilia Cordata, and Carpinus Betulus. For unidentified tree species in yards, default abstract deciduous trees (medium size, sparse canopy, cylindrical shape, medium trunk) are used.

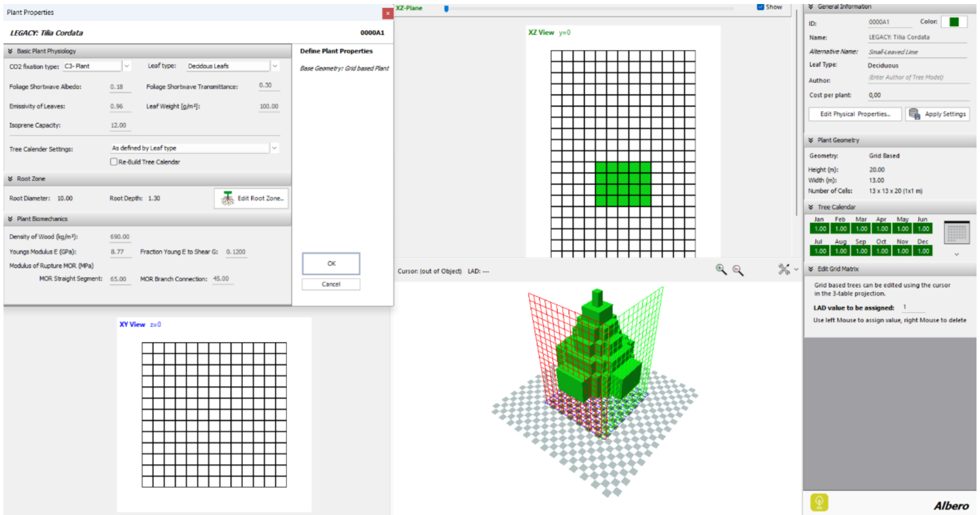


Figure 24. ENVI-met "Albero"interface and the characteristics of the used 3D plant.

The placement of single and 3D plants in the model domain follows the exact coordinates from the 2D vegetation geospatial package of Geoportale della Lombardia. No further processing of the existing plant list is done; the provided plants are used as is. This simplification in vegetation modeling, particularly for trees in yards with undefined species, may result in minor changes in environmental conditions, primarily affecting wind and relative humidity values. However, this impact is considered insignificant for this study as it does not have a spatial relation to the facades being examined.

### Soil Profile Setting

The uniformity of the street's soil type (street materiality) is one of the controlled independent variables in this research. This uniformity is a key factor in selecting Via Beato Angelico for the final analysis. Field observations and Google Earth were used to delineate and identify the 'Soil-Cover Types' and assign them to their respective positions based on the Geoportalle della Lombardia geopackage and DWG files.

The soil types used in the simulation are sourced from the 'Soil Materials' database of the ENVI-met DB Manager. These types were carefully selected to match those found in Via Beato Angelico, without further investigation into standard construction details or layering. The soil materials used in the simulation include asphalt for the street, concrete pavement (gray) for pavements, basalt brick road for rails, and default sandy loam for the soil under buildings.

Table 4. The properties of these soil profiles

| Type | Roughness | Albedo | Emissivity |
|---|---|---|---|
| Asphalt Road | 0.01 | 0.2 | 0.9 |
| Concrete Pavement Grey | 0.01 | 0.5 | 0.9 |
| Basalt brick road | 0.01 | 0.8 | 0.9 |
| Loamy Soil | 0.015 | 0 | 0.98 |

ENVI-met 'Soil Profiles' layering as provided by 'DB Manager'

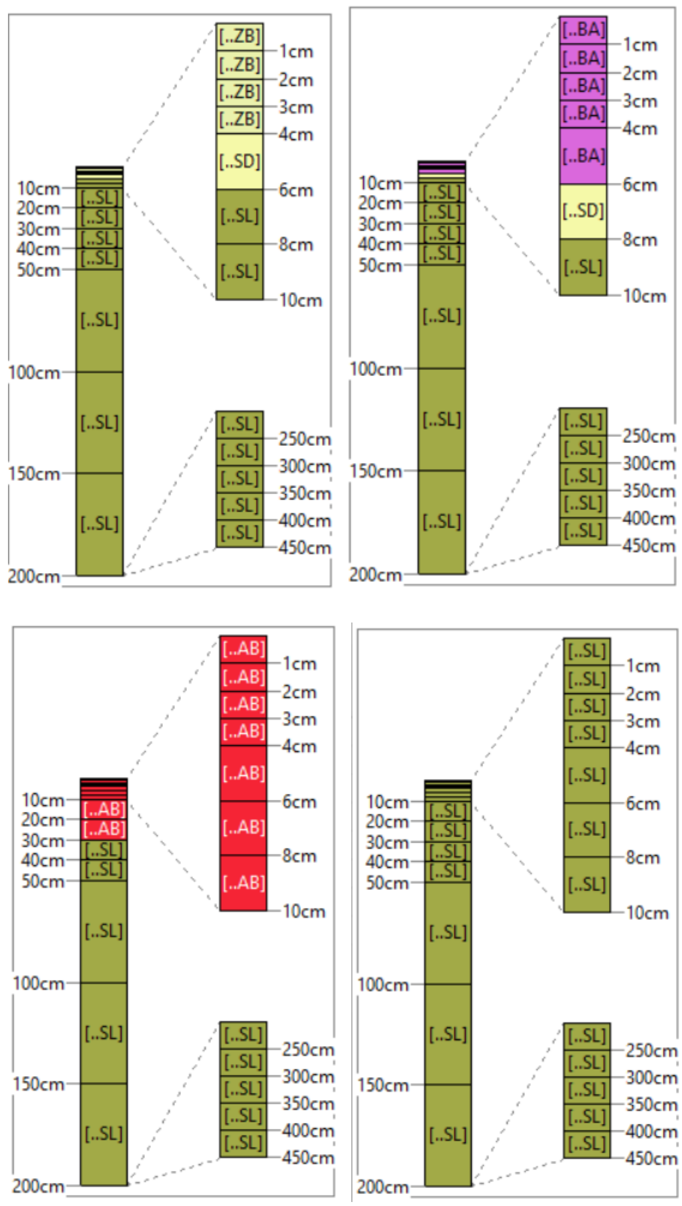



Figure 25.ENVI-met 'Soil Profiles' layering as provided by 'DB Manager'

## 5.3.2.3 Input data

### Climatic Data

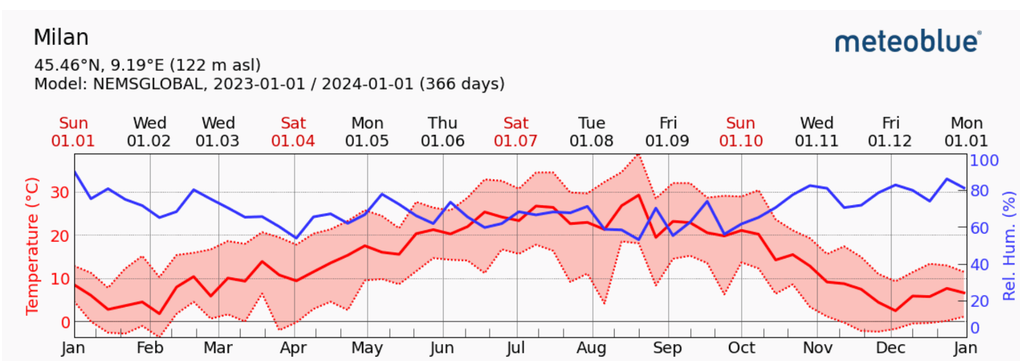



Figure 26. Anual Air temperature records of 2023 as provided by meteoblue, historic data

In order to select the most representative simulation day, the objective was to identify the period with the worst-case scenario for thermal comfort in 2023. According to Meteoblue, July and August were the hottest months in Milan during that year (*History+ | Weather History & Archive*, n.d.). The temperature data from the Juvara Weather Station, which is the closest station to the study area in Acquabella district (0.54 km away), was analyzed in detail. A statistical analysis using SPSS indicated that the most frequent temperature during these months was 30.9°C, occurring 3-4 times. Consequently, August 2nd was chosen as the simulation day because it had the highest recorded temperature of 30.9°C and a minimum temperature of 24°C.

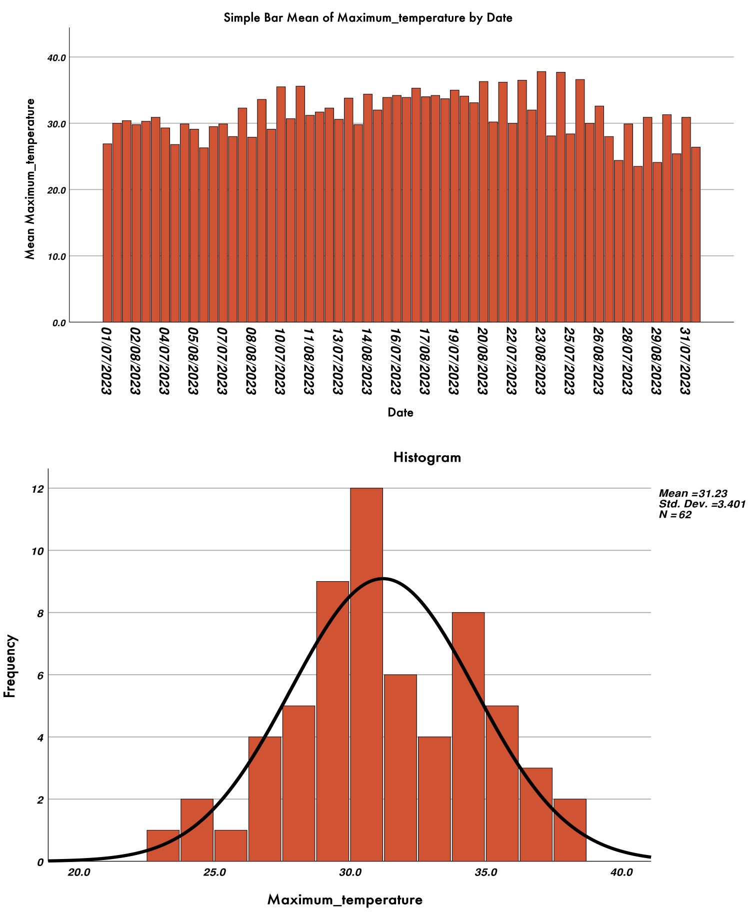



Figure 27. Diagrams for Maximum temperatures and frequency for July August 2023

To accurately represent the environmental conditions on the chosen simulation day, a 72-hour simulation run was conducted. This duration allowed the model to adjust to the meteorological conditions during the first 24 hours, while the subsequent two days were used to validate the results. Only the middle 24 hours were considered for detailed analysis. Ensuring the wind speed was at least 1 m/s and that the wind direction did not vary more than 90° in 30 minutes was critical for accurate simulation results.

Table 5. ENVI-met 'Forcing File'

| 'Forcing File' | |
|---|---|
| Parameters | Format/ Units |
| 'Date' | DD.MM.YY |
| 'Time' | HH:MM:SS |
| 'Direct shortwave radiation / low clouds' | $W/m^2$ |
| 'Diffuse shortwave radiation/ medium clouds' | $W/m^2$ |
| 'Longwave radiation/ high clouds' | $W/m^2$ |
| 'Absolute Air temperature' | K |
| 'Relative Humidity' | % |
| 'Wind velocity' | m/s |
| 'Wind Direction' | ° |
| 'Precipitation' | mm |

### Gathering Weather Data

- ARPA Model:

ARPA (Agenzia Regionale per la Protezione Ambientale) is the Regional Meteorological Service providing real-time weather forecasts and meteorological support. ARPA operates a network of 318 stations updated every ten minutes, measuring parameters such as temperature, precipitation, pressure, global and net solar radiation, wind direction and speed, humidity, and present weather. For this study, data from ARPA was used due to its high resolution and proximity to the study area (dilium.com, n.d.).

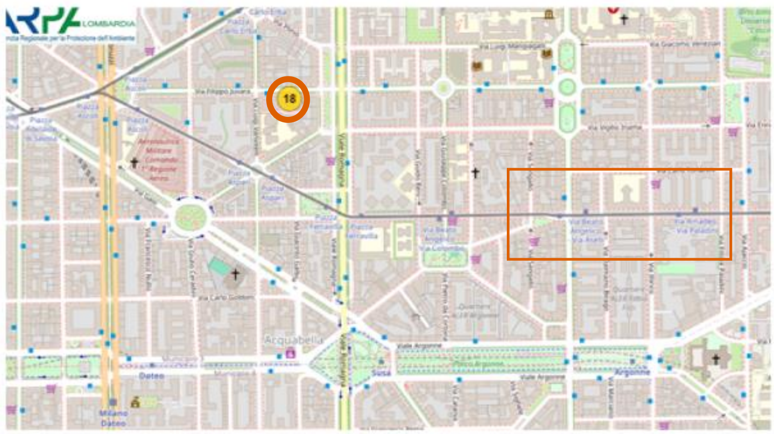



Figure 28.the Juvara Weather Station's location, closest weather staion to Acquabella

- CAMS:

The Copernicus Atmosphere Monitoring Service (CAMS) provides time series of global, direct, and diffuse irradiations on horizontal surfaces, and direct irradiation on normal planes (DNI) for both actual and clear-sky conditions (*CAMS Radiation Service - SoDa*, n.d.). CAMS data, available from 2004 to two days ago with time steps ranging from 1 minute to 1 month, were used to gather radiation data specific to the study area. The necessary information, including longitude, latitude, altitude, start and end date, and time step, was requested in CSV format.

For accurate simulations, the elevation of Milan above sea level (120m) was considered. The ARPA sensors measured at a pedestrian level of 122m, while CAMS radiation service data were recorded at123m above surface level, ensuring that all measurements were taken at comparable levels to provide consistency in the simulation.

### Receptors

Receptors are designated points within the model area that monitor detailed atmospheric and soil processes. In this study, 21 receptors are strategically placed, each positioned in front of a façade under inspection, at a maximum distance of 2 meters. The exact coordinates (x, y) of these receptors are determined prior to starting the simulation (ENVI-met, 2024). Receptor data files are generated at each receptor output interval, typically every 10 minutes, capturing the general state of the receptor at the specified model time. These files include atmospheric and soil data for each cell height.

The receptors are situated such that their lowest cell is on the pavement, ensuring that the surfaces affecting the temperature around each receptor, aside from the building façades they face, remain constant. This setup allows for precise environmental monitoring and provides reliable data for analyzing the impact of façade materials and configurations on microclimatic conditions.

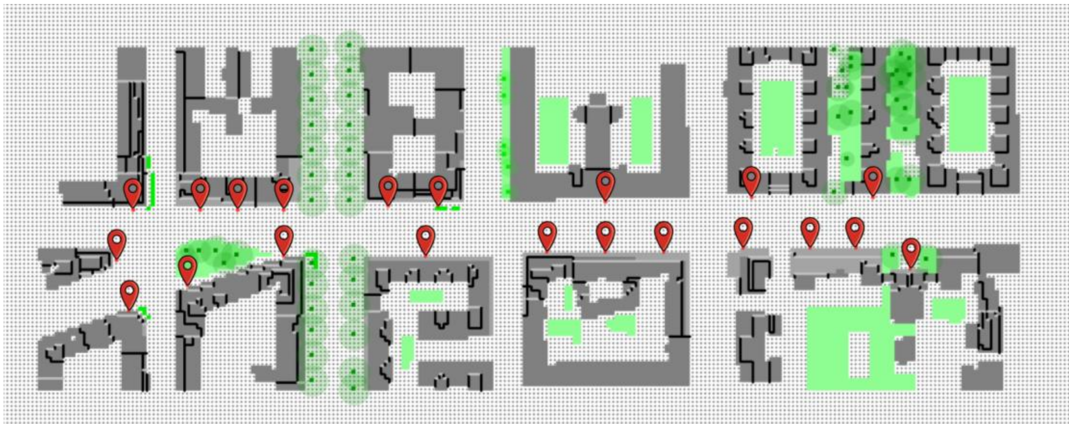


Figure 29. Placement of receptors in the 'Model Area' in ENVI-met's 'Spaces'

The critical variables measured by the receptors for this research include:

- Air temperature
- Mean Radiant temperature
- Direct, diffuse shortwave radiation
- SVF
- Sensible heat from Leaf Area Unit if a plant is present
- Temperature divergence due to longwave fluxes

## 5.3.2.4 Biomet

ENVI-met Biomet is a post-processing tool used to determine human thermal comfort indices based on the output from simulation data. In this study, the chosen index is the Physiologically Equivalent Temperature (PET). PET is defined, as already mentioned, as the indoor air temperature at which the human body's heat budget remains balanced, maintaining the same core and skin temperatures as experienced under outdoor conditions (Piselli et al., 2018). This index is vital for assessing thermal comfort in outdoor environments.

Accurate PET calculation requires identifying the meteorological parameters that critically influence the energy balance of humans at a height significant for biometeorological studies. This height is standardized at 1.1 meters above ground level, representing the average height of a standing person's center of gravity (Milano Leonardo et al., n.d.).

The concept behind PET and other outdoor thermal comfort indices is that the thermal comfort of a human body can be expressed using skin and core temperature as reference indicators (ENVI-met, 2024).

### User Profiles for PET Simulations in ENVI-met

The development of user profiles for PET (Physiological Equivalent Temperature) simulations in Biomet is a critical step in assessing outdoor thermal comfort for various demographic segments within Municipio 3 of Milan. These profiles are based on demographic data, including gender, age, height, weight, BMI, clothing insulation, and activity levels, validated by survey results. This approach allows for a nuanced understanding of how different personal characteristics influence thermal comfort and how various façade properties might affect these user types differently.

## 5.3.2.5 Leonardo

The Leonardo interface is a specialized tool within ENVI-met used to render selected output data into 2D or 3D maps for specific times or datasets. For 2D images, users can select the plane's position—X-Y, Y-Z, or X-Z—where the area should be cut. To facilitate easy comparisons, all 2D simulations are set at 1 meter above ground level, aligning with the height used in PET simulations(Milano Leonardo et al., n.d.).

In this study, the primary parameters exported in Leonardo include potential air temperature, mean radiant temperature, PET, relative humidity, and direct solar radiation. One valuable feature of Leonardo is its ability to explore and analyze changes in one or more data points within a single grid cell. The grid cell dimensions vary depending on the resolution. This information can be exported to an Excel datasheet or as a .csv file for further analysis. For this paper, specific points within the urban context were analyzed to observe the variation of PET over time, corresponding to the same cells where receptors are placed in front of each façade.

Leonardo also enables the creation of sensible difference maps when comparing two scenarios with identical dimensions. It automatically displays the absolute difference in parameters, such as air temperature, between the two scenarios at a specific hour by subtracting the values from both files. This function has been utilized to understand the differences in PET between the six user profiles.

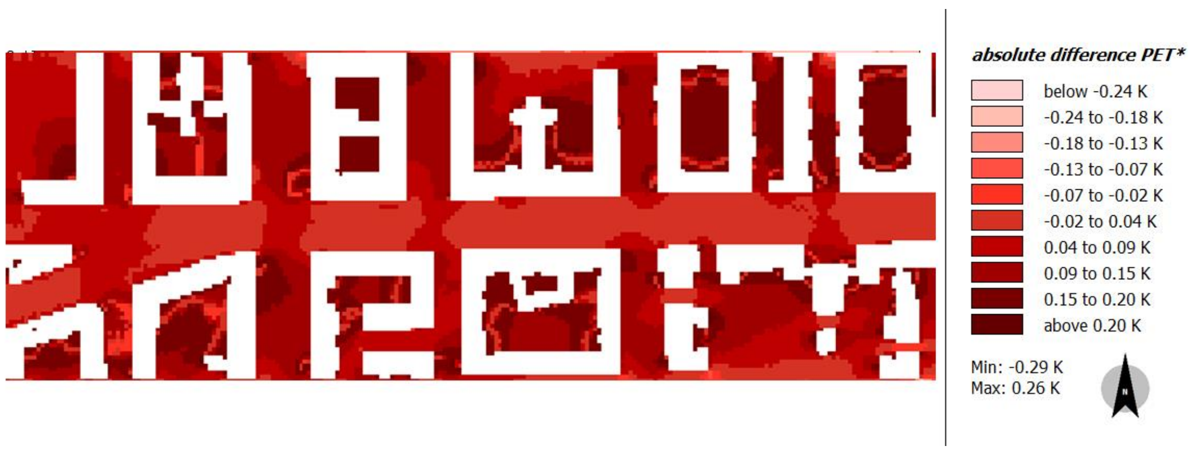



Figure 30. Leonardo - Absolute difference in PET between user profiles at 04.00.00, 03/08/2023

## 5.3.2.6 Conclusions

The ENVI-met methodology involves three stages: field survey, input data, and analysis. In the field survey stage, the site is systematically characterized onto a plan-referenced database. The input data stage sets up the model with detailed environmental data and specifies simulation parameters.

Climatic data for the simulation is gathered from multiple sources, including ARPA, and CAMS, to accurately represent the worst-case scenario for thermal comfort in 2023. August 2nd is chosen as the simulation day, with a 72-hour simulation run to validate results. Receptors are strategically placed to monitor detailed atmospheric and soil processes, capturing critical variables such as air temperature, mean radiant temperature, and direct solar radiation. ENVI-met Biomet post-processing tool calculates the Physiologically Equivalent Temperature (PET) to assess human thermal comfort, incorporating user profiles based on demographic data from Milan. The Leonardo interface renders output data into 2D or 3D maps, facilitating comparisons and analyzing changes in data points within grid cells. The analysis stage interprets the simulation results to understand heat and energy fluxes, the impact of surfaces and vegetation on thermal comfort, and the overall microclimate of the study area.

### 5.3.3 Thermal Walk

#### 5.3.3.1 Design of Thermal walk

The thermal walk is a final participatory step designed to validate the PET results obtained from simulations and the findings from the workshops, while exploring how on-site observations may influence the thermal perception of pedestrians in different ways. The event, scheduled for June 22, involves participants from Cista and other members of the Acquabella district. During the thermal walk, participants stop in front of facades identified through the research investigation. The selection criteria for these facades are based on the results and indications from previous analyses on the particular street. At these specific points, participants fill out three surveys that include questions about:

Survey 1(once at the beginning of the walk):

- Personal characteristics (height, weight, age, gender).
- Clothing insulation (a multiple-choice question regarding clothing level to assess each participant's clothing insulation level) – this will only be used in extreme cases where a participant's thermal perception answer is questionable compared to the rest of the data, or the dressing level of the participant is not expected- out of ordinary.
- Previous Activity (Question on the participant’s activity for the past half hour).

Survey 2 (filled out at each stop):

- Perceived environmental conditions (questions about the sun exposure and perceived wind)
- Participant’s thermal comfort level on a 7-point scale Likert at that particular moment.
- The participant's thermal sensation on a 7-point scale ASHRAE associated with the façade they are facing at that particular moment.
- The participant's aesthetic perception on a 7-point Likert scale associated with the same facade at that particular moment.
- A photo of the building façade they are facing

Survey 3 (once at the end of the walk):

- The level of difficulty of the walk in a 7-point Likert scale
- A ranking of the stops in terms of thermal perception and aesthetic perception
- Proposals for changes to mitigate heat


Figure 31. Map of Via Beato Angelico with indications for every stop of the thermal walk.

During the thermal walk, 10 stops are made in front of each study's building facades. Field measurements are taken using portable sensors worn by the participants, including a thermohygrometer and a pyrometer to measure air humidity (%), air temperature (°C), surface temperature (°C), dew point temperature (DPT), heat index (HI), wet bulb temperature (WBT), globe temperature (GT), WBGT index, and air pressure (hPa). These instruments are operated by the event coordinator, a member of Cista social district.

Figure 32. a)pyrometer bp21 b)Thermohygrometer TC100. Instruments used for the field measurements during thermal walk (Thermohygrometer TC100, n.d.)

These measurements aim to verify the participants' responses to see if personal characteristics affect the perception of standard temperature and help validate the receptor results for air temperature differences in front of facades with varying materiality. This step provides final feedback from the true users, testing potential confounding variables and reinforcing the workflow with additional data from the users' real-time experience, ensuring a comprehensive and verified combination of methods in the thesis.

### 5.3.4.2 Data processing & Analysis of thermal walk

The processing of data retrieved from the thermal walk replicates the steps of the previous events. Initially, a demographic analysis of the participants' characteristics is conducted to determine if the sample is representative of the population and the survey results. Participants are assigned to the user profile that matches their age, gender, and the closest personal characteristics.

Next, an analysis of the environmental conditions measured during the walk is performed, focusing primarily on air temperature and surface temperature of the facades in question. The environmental measurements, date and time of the walk, geographic location, and the personal characteristics of the participants are used to calculate the PET for the individuals. Two vulnerable groups are targeted in this phase as representatives for the calculated PET. The RayMan Urban Climate software is used to calculate the PET for the individuals. Wind speed data during the walk is sourced from the ARPA weather station.

Comparisons and correlations between thermal comfort, thermal sensation vote (TSV), and perceived aesthetics are performed. Votes are associated with the facades they refer to, allowing for an evaluation of these facades. The effects of other parameters, such as sun exposure and perception of wind, on the TSV are also analyzed. Additionally, the efficacy of PET as a representative index for more vulnerable groups is tested by comparing TSV to the calculated PET.

The significance of material properties over TSV and PET is examined using a one-way ANOVA test to identify the worst-rated facades. This comprehensive analysis aims to validate the findings of the workflow and provide actionable insights for improving thermal comfort and aesthetic appeal in urban environments.

## 5.4 Decision matrix & Design

### 5.4.1 Decision matrix

The decision matrix serves as a table that visualizes the findings from simulations regarding the neighborhood configuration and the implications of each factor on PET and mean radiant temperature (Tmrt). By categorizing these factors, the matrix provides clear design options for the specific street, aimed at improving thermal conditions. These options can be filtered based on their applicability, considering the use, needs, and possibilities of the location. The matrix integrates simulation results with findings on factors affecting subjective thermal sensation and incorporates specific preferences derived from user data.

### 5.4.2 Design

Based on the decision matrix, a design proposal is formulated, utilizing filtered information from both objective and subjective data to suggest feasible solutions for creating a more thermally comfortable neighborhood. The solutions focus on building façade alterations and incorporate people's suggestions for other changes in the surrounding urban environment. Proposed interventions include modifications to upper and ground floor façade materials, pavement and street materials, vegetation, and shading devices. Aesthetic considerations also influence the choice of building facades and the extent of alterations.

The effectiveness of the design proposal is tested through simulations in ENVI-met. New simulations are performed using the same settings as the original simulation, with changes to materials or material properties based on the identified indications. The simulation focuses primarily on material properties to assess their impact on the outcomes. The simulations are conducted for the same date as the original (03/08/2023), but only for the daytime hours (4:00 – 18:00) when overheating is most critical. A comparison between the original and the design proposal is made, examining PET, air temperature (Tair), and Tmrt at street level and for each receptor. This comparison aims to evaluate the effectiveness of the workflow indications and the potential reduction in thermal discomfort in the study area.

# 6 Results

## 6.1 Workshop

### 6.1.1 Analysis of Workshop Results

The analysis of the workshop results is conducted using QGIS (Free and Open Source Geographic Information System). The choice of software is made due to its ease of use and accessibility, which benefits future researchers and residents interested in applying the workflow in different regions or circumstances. The primary aim of the analysis is to identify the most problematic areas in the district, which will define the study area for the simulations.

**Data Collection and Preparation:**

During the workshop, participants evaluate the environmental quality of the Acquabella district by providing votes on four different maps, each representing a distinct aspect of environmental quality: thermal, acoustic, air, and aesthetic. These evaluations are marked with positive and negative votes, and participants are allowed unlimited voting to express their perceptions comprehensively. An attribute table is created to organize the collected data. Each entry in the table includes an ID, the street name, the domain of environmental quality (thermal, aesthetic, acoustic, air), and the perception (good or bad).

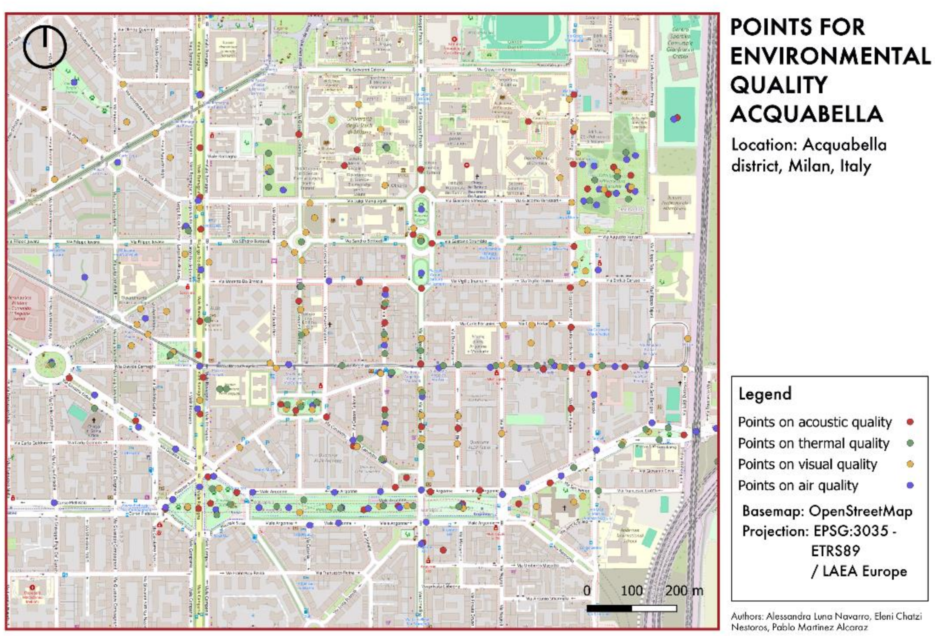



Figure 33.Workshop - Points for environmental quality in Acquabella

### Thermal & Aesthetic Point Analysis:

Given that the primary focus of this thesis is outdoor thermal comfort, the analysis concentrates on the thermal votes. The first step is to isolate the thermal points from the dataset. These points are then used to create a 15-meter radius buffer around each point. This buffer size is chosen based on the average width of streets and pavements in Milan, ensuring the analysis focuses on areas directly influenced by building facades rather than open spaces like parks (*Atlas of Urban Expansion - Milan*, n.d.).

Next, an extraction process identifies the points within this buffer that intersect with buildings in the Acquabella district. This step is crucial to ensure that the analysis remains relevant to the influence of facades on thermal comfort. Similarly, a 15-meter radius buffer is created around the aesthetic points to examine the correlation between thermal and aesthetic perceptions. To explore the relationship between thermal and aesthetic perceptions, thermal points that intersect with the visual buffer are selected. This intersection helps identify areas where both thermal and visual environmental qualities are perceived, allowing for a more integrated understanding of how these factors influence pedestrian comfort.

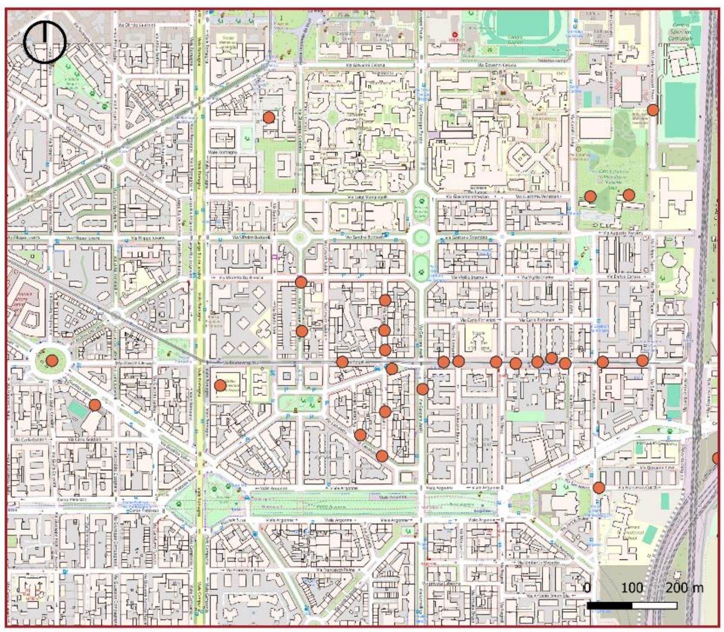



Figure 34. Filter distance from buildings 15m

### Frequency and Importance Analysis:

During the workshop, participants also provide input on the frequency and importance of various locations within the district. Maps and post-it notes allow participants to mark places they frequently visit and deem important. A 100-meter buffer is created around these points to identify areas of high pedestrian activity and significance. This buffer size is chosen to reflect a short walking distance within the district, considering Milan's overall walkability (*Milano Lombardia - Walk Score*, n.d.). Thermal points within this 100-meter buffer are then selected to narrow down the focus to areas with high pedestrian interaction and significance. This approach ensures that the subsequent analysis and recommendations will be highly relevant to the most used and valued parts of the district.

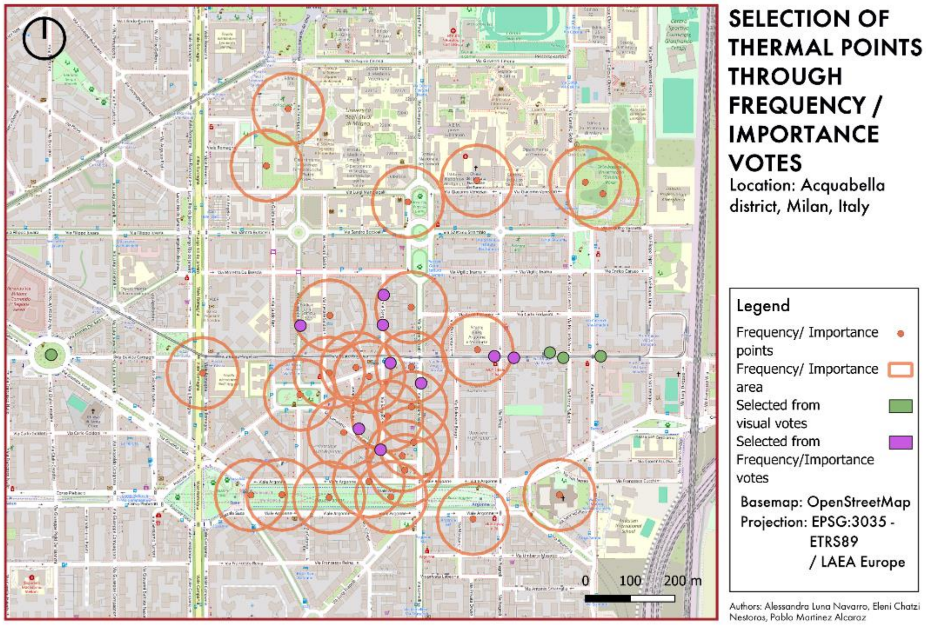



Figure 35. Filter by frequency & importance votes

### Density Mapping and Heatmap Creation:

To visualize the spatial distribution of environmental quality perceptions, a grid of 100m x 100m is created over the study area. Points within each grid cell are counted, and an attribute list is generated. This list indicates the number of environmental quality points within each grid cell.

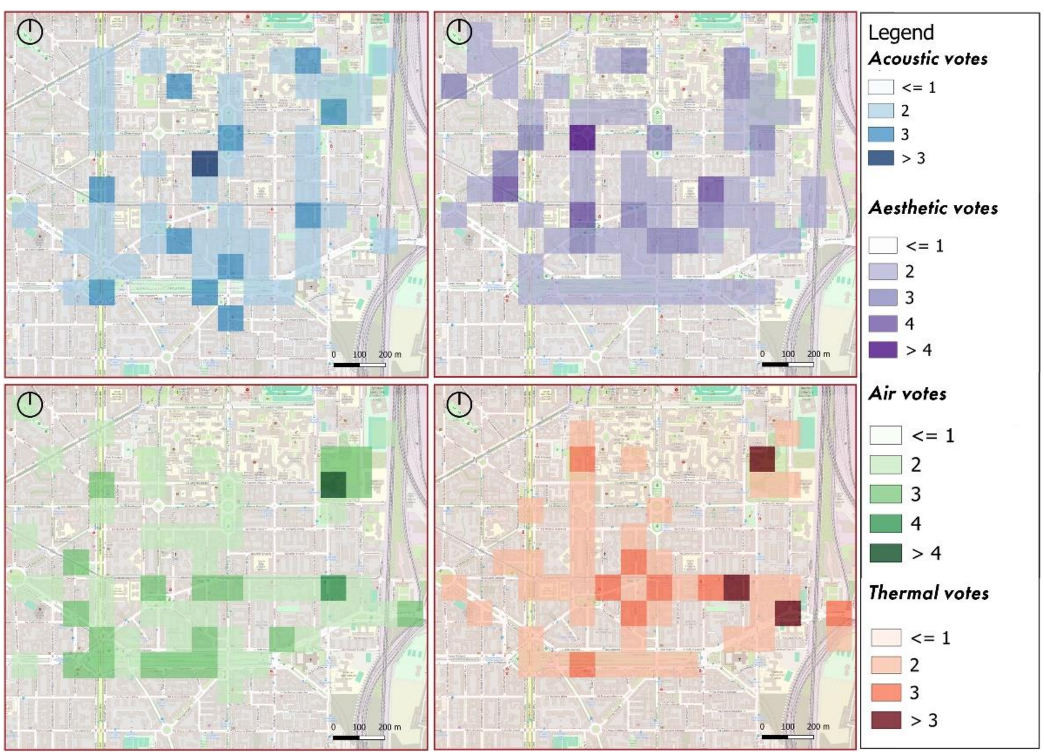



Figure 36. Heatmaps for environmental quality votes. 1. Acoustic 2. Aesthetic 3. Air 4.Thermal quality ¦ Workshop

The data is then used to create a raster layer, where the list's values are combined with weights representing the perceived importance of each environmental domain, as voted by workshop participants. The resulting density map highlights the most vulnerable or problematic areas in the district.

- ***How important do you consider the following environmental parameters?***

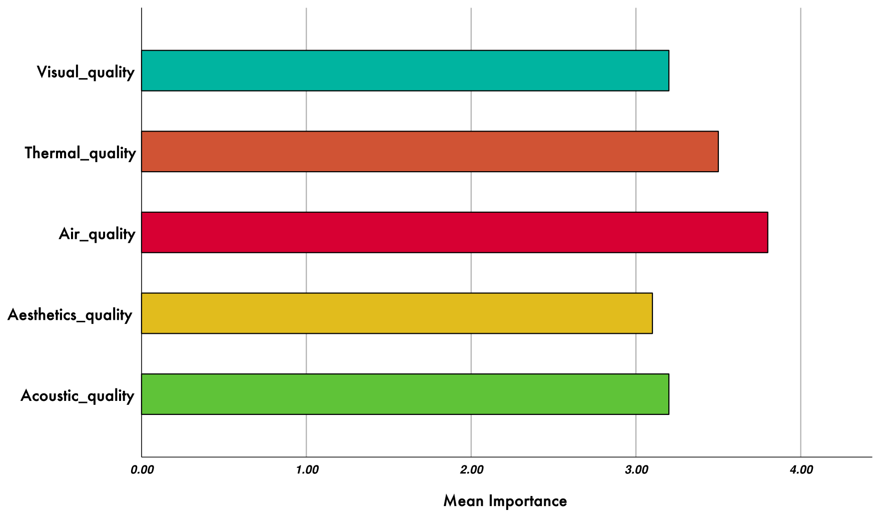



Figure 37. Workshop - Importance of environmental parameters

To further refine the analysis, heatmaps are created using Kernel Density Estimation for good and bad perception votes separately for each environmental domain. A kernel radius of 100 meters is used, reflecting the localized nature of environmental phenomena. This step helps identify specific areas of the district with the highest concentrations of positive and negative perceptions.

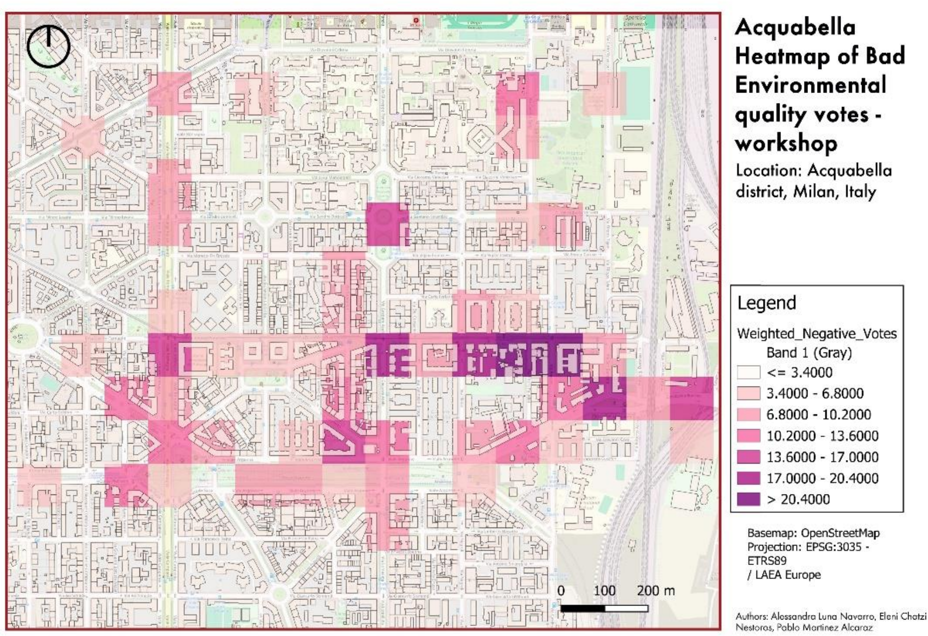



Figure 38. Density heatmap for perceived environmental quality weighted by domain importance.

## 6.1.2 Thermal sensation and materials

The workshop on "Material Evaluation and Feedback" aimed to assess the thermal perception of common facade and pavement materials. In analyzing the results, the first step involved calculating the mean thermal sensation for each material evaluated during the workshop. The thermal sensation was measured on a 5-point scale, with participants answering the question, "What thermal sensation do you associate with the material on the building?" By extracting these means, it was possible to rank the facades according to people's evaluations. This ranking allowed for an association between the depicted materials and their respective properties, as calculated for the simulations.

Subsequently, a one-way ANOVA and Spearman correlation rank were employed to test the statistical significance and correlations between thermal sensation vote (TSV) and the material properties. The results indicated that emissivity is the material property which is statistically significant, with a significance level, or p-value =0.036. Among the materials evaluated, brick received the highest thermal sensation votes, indicating the greatest perceived warmth, while marble received the lowest votes, indicating the least perceived warmth associated with the material.

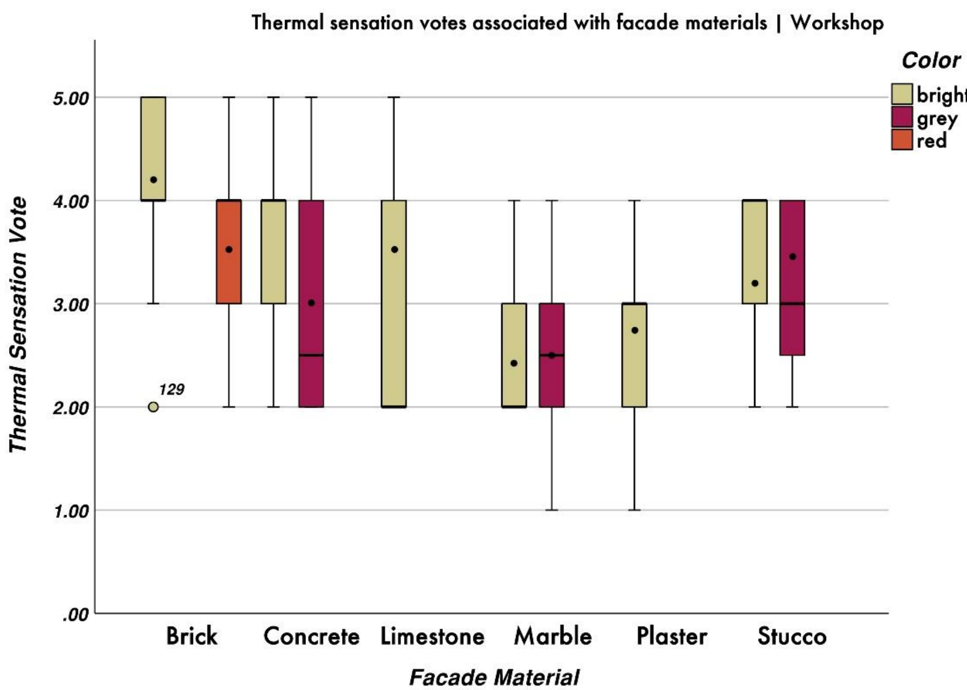



Figure 39. Boxplot of TSV associated with facade materials. N=18

## 6.1.3 Area of Study

### 6.1.3.1 Identifying the Simulation Area

Via Beato Angelico is chosen as the focus area for several reasons. It has a high concentration of negative votes for environmental quality, indicating the need for intervention. The street is wide with a uniform East-West orientation, making it ideal for controlled simulations. There is minimal vegetation, which reduces confounding factors in the analysis. The buildings along this street vary in age and height, ranging from 1920 to 1980, with different construction types and heights (3-9 stories), providing a diverse sample for analysis (*Search - Geoportale Della Lombardia*, n.d.). Furthermore, the presence of stores, a school, and bars ensures high pedestrian traffic, making it a relevant area for studying pedestrian thermal comfort.

### 6.1.3.2 Urban Geometry and Properties

Key parameters affecting canyon geometry in Via Beato Angelico:

1.Aspect Ratio

A preliminary analysis of Via Beato Angelico's aspect ratio, based on street sections, reveals it is a shallow canyon with a wide street and low-height residential buildings. The aspect ratio ranges from 0.4 to 1 in the street's wider sections.

2.Street Orientation

Via Beato Angelico is one of the worst-rated streets in the district due to its wide layout, heavy traffic, E-W orientation, and exposure to direct solar radiation year-round.

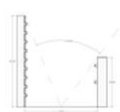
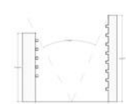
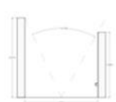
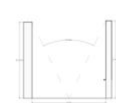
| Section of the street | Orientation | SVF % | Aspect ratio H/W | Section of the street | Orientation | SVF % | Aspect ratio H/W |
|---|---|---|---|---|---|---|---|
|  | E-W | 40.40 | Asymmetrical ~1.06 |  | E-W | 33.30 | Asymmetrical ~1.07 |
|  | E-W | 37.40 | Asymmetrical ~1.00 |  | E-W | 30.30 | Asymmetrical ~0.43 |
|  | E-W | 36.30 | Asymmetrical ~0.89 |  | E-W | 45.60 | Asymmetrical ~0.73 |
|  | E-W | 36.10 | Asymmetrical ~0.86 |  | E-W | 41.5 | Asymmetrical ~1.04 |

Figure 40. Aspect Radio (H/W), Orientation and SVF value for Via Beato Angelico

3.Sky View Factor (SVF)

Preliminary analysis using the Ladybug plugin in Grasshopper indicates that the SVF measured at pedestrian level (1.1m) on Via Beato Angelico ranges from 30-45%, a relatively high percentage.

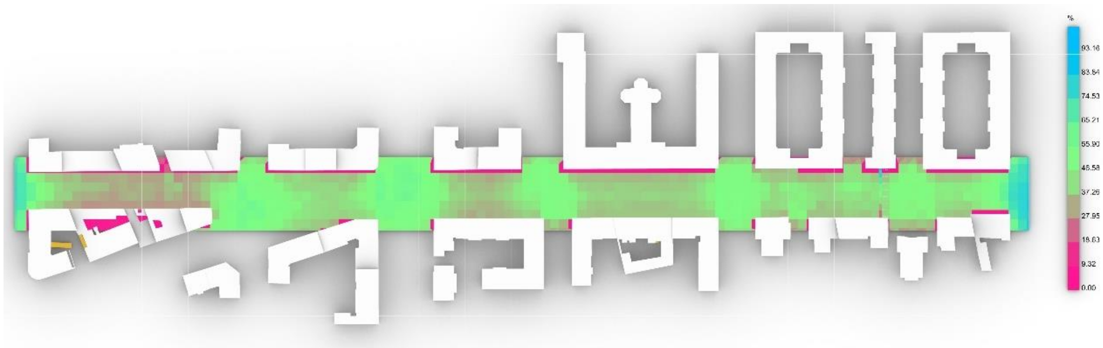



Figure 41. Ladybug simulation of SVF, section level:1.1. Simulation month: August

4. Neighborhood Geometry Complexity

In this section of neighborhood configuration, a more comprehensive research is done on the shapes, heights, and construction types of the buildings in reference, as well as the vegetation elements in the street.

- Analysis of Surface Properties in Steps:

Building Geometry Configuration: The geometries of the buildings in the chosen area are simple orthogonal shapes with roofs sloped on both sides. The tallest buildings have terraces that recede at the upper levels. The building height for each of the buildings is found in the LOD1 geopackage provided by Geoportale della Lombardia (*Search - Geoportale Della Lombardia*, n.d.-b).

Balconies: To comply with the limitations of the ENVI-met software, a preliminary analysis was conducted using Grasshopper-Ladybug. Balconies in the area start at heights of 5m to 8m. Further analysis is required to determine if the balconies affect pedestrian thermal perception. The preliminary simulation indicated insignificant differences in received radiation and no difference in direct sun hours between geometries with and without balconies.


Figure 42. Radiation and direct sun hour simulations/ with and without balconies. Simulation month: August

Material Analysis: Record the base and facade materials for each building, considering the construction period and type. Using historical records (Corrado et al., 2014) (ABACO DELLE STRUTTURE COSTITUENTI L'INVOLUCRO OPACO, n.d.) and visual investigation through Google Earth, the construction type and materiality were approximated. For the analysis the following material properties and parameters were considered:

- Optical, Thermal, and Physical Properties: Analyze and record properties such as albedo, light reflectance factor (LRF), absorption, thermal conductivity, specific heat capacity, U-value, emissivity, and density.
- Ground Floor Glass Coverage: Determine the percentage of glass coverage at the pedestrian level for each building, indicating the presence of stores.


Figure 43. Identification of the buildings, subdivided in blocks from letter A to K

| Building Code | Ground Floor Facade material | Upper Façade material | Construction type | Height (m) | Construction | U-value (W/(m^2K) |
|---|---|---|---|---|---|---|
| A1 | stucco | stucco | Stone masonry striped with bricks | 18.027 | 1930 | 1.61 |
| A2 | stucco | stucco | Stone masonry striped with bricks | 23.97 | 1930 | 1.61 |
| B1 | plaster | plaster | Solid break masonry | 20 | 1930 | 1.48 |
| C1 | concrete | plaster | Solid break masonry | 31.26 | 1960 | 1.48 |
| C2 | concrete | ceramic | Hollow Brick masonry | 28.71 | 1934 | 1.26 |
| D1 | concrete | brick | Hollow-case masonry with perforated bricks | 28.61 | 1930 | 1.10 |
| D2 | concrete | brick | Solid break masonry | 31.92 | 1930 | 1.48 |
| D3 | concrete | brick | Solid break masonry | 29.85 | 1930 | 1.48 |
| E1 | stucco | plaster | Stone masonry striped with bricks | 22.78 | 1930 | 1.61 |
| F1 | Marble | brick | Hollow-case masonry with perforated bricks medium level of insulation | 30.74 | 1990 | 0.59 |
| G1 | concrete | brick | Solid break masonry | 22.39 | 1920 | 1.48 |
| G2 | stucco | brick | Hollow-case masonry with perforated bricks | 19.14 | 1932 | 1.10 |
| H1 | stucco | stucco | Stone masonry striped with bricks | 28.95 | 1930 | 1.61 |
| H2 | stucco | Plaster | Plastered stone masonry | 27.37 | 1920 | 2.40 |
| I1 | stucco | plaster | Stone masonry striped with bricks | 24.84 | 1928 | 1.61 |
| J1 | concrete | brick | Solid break masonry | 26.08 | 1936 | 1.48 |
| J2 | concrete | brick | Hollow-case masonry with perforated bricks low level of insulation | 27.10 | 1980 | 0.78 |
| J3 | stucco | plaster | Perforated brick masonry medium level of insulation | 26.95 | 1990 | 0.61 |
| K1 | marble | plaster | Hollow-case masonry with perforated bricks low level of insulation | 29.13 | 1980 | 0.78 |
| K2 | marble | plaster | Hollow-case masonry with perforated bricks low level of insulation | 29.17 | 1980 | 0.78 |
| K3 | Marble | brick | Hollow-case masonry with perforated bricks low level of insulation | 33.19 | 1980 | 0.78 |
| K4 | marble | brick | Hollow-case masonry with perforated bricks low level of insulation | 30.57 | 1980 | 0.78 |

Table 6. Building codes, construction and material information

Table 7. Percentage of glass coverage at the pedestrian level (1m) for each building in the simulation

| Building Number | Glass Percentage (%) |
|---|---|
| A1 | 0 |
| A2 | 0 |
| B1 | 0 |
| C2 | 25 |
| C1 | 50 |
| D3 | 54.5 |
| D2 | 50 |
| D1 | 45.4 |
| E1 | 0 |
| F1 | 72.7 |
| G1 | 29.4 |
| G2 | 0 |
| H1 | 25.8 |
| H2 | 48. |
| I1 | 0 |
| J1 | 0 |
| J2 | 50 |
| J3 | 71.4 |
| K1 | 38.5 |
| K2 | 46.7 |
| K3 | 80 |
| K4 | 33.4 |

5.Vegetation

Vegetation Analysis: Using a shapefile from Geoportale Comune di Milano, record the tree species and classify them into height categories to assess their impact on the urban environment. The tree species in the study area include Acer Platanoides, Acer Pseudoplatanus, Platanus A- Acerifolia, Quercus Robur, Acer Negundo, Tilia Cordata, and Carpinus Betulus (SPAZIO PUBBLICO SPAZIO PUBBLICO Linee Guida Di Progettazione, n.d.). The trees are categorized as follows:

- Class 1: H > 25m
- Class 2: 15m < H ≤ 25m
- Class 3: 8m < H ≤ 15m
- Class 4: H ≤ 8m
- Class 5: H ≤ 2m (bushes and small trees)

### 6.1.4 Conclusions

The analysis of workshop results, conducted using QGIS, identifies the most problematic areas in the district for further investigation. Data collection involved participants evaluating the environmental quality of the Acquabella district through votes on thermal, acoustic, air, and aesthetic quality maps. The analysis focuses on thermal votes, using buffers to ensure relevance to facade influence, and highlights areas of high pedestrian activity and significance. Density mapping and heatmap creation visualize spatial distribution of environmental quality perceptions, refining the analysis to identify specific areas with high concentrations of positive and negative perceptions. The study area, centered around Via Beato Angelico, is chosen for its high concentration of negative environmental quality votes, wide street, uniform East-West orientation, minimal vegetation, and diverse building ages and heights. Aspect ratio, SVF, neighborhood geometry complexity , materiality and vegetation analyses are conducted to understand their impact on the urban environment, ensuring subsequent simulations focus on areas where facade materiality significantly influences outdoor thermal comfort.

## 6.2 Long-term survey

### 6.2.1 Socio-demographic Characteristics

In this paper, statistical methods are used to assess the collected data using SPSS (Statistical Package for the Social Sciences) software, version 25.0. Firstly, the demographic characteristics of the sample are summarized to measure the variability of the collected data.

A total of 200 responses are gathered. The analysis of the results with the final number of respondents starts on the 17th of May. However, the survey is still being distributed in the district, gathering more answers for the perception of pedestrians in all four domains as part of the larger project, CoSMoPolis.

Regarding gender distribution, it is found that 70.5% of the respondents are females, 26.7% are males, and 2.9% identify as non-binary. The most frequent age range of the respondents is identified as 40-60 years old, representing 50.5% of the sample. This is followed by the age range of 20-40 years old, which accounts for 21.9% of the respondents. Additionally, 20.5% of the respondents are found to be over 60 years old. The least common age range is under 20 years old, comprising 7.1% of the respondents. It is observed that most respondents live in the district and use public spaces once a day, as indicated by 42.4% of the responses.

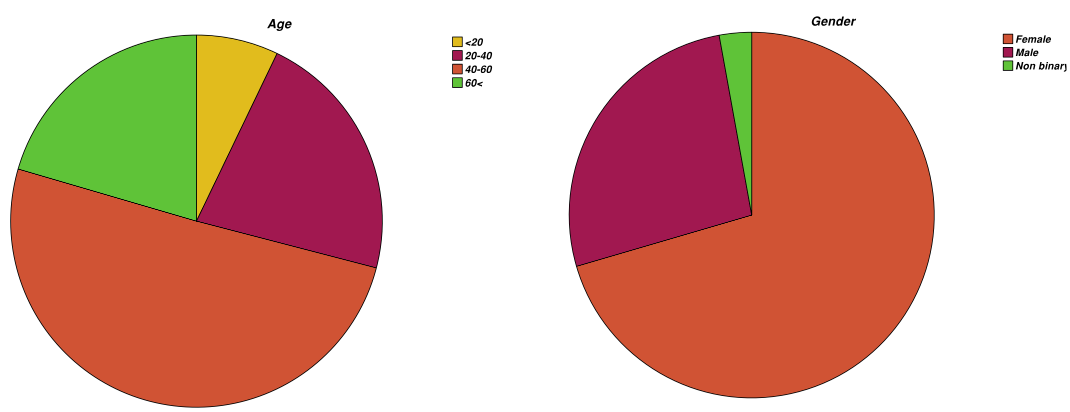



Figure 44. Survey sample composition - gender , age. N=200

When asked about the usual duration of their stay in the public spaces of Acquabella, it is reported that the most common answer is 'about an hour,' as mentioned by 31.4% of the respondents. The second most common response is 'up to 30 minutes,' accounting for 24.3%.

Regarding usual activities in these public spaces, it is found that the most common activity is 'going for a stroll in the district,' reported by 38.1% of the respondents. This is followed by 'leisure-related activities,' mentioned by 16.7%.

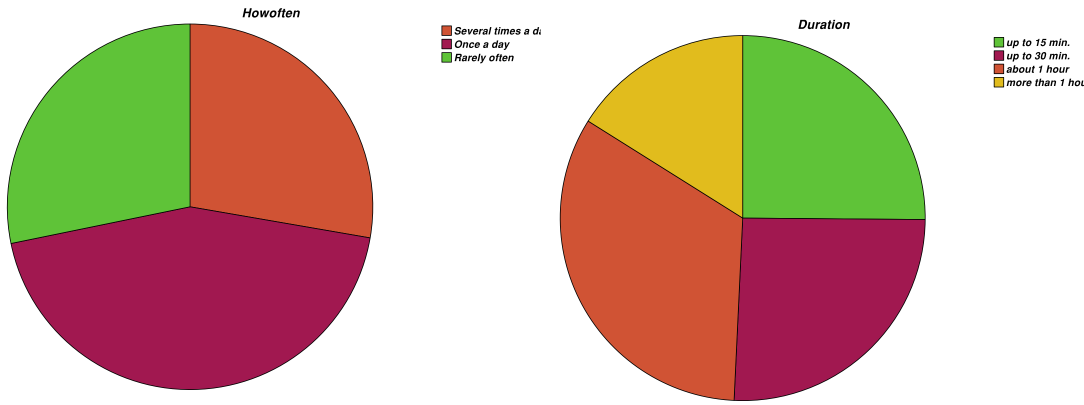



Figure 45. Survey sample composition - Frequency and duration of stay.N=200

## 6.2.2 Multi-domain analysis

To visualize the spatial distribution of environmental quality perceptions in the study area, a grid of 100m x 100m is created. This grid allows for the systematic counting of points within each cell, generating an attribute list that indicates the number of environmental quality points present. This methodological approach is consistent with the analysis used for the workshop results, ensuring comparability across different data sets.

The data visualization process involves creating heatmaps that show the density of both negative and positive votes across the district for four domains: thermal comfort, air quality, acoustics, and aesthetics. According to the survey results, these heatmaps provide a visual representation of how environmental quality is perceived within each grid cell. By illustrating areas with high and low densities of positive and negative feedback, these heatmaps highlight specific zones that may require attention or improvement.

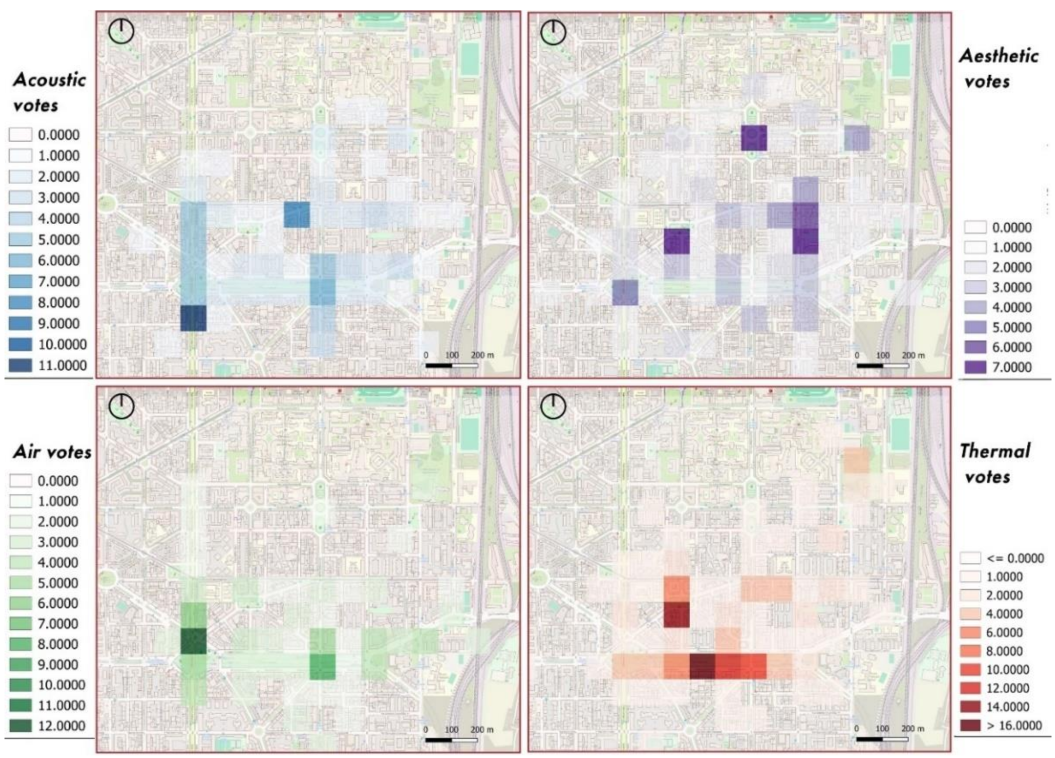



Figure 46.Heatmaps for environmental quality votes. 1. Acoustic 2. Aesthetic 3. Air 4.Thermal quality ¦ Survey

Weighted Heatmaps

The next step involves creating a heatmap that weighs the negative votes for each domain. The weights are calculated based on the values used in the workshop, where participants ranked the domains by their level of importance. By applying these weights to the negative votes, a composite map of weighted cluster values is produced. This weighted heatmap offers a more holistic understanding of which areas are perceived to have the most significant environmental quality issues, reflecting the relative importance of each domain as determined by community input.

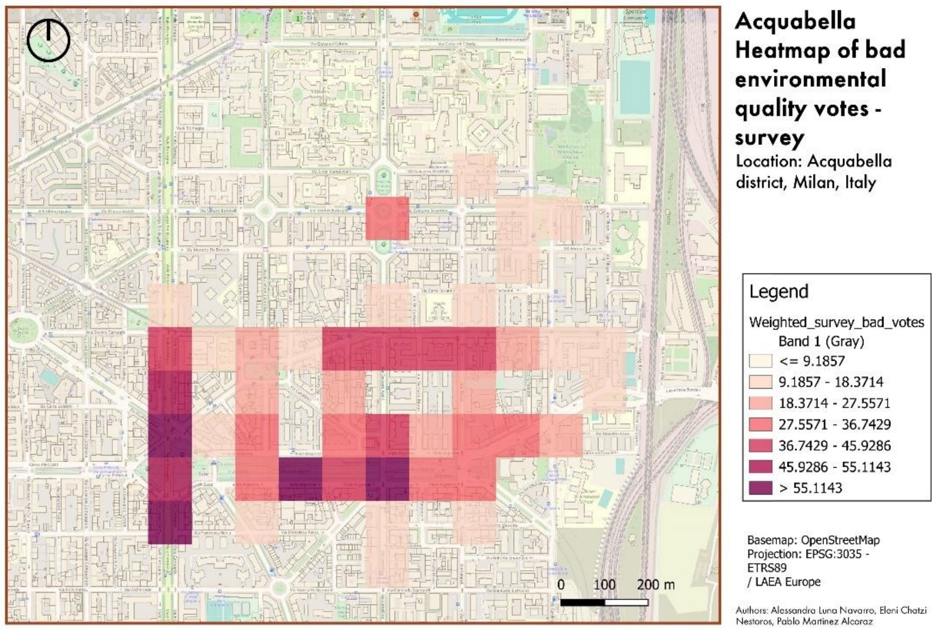



Figure 47.Density heatmap for perceived environmental quality weighted by domain importance¦Survey

## 6.2.3 Subjective Thermal Responses

In this analysis, the correlations between various variables derived from survey data are examined using Spearman's rank correlation coefficient. The variables include age, gender, subjective thermal and aesthetic perception, thermal and visual street characteristics, frequency of use ("howoften"), duration of stay, usual activity, reaction to thermal discomfort ("action"), and whether the location is a park (Park_A). The primary focus is on identifying factors that influence subjective thermal perception in specific locations.

- A significant negative correlation exists between thermal perception and aesthetic perception ($\rho = -0.352$, $p < 0.001$). This implies that higher thermal discomfort is associated with lower aesthetic satisfaction.

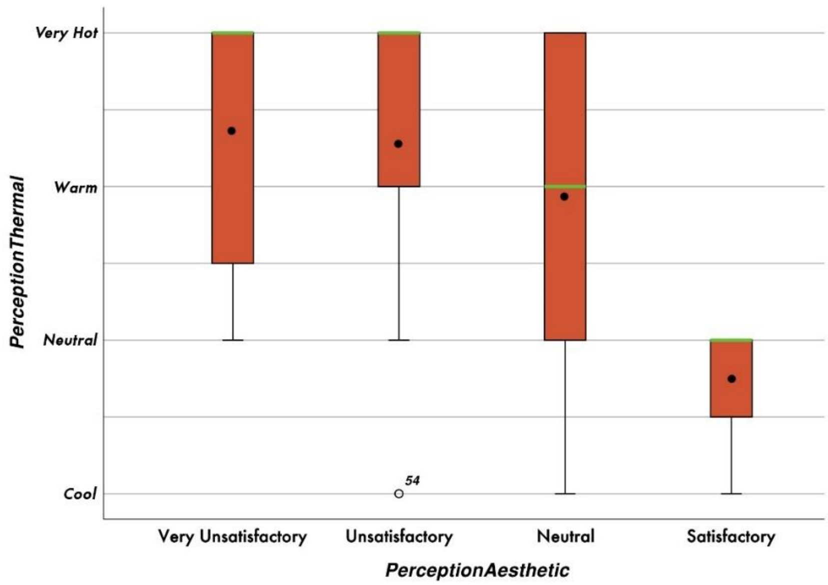



Figure 48. Boxplot of Thermal and Aesthetic sensation votes. N=135

- The correlation between thermal perception and the variable 'how often' (which measures the frequency of visits to the voted areas) is significant and negative (ρ = -0.198, p = 0.007).
- Thermal perception is significantly correlated with the variable 'Park' (ρ = 0.298, p < 0.001), which indicates whether the voted spot is located in a place with vegetation.

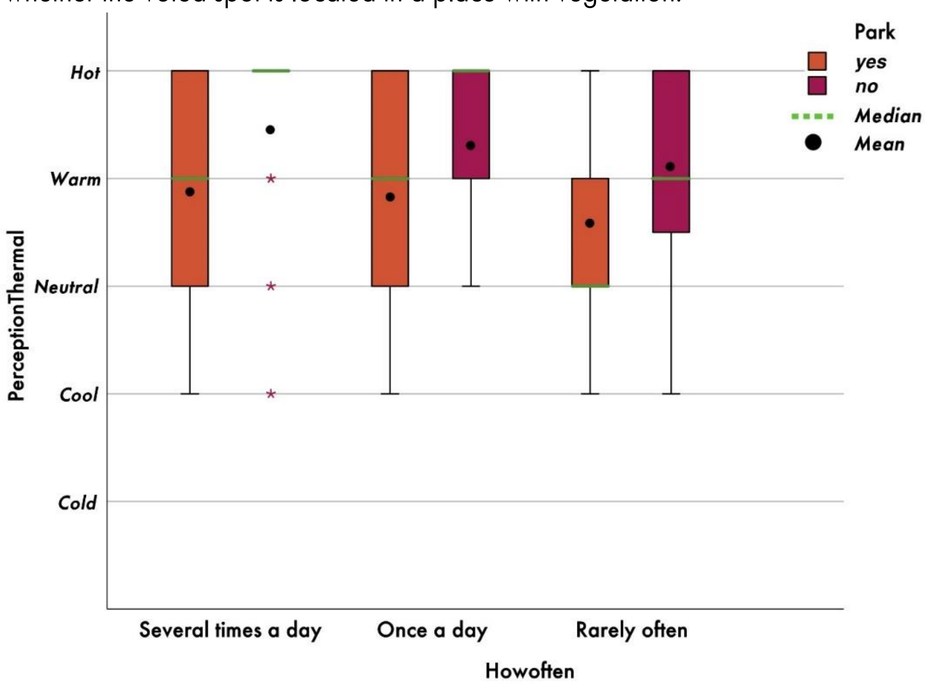



Figure 49. Boxplot for thermal sensation votes and frequency of visits filtered by proximity in vegetated area.N=186

- Age does not show a significant correlation with thermal perception (ρ = -0.013, p = 0.863), indicating that age does not significantly influence thermal comfort levels among respondents in the preliminary stage of the analysis. Also, in this stage of the analysis, gender does not show a significant correlation with thermal perception (ρ = -0.070, p = 0.334).

### Further Analysis and Clustering

To refine the analysis, DBSCAN clustering in QGIS is used. This method allows for the grouping of data points into clusters based on proximity, excluding outliers. The resulting clusters are then analyzed to calculate the mean thermal and aesthetic sensation votes for each group. This approach helps to control the possibility of errors by analyzing data in aggregated groups rather than individual points.

The Spearman correlation analysis of the clustered data confirms that the significant negative relationship between thermal and aesthetic perceptions persists (ρ = -0.381, p = 0.014), even without outliers. This demonstrates the robustness of the correlation between thermal discomfort and aesthetic dissatisfaction.

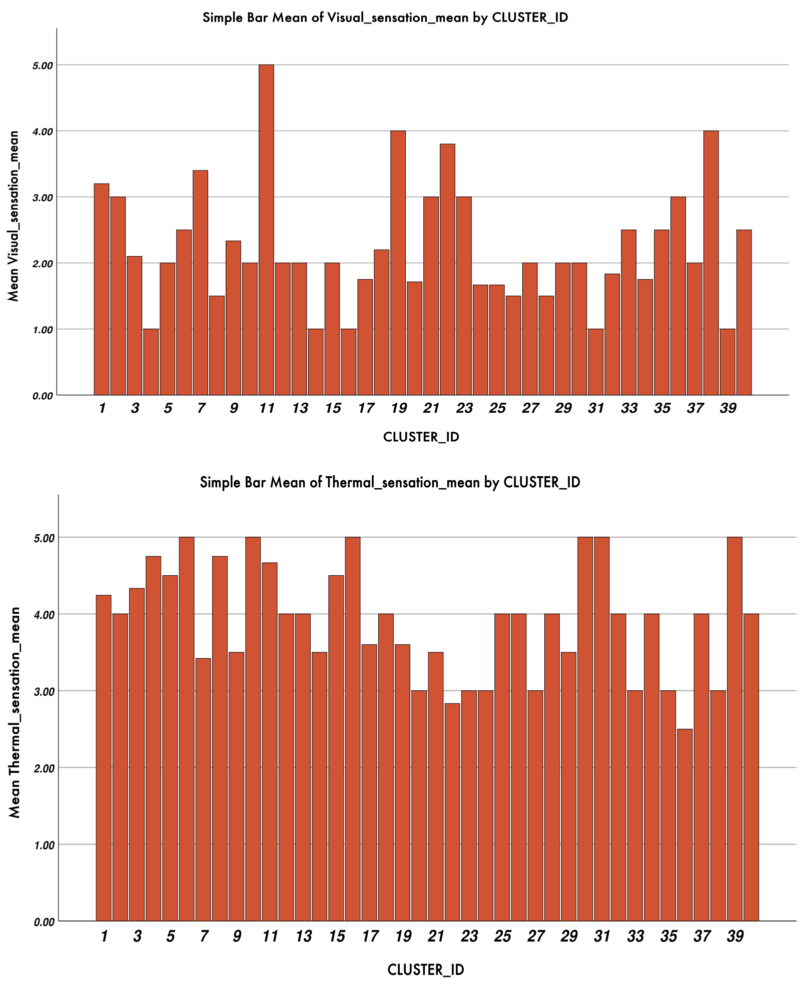



Figure 50. Mean aesthetic and thermal sensation votes for each cluster.

### Descriptive Statistics for Via Beato Angelico Clusters

Focusing on the clusters located in Via Beato Angelico (clusters 4, 6, 8, 32, and 33, containing 5, 4, 12, 8, and 3 votes respectively), descriptive statistics were performed to identify patterns. By examining the survey data for the entire district, a clear pattern emerges regarding thermal sensation and aesthetic satisfaction. Via Beato Angelico stands out as one of the most unsatisfactory streets, consistently receiving negative ratings from respondents. This indicates a significant issue in both thermal comfort and aesthetic appeal in this area. The analysis shows that 100% of the thermal votes indicate discomfort, with 78.6% of the votes being at the 'very hot' end of the scale(ASHRAE 5-point scale).

- Age Range: The majority of respondents fall within the 40-60 years age range (44.8%), followed by 20-40 years (34.5%).
- Gender: A significant majority of respondents are female (72.4%), with 24.1% males and 3.4% non-binary individuals.
- Frequency of Visits: The greatest percentage of respondents (44.8%) visit the street several times per day, with 39.7% spending up to 30 minutes there.
- Activity: The most frequently cited activity is 'going for a stroll in the district' (27.6%).
- Action in Thermal Discomfort: The most common response to thermal discomfort is to avoid the place if possible (24.1%).

The descriptive statistics for Acquabella district are similar to those for Via Beato Angelico, indicating that it is representative of the problematic areas within the district. Notably, the best aesthetic votes were given by respondents aged 20-40 years, predominantly female and non-binary, while the worst aesthetic votes were from males over 60 years.

A deeper analysis differentiating respondents by age and gender uncovers further insights:

- Gender-Based Analysis: Both male and female respondents rated Via Beato Angelico with higher thermal sensation votes, indicating greater discomfort. However, females reported greater discomfort compared to males. This gender disparity suggests that women may be more sensitive to thermal conditions in this street.
- Age-Based Analysis: Within female respondents, a trend emerges where thermal sensation votes decrease with age. Women over 60 years old reported being within thermal comfort ranges, contrasting with younger female respondents who reported higher discomfort levels. In contrast to females, male respondents over 60 report the highest thermal sensation votes both district-wide and specifically in Via Beato Angelico. This indicates an increasing discomfort with age among male differing from the trend observed in females.

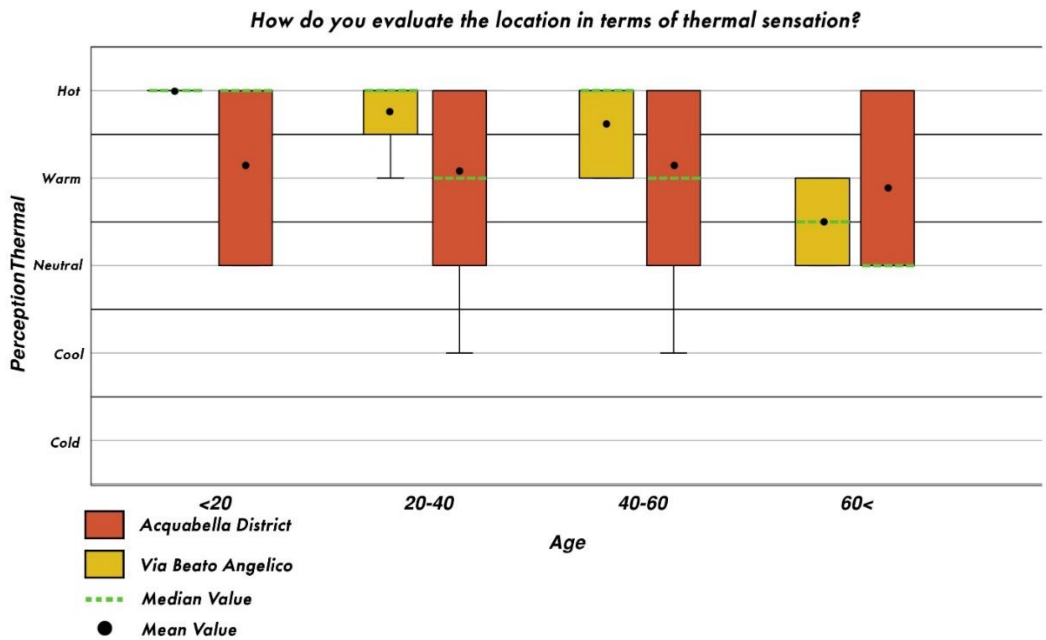



Figure 51. Mean thermal sensation votes for females of different ages. Comparison between general thermal sensation votes (N1=211) in Acquabella and thermal sensation votes (N2=21) in Via Beato Angelico.

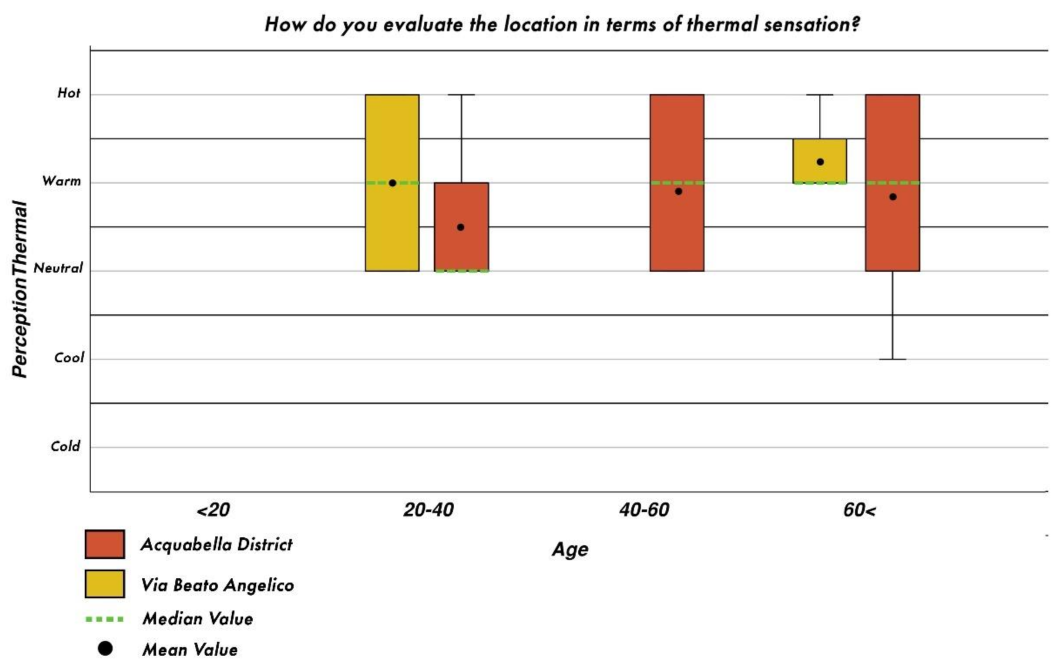



Figure 52.Mean thermal sensation votes for males of different ages. Comparison between general thermal sensation votes (N1=211) in Acquabella and thermal sensation votes (N2=11) in Via Beato Angelico.

The study highlights the strong relation between aesthetic and thermal perceptions.The analysis of thermal sensation and aesthetic perception was further refined by clustering the negative votes in Via Beato Angelico. By measuring the distance from these clusters to the closest façades, specific buildings in the district were identified as having the worst ratings. This method allowed for a detailed understanding of the spatial distribution of thermal discomfort and aesthetic dissatisfaction. The worst rated clusters are 32 –8 requiring interventions on façade appearance and thermal properties.

Table 8. Clusters of worst aesthetic and thermal votes in Via Beato Angelico, and to closest facades to each cluster

| Cluster Number | Cluster rate | Closest Facades |
|---|---|---|
| 4 | 1.82 | A1, K4 |
| 32 | 1.25 | A2, B1, J3, K1, K2 |
| 8 | 1.4 | B1, J1, J2, C1, I1 |
| 6 | 1.75 | D1, H2 |


Figure 53. Clustered negative thermal & aesthetic votes in Via Beato Angelico & closest buildings to each cluster.

## 6.2.4 Community-Driven Recommendations

In the survey, participants were asked an open-ended question: "What changes would you propose to make the locations more comfortable on hot days?" The responses were then grouped based on their context into categories such as trees, vegetation, water bodies, shading devices, decrease of street and parking width to increase pavement, urban furniture, change of pavement material, and addressing degradation issues while requesting interventions. These suggestions were subsequently assigned to the areas where the same respondents had evaluated the thermal conditions negatively on the map.

Focusing on Via Beato Angelico, the responses were gathered to investigate the desired changes on this street by those who voted negatively for it. Out of 200 respondents, only 55 provided both a negative thermal sensation vote and a suggestion for changes. Although the sample size is not large, it includes a diverse range of areas and suggested strategies.

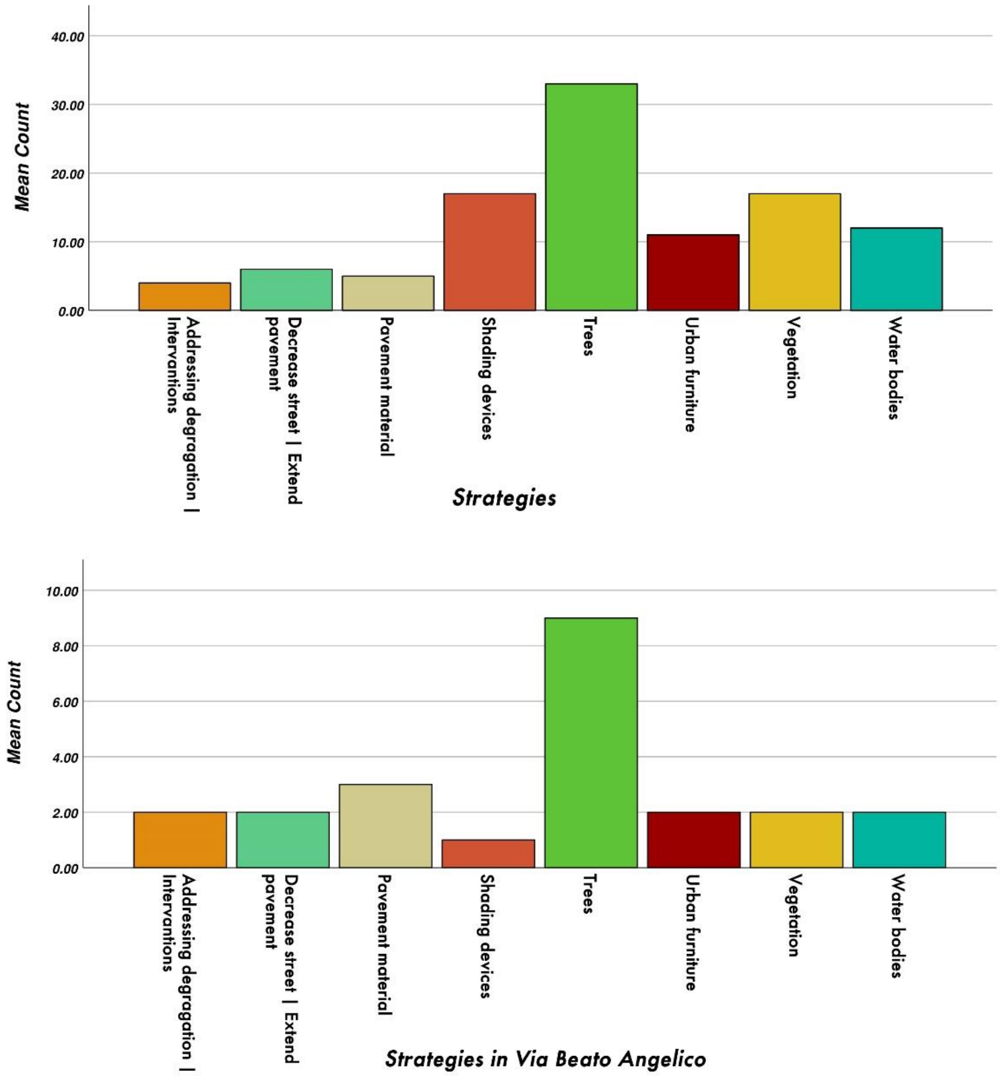



Figure 54. Community recommendations in district level (N1=55) and in street Via Beato Angelico (N2=15).

A comparison between the district-wide suggested strategies and those specific to Via Beato Angelico reveals that the most frequent recommendation in both cases is the addition of trees. At the district level, shading devices and greenery are the second most frequent suggestions, whereas, for Via Beato Angelico, the second most common recommendation is changing the pavement material.

## 6.2.5 Conclusions

The survey gathered 200 responses, revealing crucial insights into the demographic characteristics and subjective thermal perceptions of the Acquabella district's inhabitants. The sample comprised 70.5% females, 26.7% males, and 2.9% non-binary individuals, with the majority aged 40-60 years (50.5%). Most respondents are daily users of public spaces, with 42.4% reporting daily visits, and the primary activity being casual strolling (38.1%).

The analysis highlights significant correlations between thermal discomfort and frequency of visits and between thermal discomfort and aesthetic dissatisfaction. Areas with less vegetation correlate with higher thermal discomfort. These findings underscore the critical role of greenery in enhancing thermal comfort and the intertwined nature of thermal and aesthetic perceptions.

Further clustering analysis using DBSCAN in QGIS reinforces these correlations. Descriptive statistics for clusters in Via Beato Angelico reveal consistent thermal discomfort, with 78.6% of votes at the 'very hot' end of the scale. The majority of respondents in these clusters are females (72.4%), aged 40-60 years (44.8%), who visit the area multiple times a day. The study indicates that older male respondents tend to have more negative thermal and aesthetic perceptions, emphasizing the need for targeted interventions.

Finally, the survey indications assist in further clustering the responses to identify the most thermally uncomfortable and unattractive spots in the simulated area. This analysis associates these problematic areas with specific buildings that, according to participants, require interventions.

Focusing on Via Beato Angelico, responses were gathered to investigate the desired changes on this street by those who voted negatively for it. Out of 200 respondents, only 55 provided both a negative thermal sensation vote and a suggestion for changes. Although the sample size is not large, it includes a diverse range of areas and suggested strategies, reveals that the most frequent recommendation is the addition of trees and change of pavement material.

## 6.3 Simulations

### 6.3.1 Comparative analysis of Air Temperature

At this point in the research, the analysis of ENVI-met simulation results begins. The simulations are run using a manually created weather file, which collects data from the ARPA weather station. The sensors of this weather station are placed a few blocks west of Via Beato Angelico at a height of 2 meters. Additional data is sourced from the CAMS Radiation Service. For the simulations, 21 receptors are positioned in front of each façade on the street to measure the impact of the façades on PET and outdoor conditions at a height of 1.1 meter.

The focus is now on examining the difference between the measured air temperature from ARPA sensors, which was used for the simulation weather file, and the simulated potential air temperature in front of every façade. This comparison aims to determine how each building influences air temperature differently throughout the day according to ENVI-met.

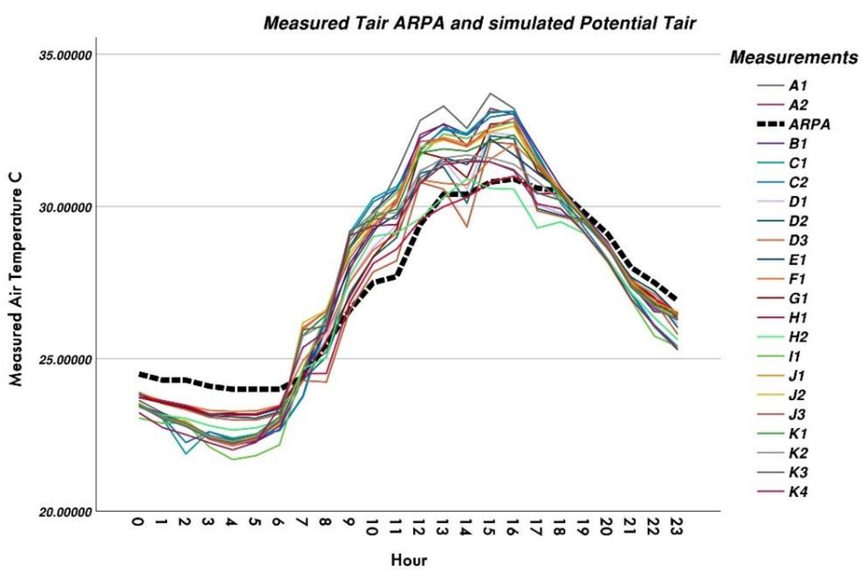



Figure 55. Actual Air Temperature Measured by ARPA Weather Station and Simulated Potential Air Temperature on 03.08.2023.

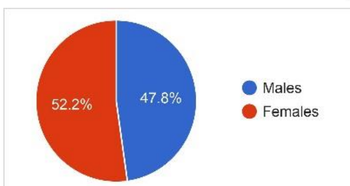
A significant difference between day and night values is detected. The simulated air temperature is lower than the measured air temperature during the night hours (18.00 – 07.00), while it can reach much higher values during the day hours (07.00 – 18.00). Specifically, receptors placed in front of façades A1, B1, C1, C2, I1, J1, J2, and J3 exhibit the greatest difference from the measured ARPA air temperature. These façades perform poorly, showing very high potential air temperatures—up to 3 degrees Celsius above the measured values during the day—and much lower temperatures during the night, up to 1.5 degrees Celsius below the measured values.

Conversely, receptors placed in front of buildings H1, H2, and D3 show similar values between the simulated and measured air temperatures. These façades perform better, with lower air temperature values during the day and higher values during the night.

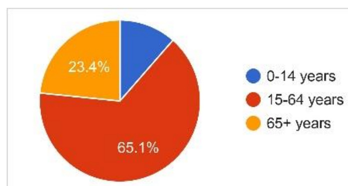
## 6.3.2 User profiles

### Demographic Analysis and Profile Creation in Biomet

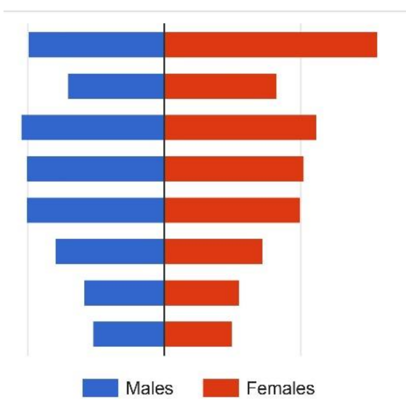
The demographic analysis is grounded on data from multiple sources, ensuring a representative cross-section of the community. According to the demographics of Milan, specifically Municipio 3, the female population slightly exceeds the male population, with women making up 52.2% and men 47.8% (*Milan City (Italy): Boroughs - Population Statistics, Charts and Map*, n.d.). The most common age group is 50-59 years for both genders, with a significant representation of women aged over 70.




| Gender (R 2021) | |
|---|---|
| Males | 67,309 |
| Females | 73,558 |




| Age Groups (R 2021) | |
|---|---|
| 0-14 years | 16,155 |
| 15-64 years | 91,735 |
| 65+ years | 32,977 |




| Age Distribution (R 2021) | |
|---|---|
| 70+ years | 25,794 |
| 60-69 years | 15,413 |
| 50-59 years | 21,805 |
| 40-49 years | 20,537 |
| 30-39 years | 20,203 |
| 20-29 years | 15,227 |
| 10-19 years | 11,499 |
| 0-9 years | 10,389 |

Figure 56. Population statistics in Municipio 3, Milan (Milan City (Italy): Boroughs - Population Statistics, Charts and Map, n.d.)

These demographic findings indicate that the survey predominantly captures the perspectives of middle-aged and older adults, with a significant female majority. This demographic profile is crucial for interpreting the survey results and understanding the thermal perception and aesthetic satisfaction within the community.

In creating user profiles, the following considerations were made:

- Gender Distribution: Given the higher female population, more female profiles were created.
- Age Groups: Profiles were designed to represent the most prevalent age groups, including older adults who are more vulnerable to thermal discomfort (*Milan City (Italy): Boroughs - Population Statistics, Charts and Map*, n.d.).
- Body Mass Index (BMI): The average BMI for Italian adults was used to inform the profiles. For instance, the average BMI is 25.8 for females and 26.8 for males (Bracale et al., 2013).
- Clothing Insulation: Clothing insulation values were derived from standard tables, taking into account seasonal variations (*ashrae.org*, n.d.).
- Height and Weight: Average heights for Italian adults were considered, with women averaging 165 cm and men 178 cm.

Based on the demographic data, six user profiles are created to capture a broad spectrum of the population (Table 8):

Table 9. User profiles based on demographic data from Zone 3

| User | Gender | Age | Height (m) | Weight (kg) | BMI (kg/m²) | Clothing Icl (clo) | Metabolic Rate (W) | Walking Speed (m/s) |
|---|---|---|---|---|---|---|---|---|
| 1 | Female | 75 | 1.50 | 45 | 20.0 | 0.31 | 106.43 | 0.95 |
| 2 | Male | 50 | 1.75 | 90 | 29.4 | 0.31 | 174.41 | 1.27 |
| 3 | Female | 50 | 1.60 | 58 | 22.7 | 0.31 | 147.84 | 1.28 |
| 4 | Female | 30 | 1.60 | 45 | 17.6 | 0.31 | 143.34 | 1.26 |
| 5 | Female | 9 | 1.40 | 30 | 16.0 | 0.29 | 127.96 | 1.20 |
| 6 | Male | 75 | 1.75 | 75 | 24.5 | 0.35 | 139.10 | 1.07 |

Figure 57. User profiles created for PET simulations in BioMet.

The choice of these specific profiles is justified by the demographic characteristics of the Milanese population and the need to understand thermal comfort across different segments, including vulnerable groups like the elderly and children. However, it should be noted that toddlers and children under nine years old cannot be accurately simulated using ENVI-met 5.5.1.

## 6.3.3 Simulations and Output Data Analysis

Following the modeling of the urban context in the "Spaces" section and the setup of the weather file using the "ENVI-met guide," simulations for the different user profiles are executed. PET simulations are conducted for each profile on August 3, 2023, for every hour of the day using Leonardo. By examining the maximum and minimum PET for each user, the most comfortable hours in the street (where every user's PET falls within the neutral PET range of 26.4 to 29.2 °C) and the most uncomfortable hours (where PET values exceed 29.2 °C) are identified. This analysis reveals that 4:00 AM represents the most comfortable hour, while 3:00 PM is the most uncomfortable.

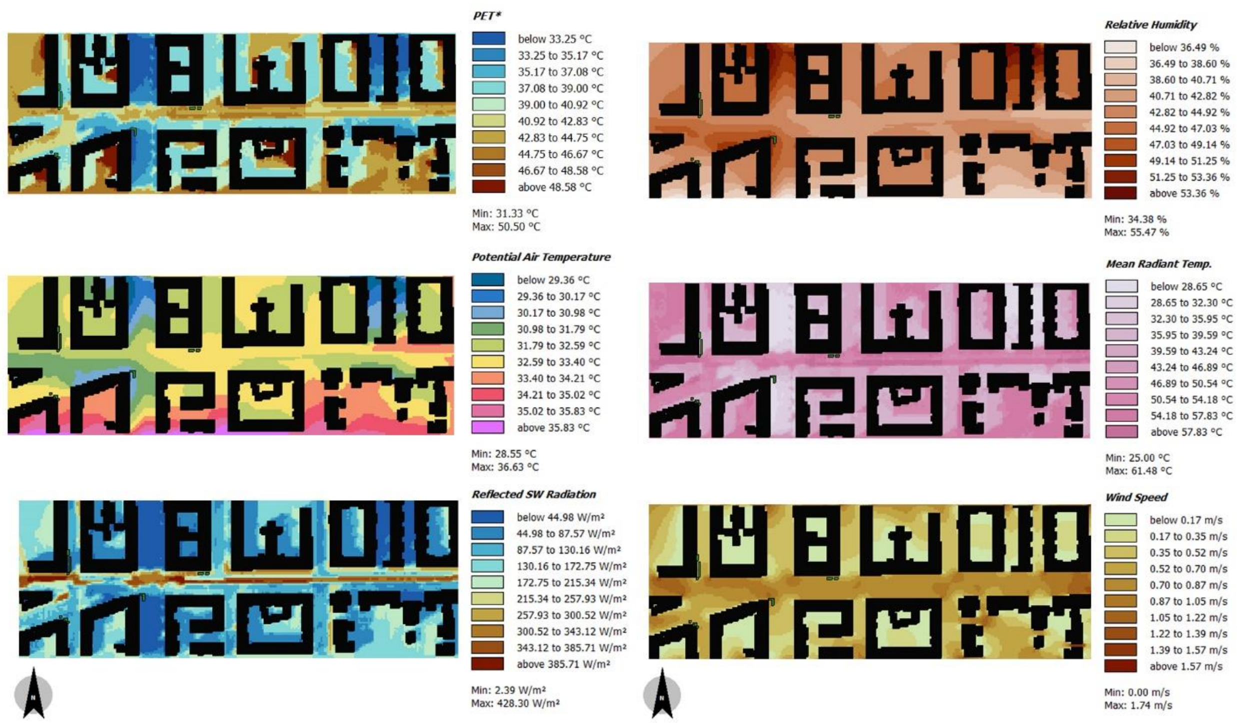



Figure 58. Mapping environmental conditions and PET of user3 at 3:00 PM 03/08/2023. ¦ 1.PET ¦ 2.RH% ¦ 3.Potential Air Temperature°C ¦ 4. Tmrt°C ¦ 5.Reflected short-wave radiation W/m^2 ¦ 6.Wind speed m/s

Subsequently, environmental parameters in the district are simulated for these specific hours, including potential air temperature, mean radiant temperature, wind velocity, relative humidity, and direct, diffuse, and reflected radiation. Visualizing the results shows that these two critical hours for PET correspond to the lowest and highest values for air temperature and mean radiant temperature, respectively.

Additionally, the absolute difference in PET between the users is compared to identify which spots in the street cause greater discomfort for each user. The visualization demonstrates minimal perception differences (maximum 3.7 Kelvin) between users 5 (a 9-year-old girl) and 6 (a 75-year-old man) during the most comfortable hour (4:00 AM). These differences are particularly noted in front of several façades (buildings F1, G1, H1, H2, K4). Further investigation of these façade effects is planned for subsequent analysis steps. During the hottest hour (3:00 PM), the greatest differences in perception remain almost negligible (8.6 K) between user 1 (a 75-year-old woman) and user 5 (a 9-year-old girl), with user 5 experiencing greater discomfort in front of façades B1 and A1 than user 1. It is observed that the largest PET differences between users occur on streets perpendicular to Via Beato Angelico, suggesting greater perception diversity when users are in shaded areas. These vertical streets are not heavily exposed to direct sunlight and radiation during critical hours, and the presence of vegetation in courtyards and some streets leads to a decrease in PET and a significant difference between user perceptions.

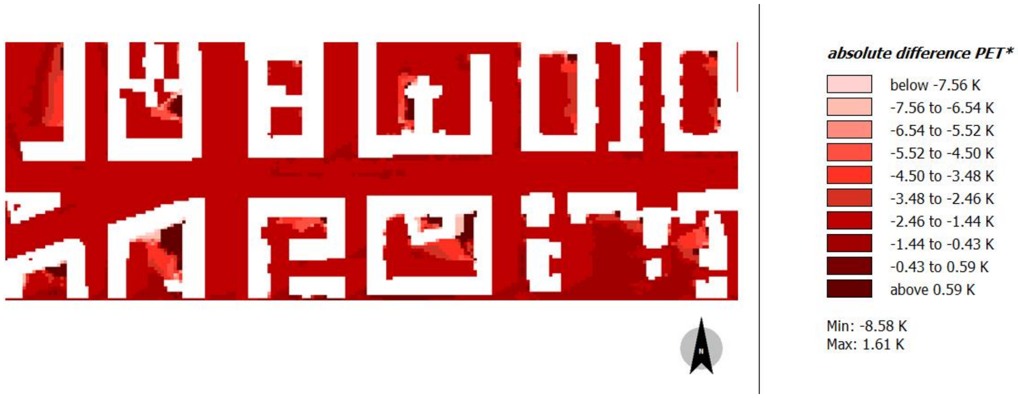



Figure 59. Absolute difference in PET (K) between user 1 and user 5 at 3:00 PM.

The next step involves creating a table to facilitate a more comprehensive data analysis. This table includes values of PET, environmental variables (such as Tmrt, diffuse-direct radiation, and temperature divergence due to longwave fluxes), and built environment parameters (SVF, building height, aspect ratio, orientation, upper and ground floor façade properties, glass percentage, distance from vertical streets, soil type). The values are measured for every user, at every receptor (21 receptors placed in front of the façades), and for every hour on August 3, 2023. This table contains precise values obtained from Leonardo simulations and .csv files of the receptors. The data is then transferred to SPSS for a more detailed analysis of each variable's effect on PET.

Table 10. Sample of the considered variables for statistical analysis

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

In this study, the parameters tested using one-way ANOVA are categorized into three main groups. The first group, user parameters, includes user characteristics such as age and gender, clothing, and metabolic rate. The second group consists of urban geometry parameters such as aspect ratio, sky view factor (SVF), building height, and plot size. The third group involves facade material properties, distinguishing between upper and ground floor facades, and also considering the materials themselves along with their color brightness.

The ANOVA test is conducted specifically for the day hours, as these hours exhibit the highest PET levels, making it crucial to focus on solutions for mitigating heat during peak hours. Given that all these variables are factored into the outcome of the simulations, it is expected that all the aforementioned parameters show statistical significance.

## 6.3.4 Effects of User Characteristics on PET

The provided table presents the results of Spearman's correlation and one-way ANOVA analysis, focusing on the variable Physiological Equivalent Temperature (PET) and its relationship with various user characteristics, including gender, age, height, weight, clothing, and total metabolic rate according to the simulations.

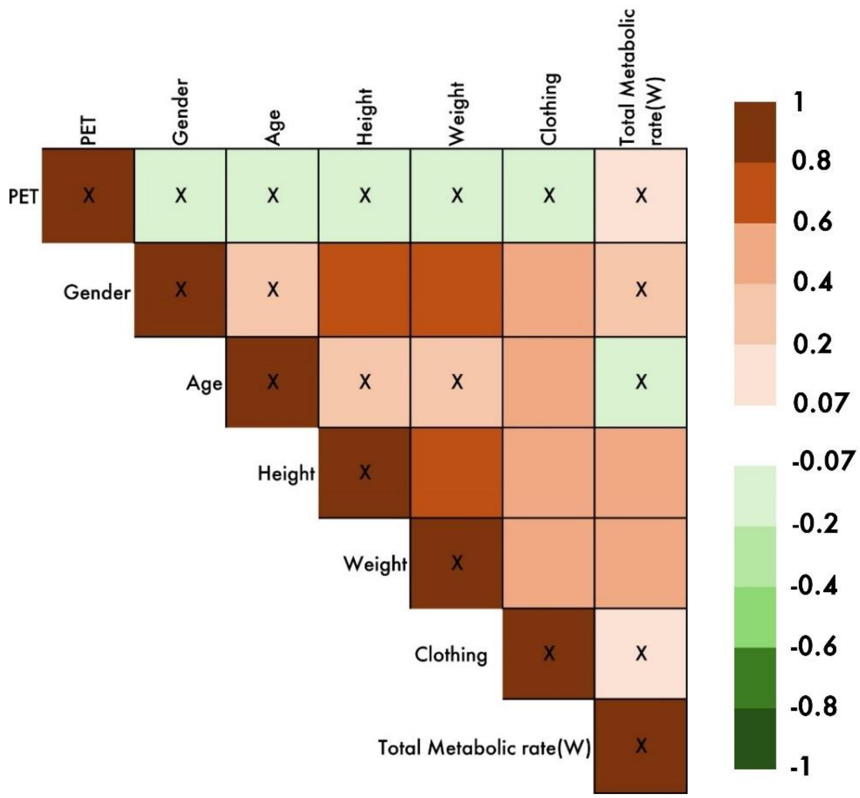



Figure 60. Spearman correlation rank between PET and user characteristics, X: Statistical significance over PET.

Spearman correlations:

- The correlation coefficient between PET and gender is found to be -0.076 with a significance level of $p < 0.001$. This indicates a weak negative correlation, suggesting that male users experience slightly lower PET.
- Age is negatively correlated with PET with a coefficient of -0.133 ($p < 0.001$), indicating that as age increases, PET tends to decrease slightly.
- Height shows a weak negative correlation with PET, having a coefficient of -0.063 ($p < 0.001$).
- Weight also exhibits a weak negative correlation with PET, with a coefficient of -0.072 ($p < 0.001$).
- Clothing, which is a significant factor in thermal comfort, shows a negative correlation with PET (coefficient of -0.103, $p < 0.001$). Higher clothing insulation levels are associated with lower PET values.
- The total metabolic rate shows a weak positive correlation with PET (coefficient of 0.031, $p = 0.084$), although statistically significant.

In this part, the focus is on examining the effect of user characteristics, specifically age and gender, on PET (Physiological Equivalent Temperature). After testing the hypothesis, it has been determined that both age and gender have statistical significance over PET. The survey results for Via Beato Angelico are now being compared to check for similarities between the objective and subjective thermal perceptions of the users. This comparison is achieved by converting the thermal sensation votes into PET ranges using the reference from Figure 8.

In a comparison between genders, the simulated PET results indicate that there is no noticeable difference between females and males. For male users, the mean PET is calculated as 32.20 °C for ages 40-60 and 31.54 °C for ages above 60, suggesting that male users are generally comfortable throughout the day. In contrast, the mean PET for female users reaches 32.95 for ages 20-40, the highest among all age groups, indicating slight discomfort.

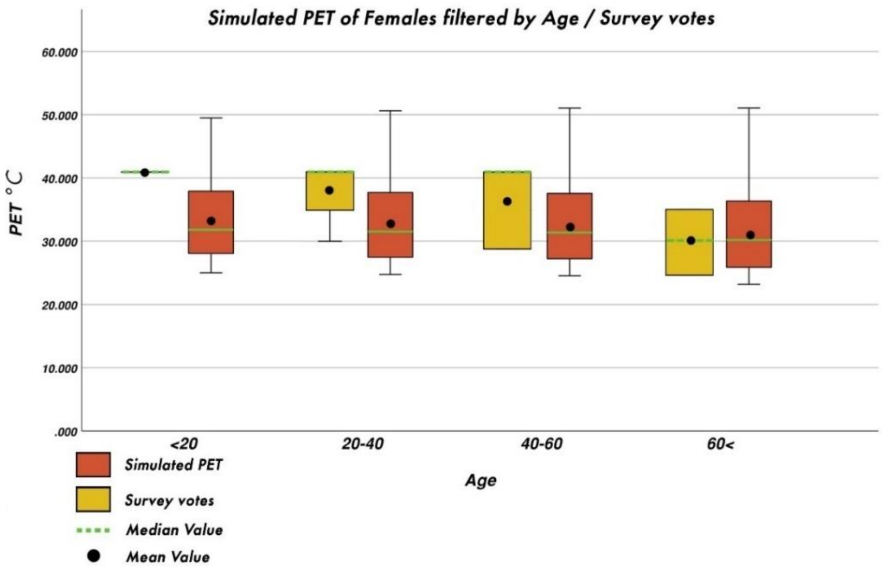



Figure 61. Simulated PET of Females by Age Group / Thermal Sensation Votes of Females by Age Group from Survey Responses (N=149)

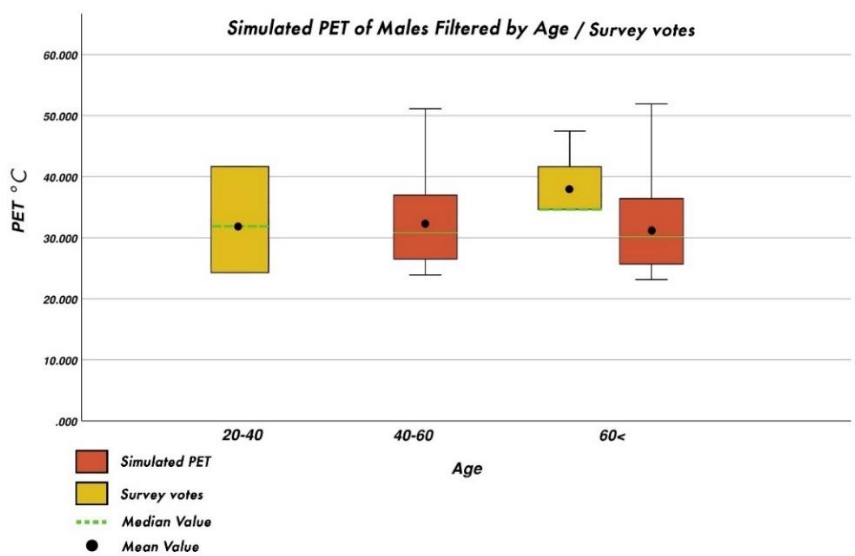



Figure 62.Simulated PET of Males by Age Group / Thermal Sensation Votes of Males by Age Group from Survey Responses (N=58)

When comparing the survey results with simulations for both genders, distinct patterns emerge. For females, the difference between age groups is inverse to the PET values. As age increases, PET decreases, with users over 60 experiencing the lowest PET and the best comfort ratings in both the survey and simulations. However, a significant gap exists between the simulated and measured thermal sensations for younger females. Females under 20 report a thermal sensation on the street up to 6 degrees higher than the simulated PET.

This discrepancy could be attributed to the survey not being conducted on-site, leading to psychological adaptation factors, such as previous experiences, affecting the votes and possibly exaggerating the results. Additionally, inaccuracies in converting thermal sensation votes into PET units might contribute to this gap, which could be addressed by establishing a more direct link between them to derive an equation expressing a more accurate relationship between PET and TSV in the district.

For males, there are substantial differences between the survey and simulations. While simulations show that PET decreases with age, the survey results indicate much greater discomfort for older male users. This discrepancy suggests that the subjective thermal perceptions of older males differ significantly from the objective PET values obtained from simulations.

### 6.3.5 Analysis of PET and Neighborhood Configuration Factors

The correlation analysis reveals the relationship between PET and various neighborhood configuration factors, including Sky View Factor (SVF), SVF with vegetation, aspect ratio, building height, and distance from vertical streets. These parameters are critical in understanding the microclimatic conditions that influence outdoor thermal comfort (OTC) in urban environments.

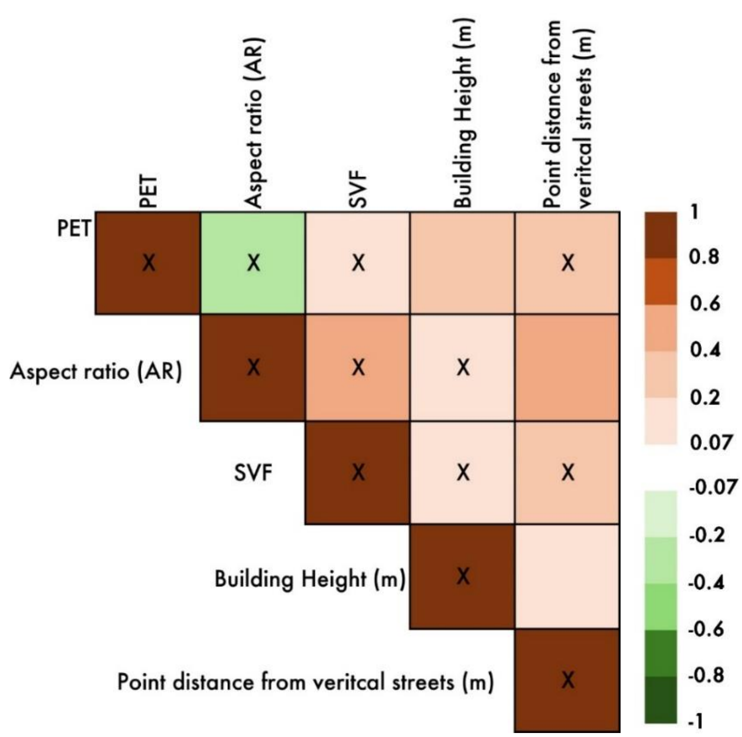



Figure 63. Spearman correlation rank between PET and built environment, X: Statistical significance

- The correlation between PET and SVF is significant (coefficient of 0.036, $p = 0.005$).
- Aspect ratio, another significant urban configuration parameter, shows statistical significance over PET (coefficient of -0.034, p = <0.001).
- Building height presents a weak negative correlation with PET (coefficient of -0.056, $p = 0.02$).
- The distance from vertical streets shows a modest negative correlation with PET (coefficient of -0.043, $p = 0.018$). This parameter was investigated due to preliminary visual assessments of simulated PET values, which indicated that proximity to vertical streets influences thermal perception. Streets perpendicular to Via Beato Angelico tend to offer shaded areas, which enhance pedestrian comfort by reducing PET.

Fixed parameters, such as street orientation and soil type, are not considered in this analysis. The street orientation remains constant across the study area, thereby eliminating its potential variability. Similarly, the soil type refers to the uniform materiality of the street, which in this case is grey concrete pavement for all receptor placements.

Bonferroni correction is applied to determine specific ranges of values that can lead to higher PET and MRT, leading to greater discomfort levels in the street of reference.

Table 11. Bonferroni correction for neighborhood geometry parameters.

| **Parameters** | | **PET** | | | **Tmrt** | |
|---|---|---|---|---|---|---|
| | | Mean difference (High-Low) | P-value | Margin of error | Mean difference (I-J) | P-value |
| **SVF** | High (0.4) | 7.496179 | <0.001 | 0.732154 | 13.16615 | <0.001 |
| | Low (0.16) | | | | | |
| **Height(m)** | High 27) | -4.254419 | <0.001 | 0.623775 | -10.86667 | <0.001 |
| | Low (23) | | | | | |
| **Distance from vertical streets (m)** | High (52) | -5.965603 | <0.001 | 0.656930 | -17.878805 | <0.001 |
| | Low (40) | | | | | |
| | Low (1500) | | | | | |

## 6.3.6 PET and Façade Materiality

The analysis will now focus on the impact of materiality on pedestrians' thermal comfort.

The Spearman correlation analysis reveals that Mean Radiant Temperature (Tmrt) has the most significant correlation with PET, with a coefficient of 0.963 ($p < 0.001$).

Given that pavement materiality is a fixed parameter, and receptors are placed centrally along the building's length, other surface temperatures primarily influence Tmrt. These surfaces' thermal properties significantly impact the radiative heat exchange between the human body and its environment, thereby influencing PET.

Most receptors, when placed at a height of 1.1 meters, receive direct radiation between the hours of 08:00 and 17:00, and diffuse radiation between 04:00 and 18:00. The analysis will be conducted over two distinct periods: day (06:00-18:00) and night (all other hours). This separation aims to discern which facade properties—radiative, thermal, or physical—affect PET and Tmrt. This distinction is crucial as different material properties may influence thermal comfort differently depending on the time of day.

Performing one-way ANOVA significance test revealed that material properties that affect PET during night time are the thermal properties of ground floor materials. For the following analysis only properties that show statistical significance over PET ($p<0.001$) are mentioned.

**Nighttime Ground floor facade:**

- Albedo, Longwave Radiation Flux (LRF), and Absorption

The correlations between PET and albedo ($r = 0.004$, $p = 0.892$), LRF ($r = 0.077$, $p = 0.004$), and absorption ($r = 0.045$, $p = 0.095$) are weak and insignificant. This lack of strong correlation validates the theory that thermal properties, rather than reflective properties, play a more significant role during the night.

- Specific Heat Capacity, Density, and Emissivity

Specific Heat Capacity shows a significant positive correlation with PET ($r = 0.075$, $p = 0.006$).

Density correlates positively with PET ($r = 0.058$, $p = 0.030$). Higher density materials, like marble, retain heat longer, leading to elevated surface temperatures and increased Tmrt, subsequently raising PET values during the night.

Emissivity shows a significant positive correlation with PET ($r = 0.093$, $p < 0.001$). Materials with high emissivity, such as certain ceramics, can help reduce surface temperatures and thus lower PET, contributing to a more comfortable environment.

**Daytime:**

This analysis distinguishes between the effects of upper facade materials and ground floor materials. The upper facades significantly influence PET due to their larger surface area and higher exposure to solar radiation. The following analyzed properties are the ones showing statistical significance over PET ($p<0.001$).

- Upper façade:

Starting with the upper facade materials, **albedo** is negatively correlated with PET ($r = -0.086$, $p < 0.001$).

**Absorption** shows a positive and significant correlation ($r = 0.137$, $p < 0.001$).

**Thermal conductivity** of upper facade materials has a weak but significant positive correlation with PET ($r = 0.083$, $p < 0.001$).

**Density** affects a material's thermal mass and shows a significant positive correlation with PET ($r = 0.157$, $p < 0.001$).

The overall material characteristics of the upper facade are captured in the variable Upper_Facade_Material, which shows a significant correlation with PET ($r = 0.146$, $p < 0.001$). This suggests that certain materials used in upper facades have a notable impact on increasing PET. Also, color brightness of upper facades, has a significant negative correlation with PET ($r = -0.148$, $p < 0.001$. The negative correlation indicates that brighter upper facade colors are associated with lower PET values, reducing heat absorption.

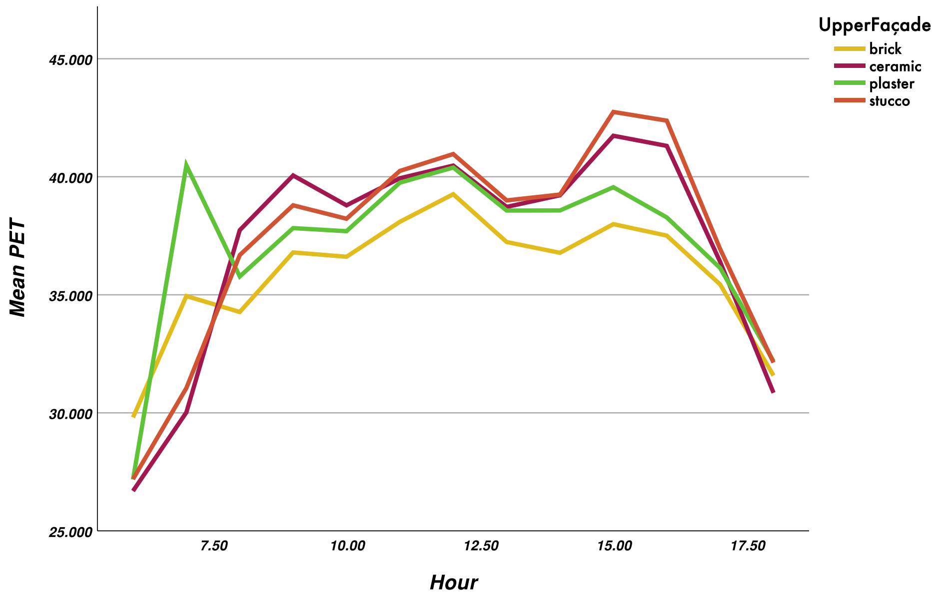



Figure 64. Mean PET calculated for each Upper facade material during day time for 0.3.08.2023

- Ground Floor Facade:

For the ground floor facade, while radiative properties such as color do not significantly affect PET, the other properties like thermal conductivity, specific heat capacity, and density play a crucial role. These properties influence how heat is absorbed, stored, and released by the materials. Ground floor materials like marble consistently show, the lowest PET values, indicating their effectiveness in maintaining lower surface temperatures and improving pedestrian thermal comfort.

Finally, the percentage of glass in facades shows a significant positive correlation with PET ($r = 0.198$, $p < 0.001$). The percentage of glass in facades affects solar gain and heat retention.

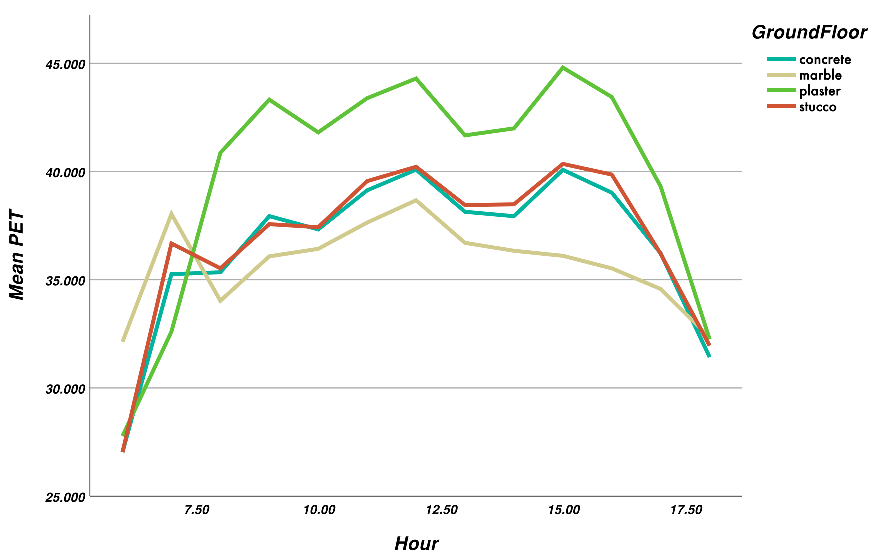



Figure 65 Mean PET calculated for each Upper facade material during day time for 0.3.08.2023

After significant correlations from the Spearman analysis for both day and night on the upper and ground floor façade materials are identified, the Bonferroni correction is applied to determine specific ranges of values that can lead to higher PET and MRT, indicative of greater pedestrian discomfort (Shaffer, 1995). This correction is particularly suitable for comparing means and proportions using the one-way ANOVA test. The analysis will focus on daytime hours, when the most extreme temperatures occur, and be separated in upper and ground floor façade material properties. Only properties that show statistical significance (p <0.001) over PET will be analyzed.

- Upper Façade

Table 12. Bonferroni correction for upper facade properties during the day.

| **Parameters** | | **PET** | | | **Tmrt** | |
|---|---|---|---|---|---|---|
| | | Mean difference (High-Low) | P-value | Margin of error | Mean difference (I-J) | P-value |
| **Albedo** | High (0.7) | 1.668990 | <0.001 | 0.324283 | 3.61827 | <0.001 |
| | Low (0.6) | | | | | |
| **Absorption** | High (0.68) | -2.427036 | <0.001 | 0.315051 | -5.99821 | <0.001 |
| | Low (0.35) | | | | | |
| **Emissivity** | High (0.92) | 2.178663 | <0.001 | 0.304306 | 5.35244 | <0.001 |
| | Low (0.85) | | | | | |
| **Thermal Conductivity W/(m·°C)** | High (0.8) | 1.889773 | <0.001 | 0.316633 | 4.58474 | <0.001 |
| | Low (0.6) | | | | | |
| **Density (kg/m^3)** | High (2275) | -1.289359 | <0.001 | 0.332087 | -4.58474 | <0.001 |
| | Low (1500) | | | | | |

- Ground Floor Façade

Table 13.Bonferroni correction for ground floor facade properties during the day.

| **Parameters** | | **PET** | | | **Tmrt** | |
|---|---|---|---|---|---|---|
| | | Mean difference (I-J) | P-value | Margin of error | Mean difference (I-J) | P-value |
| **Glass percentage %** | High (70) | 5.060244 | <0.001 | 0.735571 | 13.29615 | <0.001 |
| | Low (35) | | | | | |
| **Emissivity** | High (0.95) | 1.611671 | 0.005 | 0.447682 | 6.49667 | <0.001 |
| | Low (0.86) | | | | | |
| **Specific Heat Capacity J/(kg·°C)** | High (890) | -1.498512 | <0.001 | 0.314514 | -5.07110 | <0.001 |
| | Low (850) | | | | | |

**The negative values in mean difference show that the higher the value of the parameters the lower PET -Tmrt respectively.*

### 6.3.8 Conclusions

The simulation results using ENVI-met V5.5.1 reveal critical insights into the microclimatic impacts of façade materials and user characteristics on pedestrian thermal comfort. PET simulations conducted for six distinct user profiles on August 3, 2023, identify 4:00 AM as the most comfortable hour and 3:00 PM as the most uncomfortable. This analysis correlates maximum thermal discomfort with peak air and radiant temperatures.

Key findings show that façade materials significantly influence PET and MRT. Specifically, materials with higher albedo and lower absorption rates on upper façades help reduce PET. Ground floor materials, particularly those with low emissivity and high specific heat capacity and density, exacerbate thermal comfort. For example, marble facades, with low PET values, are more thermally comfortable, while plaster facades increase PET.

User characteristics such as gender, age, height, weight, and clothing insulation show varying degrees of correlation with PET and statistical significance.

The analysis also highlights the importance of urban configuration factors like SVF, aspect ratio and proximity to vertical streets in moderating PET. Taller buildings and shaded vertical streets correlate with lower PET values, enhancing pedestrian comfort.

Applying the Bonferroni correction, significant parameter ranges affecting PET and MRT are identified. During the day, upper facades with moderate albedo (0.41-0.55) and absorption (0.5) improve thermal comfort, while low glass percentages and high specific heat capacity on ground floors further enhance comfort levels.

The differences in the effects of upper and ground floor facades on PET can be attributed to their respective exposure to solar radiation and their physical positioning relative to pedestrians. Upper facades, being more exposed, have a more significant impact on the overall thermal environment, while ground floor facades, closer to the pedestrian level, directly influence the immediate thermal comfort experienced by pedestrians.

## 6.4 Thermal Walk

### 6.4.1 Demographic Characteristics

The thermal walk, conducted on June 22, gathered eight participants, representing a diverse sample in terms of age and gender. The group consisted of 75% females and 25% males, with age distribution as follows: 12.8% aged 20-40, 51.3% aged 40-60, and 35.9% aged over 60. The most common weight range among participants was 51-60 kg (38.5%), followed by 71-80 kg (25.6%). The prevalent height range was 161-170 cm (48.7%), with 38.5% of participants falling within the 171-180 cm range.

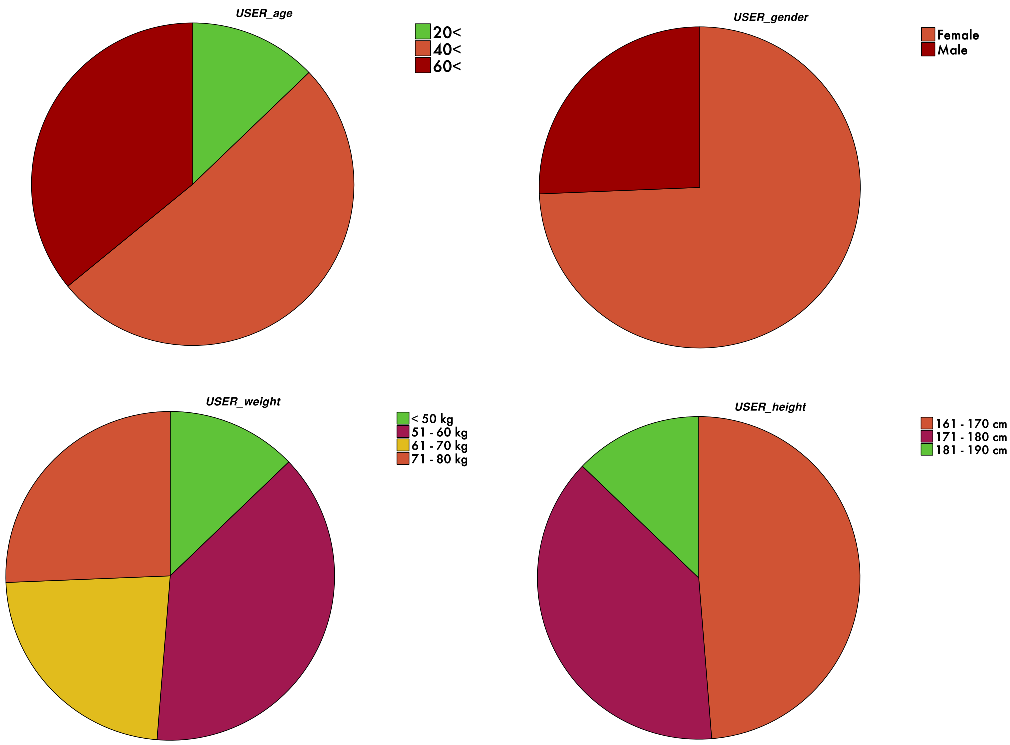



Figure 66. Thermal walk sample composition. Age ¦ Gender ¦ Weight ¦ Height. N=8

Analysis of the participants' activity history revealed no records of intense activity, with the most common responses being slowly walking (35.9%) and standing or sitting (25.6% each). The mean Thermal Sensation Vote (TSV) for both genders during the walk was 3.20 for males and 3.24 for females, indicating thermal comfort. However, significant differences in TSV were observed across age groups. Participants aged 20-40 reported a mean TSV of 2.5 (slightly cool), while those over 60 reported a mean TSV of 3.5 (slightly warm). The group most dissatisfied with the thermal environment were participants aged 40-60, with females expressing greater satisfaction with the thermal environment than males.

A strong correlation was found between the responses to the questions "What is the thermal sensation you associate with the material of the building?" and "What is your overall level of satisfaction with the thermal environment?" This validates the relationship between perceived thermal sensation and overall thermal comfort.

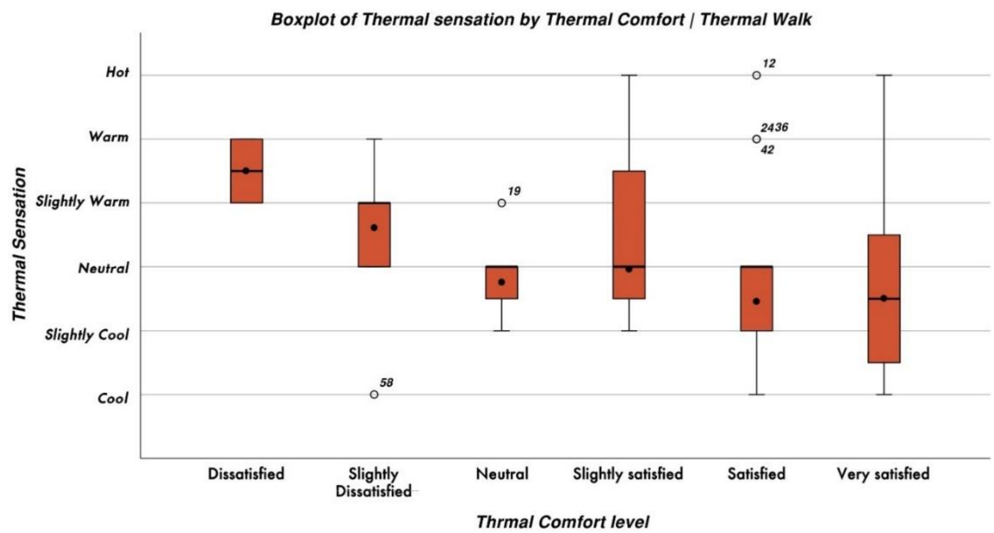



Figure 67. Boxplot of TSV to Thermal Comfort Level ¦ Thermal walk. N=8

Boxplot analysis reveals that dissatisfaction with the thermal environment aligns with warmer environments and facades associated with warmer sensations. Conversely, neutral or cooler facades are associated with greater satisfaction. This confirms a linear relationship between satisfaction with the thermal environment and perception of facades, validating the questionnaire's questions.

## 6.4.2 Perceived Aesthetics

Regarding the aesthetic evaluation of facades, male participants showed greater satisfaction with the visual appeal, with a mean aesthetic vote of 4.5 (somewhat satisfied), while females gave a mean aesthetic vote of 3.85 (somewhat dissatisfied to neutral). No apparent relationship was found between the TSV associated with a facade and its aesthetic perception. Testing the relationship between thermal comfort and perceived aesthetics revealed the lower-ranking facades that correspond to lower thermal comfort and aesthetic satisfaction.

Table 14.Mean thermal and aesthetic votes for building facades during thermal walk.

| Building Facade | A2 | B1 | C1 | D1 | 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 | |

During the walk, 55% of participants reported feeling the wind, which made them feel cold. 63% of the walk was conducted under shade and 37% exposed to the sun, according to the participants’ answers.

## 6.4.3 Influence of environmental conditions on Thermal Sensation Vote

Table 15. Significance of environmental parameters over TSV.

| | Significance over TSV | |
|---|---|---|
| | F. | P-value |
| **Air Temperature °C** | 5.843 | <0.001 |
| **Air Humidity %** | 6.026 | <0.001 |
| **Surface Temperature** | 5.843 | <0.001 |
| **HI** | 5.843 | <0.001 |
| **WBGT** | 5.843 | <0.001 |
| **DPT** | 5.843 | <0.001 |
| **WBO** | 5.432 | <0.001 |
| **GT** | 4.419 | <0.001 |
| **Air Pressure (hPa)** | 13.397 | <0.001 |
| **Sun exposure** | 32.863 | <0.001 |
| **Wind** | 3.488 | 0.020 |

A one-way ANOVA test indicated that sun exposure has the strongest effect on TSV (F=32.869). The results showed a significant difference in TSV between shaded and sun-exposed areas, with higher temperatures and surface temperatures in sun-exposed areas.


Figure 68. Shaded and exposed to sun stops-buildings during the Thermal walk.

## 6.4.4 Thermal sensation vote & Materials

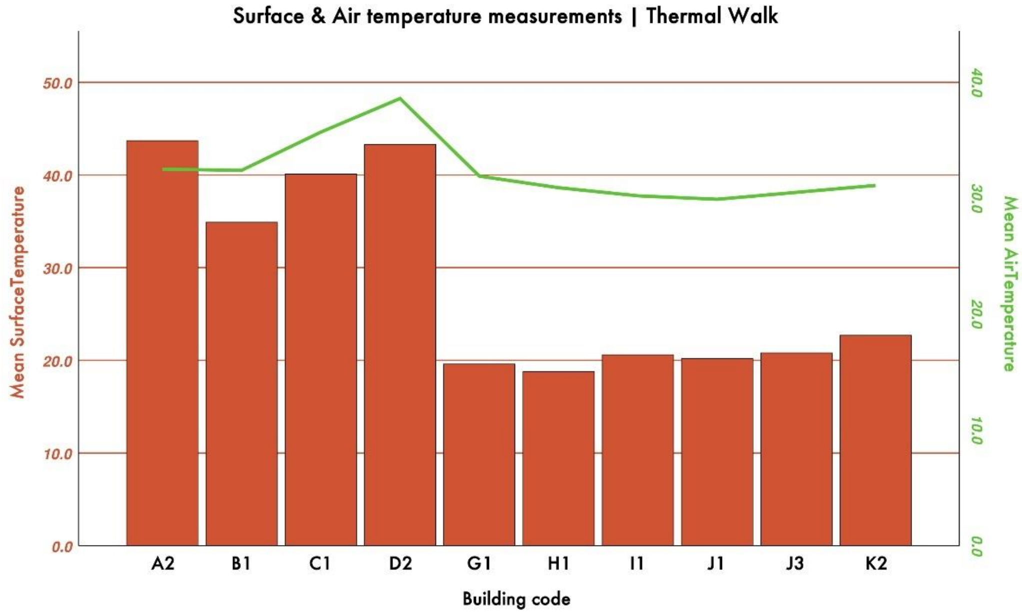



Figure 69. Measured mean surface and Air tempearture °C for every building ¦ Thermal walk

Measured surface and air temperature reveals higher temperatures for facades exposed to the sun compared to those in the shade. The biggest air temperature difference is 9 °C between J1 (29.9 °C) and D2 (38.6 °C). Surface temperature differences are even more pronounced, with a 25 °C difference between building A2 (43.7 °C) and H1 (18.8 °C). Both buildings have bright stucco on the ground floor.

In the table below the mean surface temperature of each of the façade materials is depicted.

Table 16. Measured mean surface temperature of each material.

| Ground floor façade material | Mean Surface Temperature in °C | Std. Deviation |
|---|---|---|
| Concrete | 31.142 | 11.1480 |
| Marble | 22.700 | 1.0000 |
| Plaster | 34.900 | 1.0000 |
| Stucco | 25.975 | 10.4274 |

A one-way ANOVA test examines the significance of material properties on TSV. The analysis reveals that ground floor facade properties significantly affect TSV, while upper facade properties do not. Further analysis identifies bright plaster, red brick, and grey concrete as materials associated with warmer thermal sensations, whereas grey marble and grey stucco are perceived as cooler materials. These indications of material influence on TSV contrast with the simulated PET, which depends more on upper facade material properties.

Table 17. Significance of facade material properties over TSV.

| Properties | Significance over TSV | |
|---|---|---|
| **Upper Facade** | **F.** | **Sig.** |
| **U-value** | 5.253 | <0.001 |
| **Albedo** | 0.644 | 0.528 |
| **Absorption** | 0.434 | 0.729 |
| **Emissivity** | 0.434 | 0.729 |
| **Thermal Conductivity** | 0.288 | 0.750 |
| **Specific Heat Capacity** | 0.271 | 0.604 |
| **Density** | 0.288 | 0.750 |
| **Ground Floor facade** | | |
| **Glass percentage** | 6.806 | <0.001 |
| **Albedo** | 5.163 | 0.003 |
| **Absorption** | 1.486 | 0.233 |
| **Emissivity** | 5.116 | 0.003 |
| **Thermal Conductivity** | 5.116 | 0.003 |
| **Specific Heat Capacity** | 7.777 | <0.001 |
| **Density** | 5.116 | 0.003 |

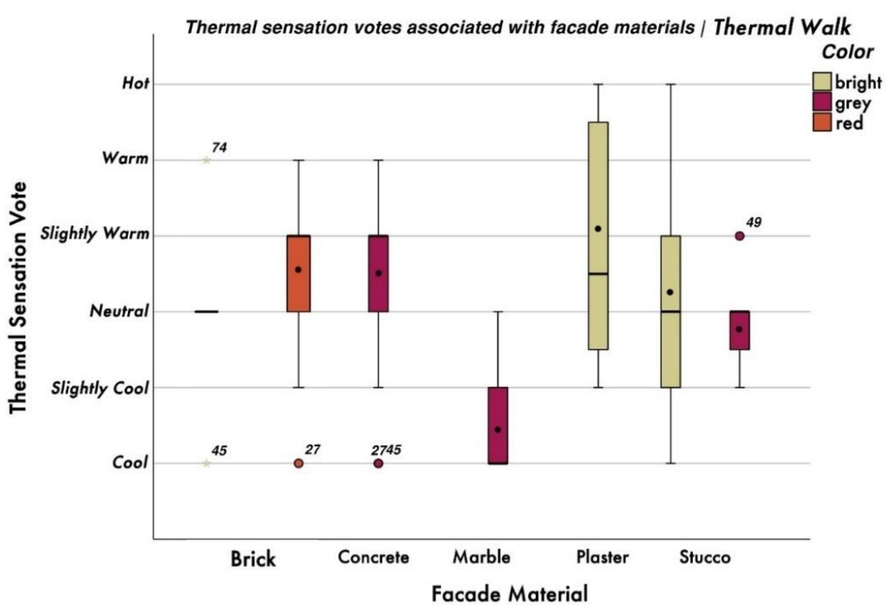



Figure 70. Boxplot of TSV associated with facade materials¦Thermal walk. N=8

## 6.4.5 PET of thermal walk

PET is calculated for the thermal walk using RayMan software, focusing on two participants (female and male over 60). Input data includ date, time, geographic location, personal characteristics, and environmental conditions. The calculated PET is ,then, compared to TSV for the target group. Significant differences are found between male and female TSV. Calculated PET does not consistently represent the thermal sensation or comfort levels associated with facades. However, female TSV shows better alignment with PET, where higher PET values correspond to lower satisfaction votes and vice versa.

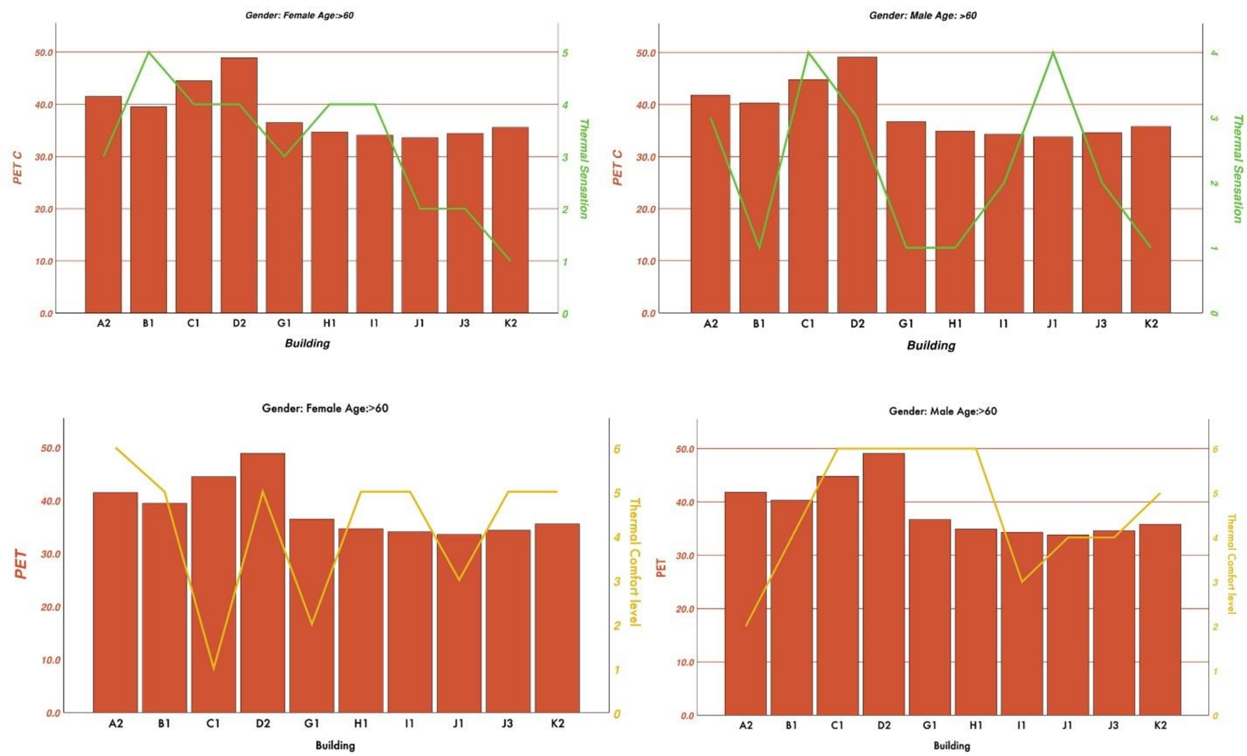



Figure 71.Dual Axes Diagrams: PET vs. TSV and Thermal Comfort Level for Males and Females (Age >60).

## 6.4.6 Conclusions

The thermal walk conducted on June 22, involving 8 participants, provides critical insights into thermal perception across diverse age and gender groups. Participants reported a mean Thermal Sensation Vote (TSV) of 3.20 for males and 3.24 for females, indicating overall thermal comfort. However, age-specific variations were notable, with younger participants (20-40 years) feeling slightly cool (TSV of 2.5) and older participants (>60 years) feeling slightly warm (TSV of 3.5).

A strong correlation emerges between the thermal sensation associated with building materials and overall satisfaction with the thermal environment. Warmer facades are linked to greater dissatisfaction, whereas cooler facades are linked to higher satisfaction, validating the questionnaire's structure.

Sun exposure significantly influences TSV, with one-way ANOVA results highlighting its strong effect ($F=32.869$, $p<0.001$). Real-time measurements show that facades exposed to the sun have significantly higher surface and air temperatures compared to shaded facades, reinforcing the importance of sun exposure in thermal comfort assessments.

Material properties of facades are also crucial, with ground floor materials significantly affecting TSV. Bright plaster, red brick, and grey concrete are associated with warmer sensations, while grey marble and stucco are perceived as cooler.

PET is calculated for the thermal walk using RayMan software for two participants (female and male over 60) and compared to TSV. Significant differences between male and female TSV are found, with PET not consistently representing thermal sensation or comfort levels associated with facades.

## 6.5 Validation of Workflow Results through Objective User Perception

### 6.5.1 Combining objective and subjective data

#### 6.5.1.1 Workshop & Survey: Multi-domain heatmaps

The goal of this multi-domain analysis is to identify focus areas with poor environmental quality throughout the district. This is achieved by comparing the weighted density maps derived from the workshop and the survey. By overlaying and analyzing these maps, differences between the perceptions captured in the workshop and those recorded in the survey are identified. This comparison helps to validate the findings and ensures that the survey results align with the priorities and concerns expressed by the community during the workshop.

The samples differ between the two methods. The workshop, a participatory event, gathered 40 participants who were able to interact during the evaluation of the district. In contrast, the survey gathered a total of 200 respondents, had a much longer duration, and was filled out individually.

Overlaying the heatmaps reveals areas of congruence and divergence in perceived environmental quality. The workshop's interactive nature allowed for dynamic discussions, leading to immediate, collective identification of problematic areas. The survey, with its broader and more diverse respondent base, provides a more extensive dataset over a longer period. This extended timeframe captures a wider range of perceptions and potentially highlights different areas of concern.

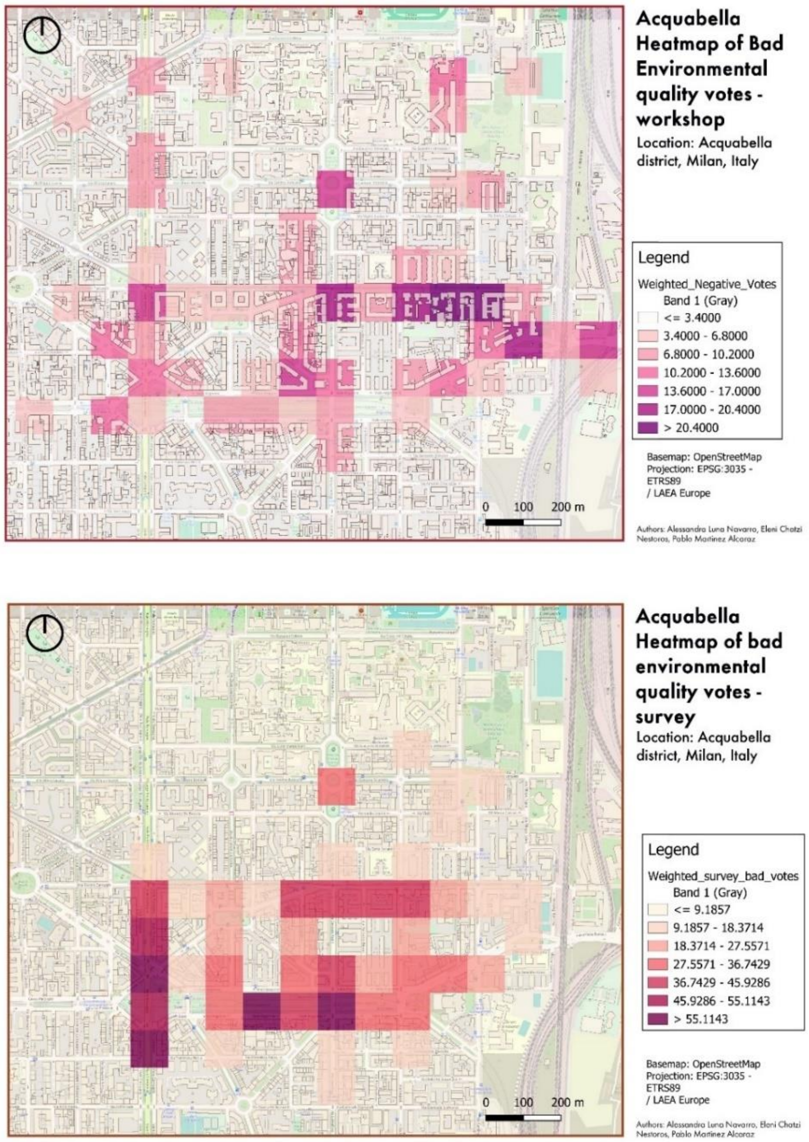



Figure 72.Density heatmaps for perceived environmental quality weighted by domain importance¦Workshop (N=299) vs. survey (N2=572).

The heatmap comparison reveals significant differences between the workshop and survey indications regarding the spatial distribution of environmental quality perceptions. Notably, Via Beato Angelico emerges as the third worst-rated street in the survey, following Viale Romagna and Viale Argonne. These two streets are high-traffic areas, which likely contributes to their poor environmental ratings. Also, the frequency with which respondents encounter these streets could also play a role. High-traffic streets like Viale Romagna and Viale Argonne are likely to be experienced regularly by a larger portion of the population, reinforcing negative perceptions due to repeated exposure to their adverse conditions.

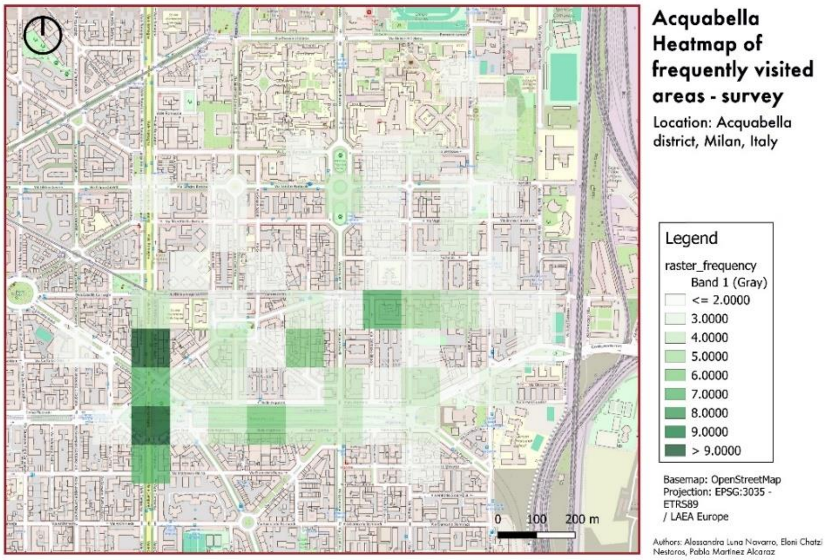



Figure 73. Heatmap of frequency of visit ¦ Survey.

## 6.5.1.2 Workshop & Thermal walk: Thermal sensation and materials

The thermal sensation votes for facade materials were collected during both the thermal walk and the workshop, with values interpreted as follows: 3 = neutral, 4 = warm, 5 = hot, 2 = cool, 1 = cold. This comparison aims to provide insights into how different materials and their colors influence thermal perception in varying contexts.

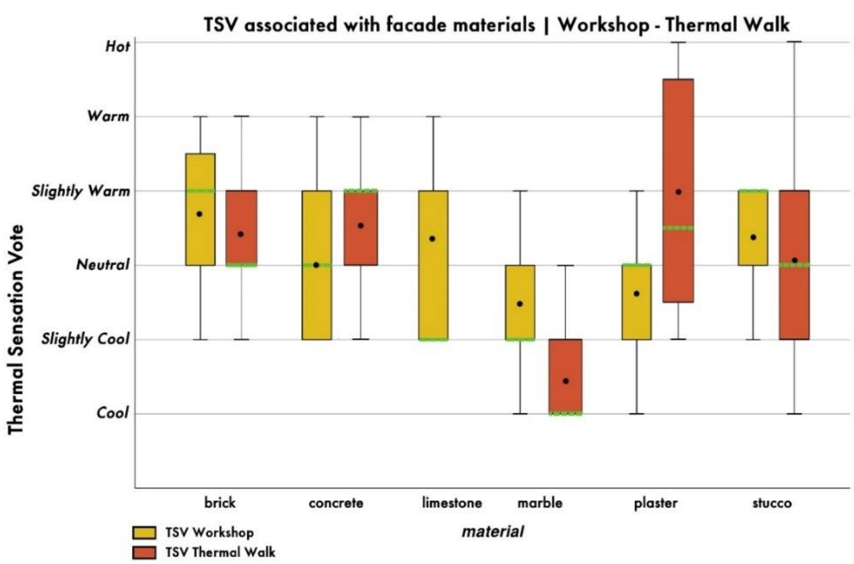



Figure 74. TSV associated with facade materials ¦ Workshop (N=18) vs Thermwal walk (N=8) ¦ ●= Mean value

Table 18. Comparison of Thermal Sensation Votes Associated with Facade Materials : Thermal walk & Workshop.

| Material | Color | Thermal Sensation Vote ¦ Thermal walk | Thermal Sensation Vote ¦ Workshop |
|---|---|---|---|
| **Brick** | Bright | 3.00 | 4.18 |
| | Red | 3.50 | 3.56 |
| **Plaster** | Bright | 3.88 | 2.75 |
| **Stucco** | Bright | 3.29 | 3.18 |
| **Stucco** | Grey | 2.88 | 3.43 |
| **Concrete** | Bright | - | 3.56 |
| | Grey | 3.48 | 3 |
| **Marble** | Bright | - | 2.43 |
| | Grey | 1.57 | 2.5 |

- Brick (Bright and Red):

Bright brick received a thermal sensation vote of 3.00 during the thermal walk, indicating neutrality, while it was rated much hotter (4.18) during the workshop.

Red brick showed more consistency between the thermal walk (3.50) and the workshop (3.56), both indicating a perception ranging from neutral to hot.

- Plaster (Bright):

Bright plaster was perceived as significantly warmer during the thermal walk (3.88) compared to the workshop (2.75), where it was rated from cool to neutral.

- Stucco (Bright and Grey):

Bright stucco had similar ratings between the thermal walk (3.29) and the workshop (3.18), indicating neutrality.

Grey stucco, however, was perceived as cooler during the thermal walk (2.88) than in the workshop (3.43), where it ranged from neutral to hot.

- Concrete (Bright and Grey):

Grey concrete had consistent ratings, with a slightly warmer perception during the thermal walk (3.48) compared to the workshop (3.00).

- Marble (Bright and Grey):

Grey marble showed a significant cooling effect in both settings, with even cooler perception during the thermal walk (1.57) compared to the workshop (2.50).

Contextual Differences: The discrepancies between thermal sensation votes during the thermal walk and the workshop highlight the influence of context. The thermal walk, involving real-time, on-site evaluations, may capture more immediate and situational thermal perceptions, while the workshop, conducted in a controlled environment, might reflect more generalized or recalled perceptions.

Material and Color Influence: Bright-colored materials, especially brick and plaster, show significant variations between contexts, suggesting that their thermal perception can be highly situational. Grey materials, particularly marble, appear to provide a consistently cooler thermal sensation across different settings.

### 6.5.1.3 Survey & Thermal walk: Aesthetic perception

The survey included various questions to identify the least and most attractive areas in the district, as well as the least and most thermally uncomfortable areas. The voted areas reflect the general perception of the environment without pinpointing specific factors influencing this perception. A strong correlation exists between areas negatively voted for aesthetics and those negatively voted for thermal perception. The thermal walk, conducted in the areas indicated by the survey, attempts to determine if these negative votes are associated with the facades themselves by focusing on thermal sensation and aesthetic votes for specific facades.

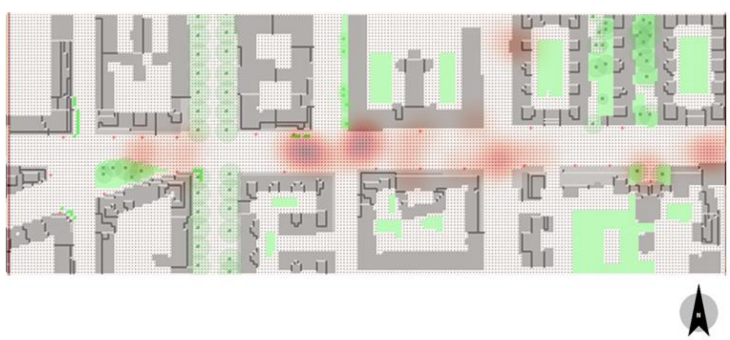
By comparing the tables from the survey (Table 8) and the thermal walk (Table 14) that combine the poor thermal and aesthetic votes, it is possible to identify buildings that are consistently rated poorly in both methods. These buildings, identified as A2, C1, D1, and J1, should be the primary focus of aesthetic interventions.

The discrepancy between survey and thermal walk results may be attributed to several factors. Firstly, the survey responses were comparative, considering the entire district, while the thermal walk focused solely on Via Beato Angelico. This broader context in the survey might have influenced the perceived severity of aesthetic and thermal discomfort. Secondly, the phrasing of the questions in the survey might have prompted respondents to consider factors beyond the facades, which were not specifically tested in this research. These additional factors could negatively impact the aesthetic perception of the street, highlighting the need for a more comprehensive approach to urban design interventions.

## 6.5.1.4 Simulations & Survey: Hot spots

The integration of objective simulation results with subjective user perception through the survey results, reveals a strong alignment, validating the thermal condition simulations in Acquabella. Analysis of mean radiant temperature (MRT), Physiologically Equivalent Temperature (PET), and air temperature for User 3, who represents the Acquabella population, shows significant temperature variations with the highest values indicating areas of intense solar exposure and thermal discomfort.

The heatmap of participant votes identifies clusters of negative thermal and aesthetic perceptions, which align well with high MRT and PET zones from the simulations. This alignment confirms the accuracy of the simulations in reflecting real-world thermal conditions. Notably, both simulations and participant votes highlight the worst pedestrian areas as being between building blocks B, C, I, J, and building K1. This consistency underscores the reliability of the simulations and the importance of integrating objective data with subjective feedback in urban thermal comfort studies.



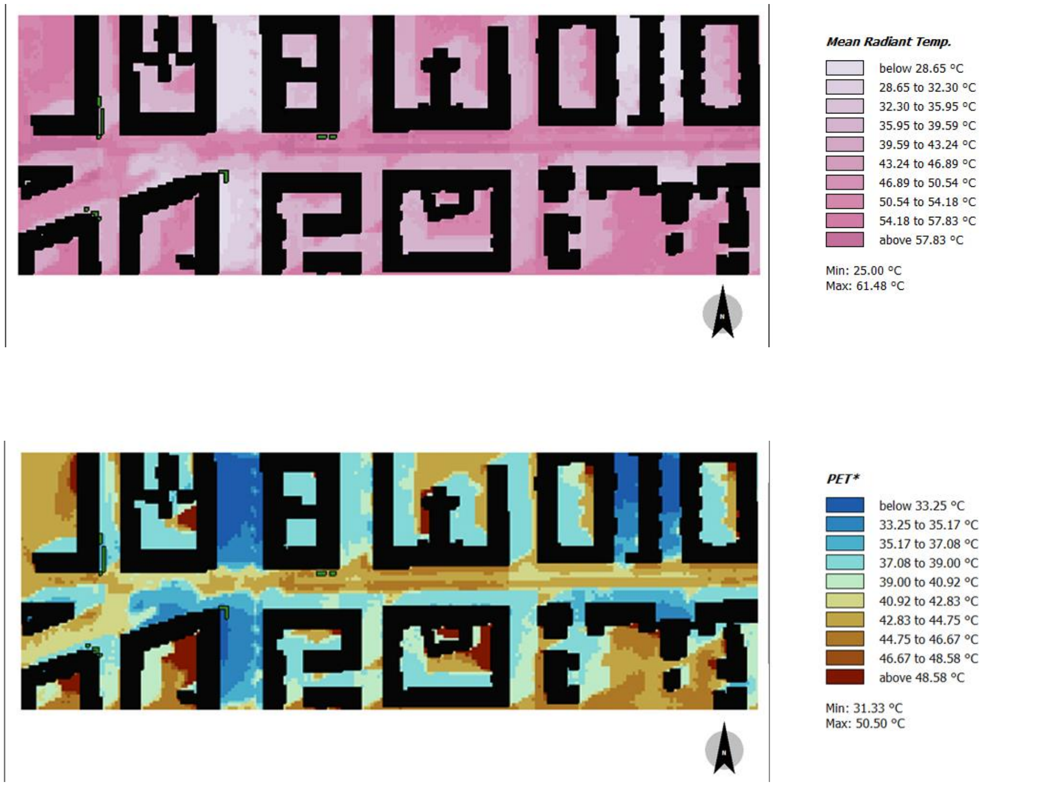



Figure 75. Heatmap of negative thermal clusters / Simulated potential air temperature , Tmrt, and PET for user3, 03.08.2023 15:00:00.

## 6.5.1.5 Simulations & Thermal walk: TSV and PET

In order to compare the PET simulated by ENVI-met, the PET of the thermal walk calculated with Rayman, and the TSV votes during the thermal walk, user profiles were assigned to the participants based on their personal characteristics such as age, gender, and BMI. These profiles were then associated with existing simulated user profiles to examine correlations between the simulated PET and subjective thermal sensation votes (TSV).

**Understanding Predictive Accuracy**: The comparison aims to test how accurately PET, simulated by ENVI-met and calculated using Rayman, predicts the thermal sensation votes of pedestrians. This comparison is crucial because TSV and simulated PET refer to different environmental conditions (simulation day –average hottest day of summer 2023). This analysis evaluates the reliability of PET as an index for predicting real-time thermal comfort as experienced by individuals.

ENVI-met uses a corrected PET model, which has undergone recent improvements to address accumulated errors and inconsistencies. This revised PET model, referred to as PET* (PET Reviewed), includes modifications suggested by Walther and Goestchel (2018) and other improvements. This updated model aims to provide a more accurate representation of thermal comfort in urban environments.

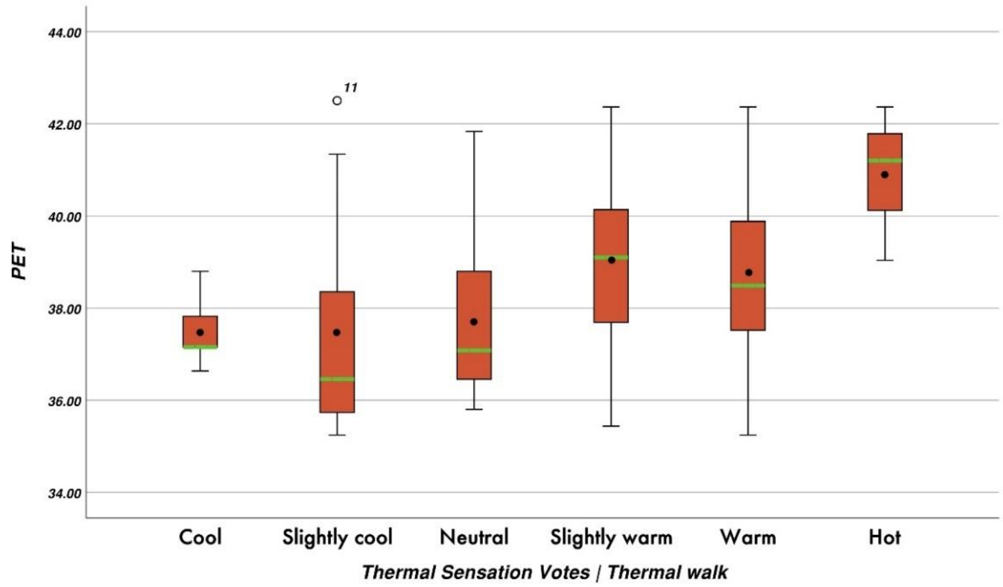



Figure 76. Boxplot of simulated PET to TSV ¦ Thermal walk

The observed findings indicate that simulated PET from ENVI-met is much closer to TSV than the calculated PET from Rayman. This suggests that the CFD (computational fluid dynamics) nature of ENVI-met allows for more dynamic simulations, accounting for various factors such as accumulated heat in surrounding surfaces, material properties, and other phenomena specific to the built environment.

Calculated PET using Rayman seems more closely related to measured air temperature at the time of the thermal walk. This could imply that Rayman’s approach, while accurate for instantaneous conditions, may not fully capture the complexities of urban environments that affect thermal sensation over time.

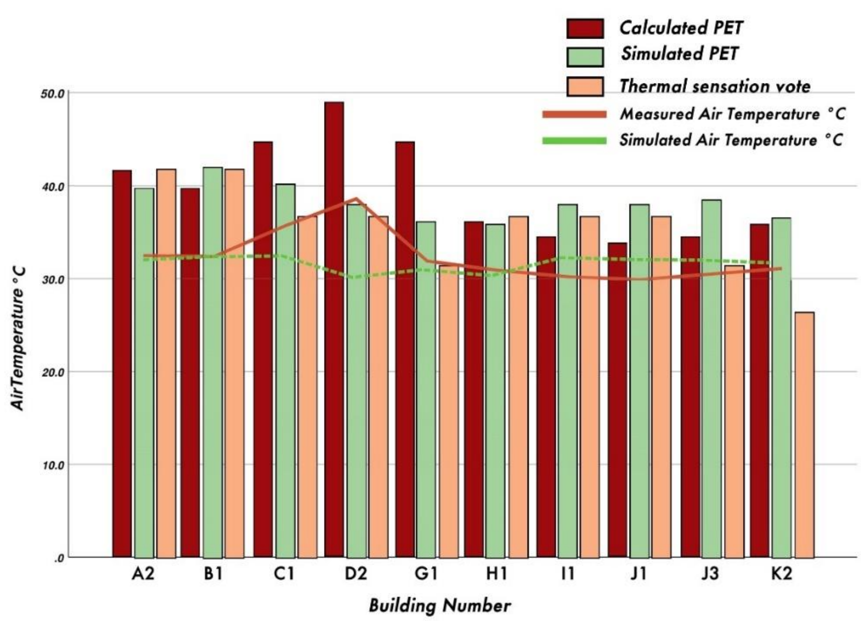



Figure 77.Temperature vs. Building Codes: Simulated PET, Calculated PET, TSV from Thermal Walk, Simulated Potential Air Temperature, and Measured Air Temperature.

### 6.5.2 Conclusions

By comparing weighted density maps derived from the workshop and the survey, differences between perceptions captured in the workshop and those recorded in the survey are identified. The survey's broader respondent base and longer duration capture a wider range of perceptions. The heatmap of participant votes aligns with high MRT and PET zones from simulations, confirming the accuracy of the simulations in reflecting real-world conditions.

Thermal sensation votes for facade materials, collected during both the thermal walk and the workshop, reveal significant contextual differences. The thermal walk's real-time evaluations capture immediate perceptions, while the workshop reflects more generalized or recalled perceptions. Bright-colored materials, such as brick and plaster, show significant variations between contexts, indicating situational thermal perceptions. Grey materials, like marble, consistently provide cooler thermal sensations across settings, highlighting the influence of material and color on thermal perception.

The survey identified the least and most attractive and thermally uncomfortable areas in the district, revealing a strong correlation between negative votes for aesthetics and thermal perception. The thermal walk focused on these areas, assessing if negative votes were directly associated with facades. Discrepancies between the survey and thermal walk results suggest that broader context and additional factors beyond facades influence aesthetic perception. Buildings consistently rated poorly in both methods (A2, C1, D1, J1) should be prioritized for aesthetic interventions.

Finally, comparing PET simulated by ENVI-met, PET calculated with Rayman, and TSV votes during the thermal walk highlights the predictive accuracy of these models. ENVI-met's corrected PET model (PET*) closely aligns with TSV, suggesting its ability to account for dynamic factors in the built environment.

# 7 Design

## 7.1 Decision Matrix & Design

In the following section, a summary of the identified parameters and their impacts is presented, categorizing the various built environment variables and their influence on Tmrt and PET. The provided matrix of indicators enables decision-makers (such as politicians and local government officials), in collaboration with building and urban designers and planners, to assign weights based on the objectives to be achieved.

Table 19. Decision matrix

| Parameters | | PET | | Tmrt | | REF. |
|---|---|---|---|---|---|---|
| Built environment | | | | | | |
| Aspect ratio(AR) | High (>1.7) | ↑nighttime | ↓daytime | ↑nighttime | ↓daytime | |
| | Low (<0.9) | ↓nighttime | ↑daytime | ↓nighttime | ↑daytime | |
| Orientation | E-W (humid subtropical climate) | ↑increases in respect to N-S | | ↑increases in respect to N-S | | |
| Sky view factor (SVF) | High(>0.40) | ↑daytime | ↓nighttime | ↑daytime | ↓nighttime | |
| | Low (<0.2) | ↓ daytime | ↑nighttime | ↓ daytime | ↑nighttime | |
| Vegetated areas | High | ↓ daytime | ↓nighttime | ↓ daytime | ↓nighttime | |
| | Low | ↑daytime | ↑daytime | ↑daytime | ↑daytime | |
| Building height (m) | High(>27) | ↓ daytime | ↑nighttime | ↓ daytime | ↑nighttime | |
| | Low (<23) | ↑daytime | ↓nighttime | ↑daytime | ↓nighttime | |
| Block size length (m)(derived from vertical street distance) | High (105) | ↑daytime | ↑nighttime | ↑daytime | ↑nighttime | |
| | Low (80) | ↓ daytime | ↓nighttime | ↓ daytime | ↓nighttime | |
| U-value (W/(m^2K) | High (>1.6) | ↑daytime | ↑nighttime | ↑daytime | ↑nighttime | |
| | Low(<0.8) | ↓ daytime | ↓nighttime | ↓ daytime | ↓nighttime | |
| Upper Facade | | | | | | |
| Albedo | High(>0.7) | ↑ daytime | ↑nighttime | ↑ daytime | ↑nighttime | |
| | Low(<0.6) | ↓daytime | ↓nighttime | ↓daytime | ↓nighttime | |
| Absorption | High(>0.6) | ↓daytime | ↑nighttime | ↓daytime | ↑nighttime | |
| | Low(<0.5) | ↑ daytime | ↓nighttime | ↑ daytime | ↓nighttime | |
| Thermal Conductivity W/(m·°C) | High(>0.8) | ↑daytime | ↓nighttime | ↑daytime | ↑nighttime | |
| | Low(<0.6) | ↓ daytime | ↑nighttime | ↓ daytime | ↓nighttime | |
| Density (kg/m^3) | High(>1500) | ↓daytime | ↑nighttime | ↓daytime | ↑nighttime | |
| | Low(<1000) | ↑ daytime | ↓nighttime | ↑ daytime | ↓nighttime | |
| Lower facade | | | | | | |
| Glass percentage % | High(>70) | ↑daytime | ↓nighttime | ↑daytime | ↓nighttime | |
| | Low(<30) | ↓ daytime | ↑nighttime | ↓ daytime | ↑nighttime | |
| Absorption | High(>0.45) | ↓daytime | ↑nighttime | ↓daytime | ↑nighttime | |
| | Low(<0.35) | ↑ daytime | ↓nighttime | ↑ daytime | ↓nighttime | |
| Thermal Conductivity W/(m·°C) | High(>5) | ↑daytime | ↓nighttime | ↑daytime | ↓nighttime | |
| | Low(<0.8) | ↓ daytime | ↑nighttime | ↓ daytime | ↑nighttime | |
| Specific Heat Capacity J/(kg·°C) | High(>890) | ↓ daytime | ↑nighttime | ↓ daytime | ↑nighttime | |
| | Low(<850) | ↑daytime | ↓nighttime | ↑daytime | ↓nighttime | |
| Emissivity | High (0.95) | ↑daytime | ↓nighttime | ↑daytime | ↓nighttime | |
| | Low (0.86) | ↓ daytime | ↑nighttime | ↓ daytime | ↑nighttime | |

Following the decision tree indications and integrating residents' preferences, the proposed design solutions aim to enhance outdoor thermal comfort in Via Beato Angelico. This multifaceted approach involves modifying façade materials, increasing vegetation, and optimizing the built environment based on research findings and community feedback. Each design option is detailed below.Upper Façade Modifications

- Upper Façade Modifications

Although brick on the upper façade outperforms other materials in terms of thermal performance, it is not considered feasible for widespread implementation. It is also observed through the participatory approaches that people associate brick with an unpleasant thermal experience.  Instead, the radiative properties of existing materials will be adjusted by moderately increasing albedo (from 0.4 to 0.6) and decreasing absorption to below 0.5. This adjustment, effective when combined with increased vegetation, helps control potential increases in mean radiant temperature due to reflected radiation (Piselli et al., 2018). The balance between surface temperature reduction and controlling reflected radiation is essential for optimizing thermal comfort.

- Lower Façade Modifications

For lower façades, a moderate albedo (0.4) and low absorption (0.35) will be maintained. Plaster, a common but poorly performing material, will either be replaced or modified with coatings and finishes. Marble and stucco, which perform well and are preferred by residents, will remain unchanged. For concrete surfaces, new paints with fresh and vivid colors that comply with the required albedo and absorption will be applied. Buildings identified as less visually attractive (A2, C1, D2, J1) will have their outer layers replaced with better-performing materials. In other areas, architectural aesthetics will be preserved with minimal changes, incorporating low emissivity paints to enhance thermal performance. Key properties for ground floor façade materials include low emissivity and high thermal mass (Tabatabaei & Fayaz, 2023).

- Glass Percentage Adjustments

Decreasing the glass percentage on the ground floor, particularly for buildings with high existing glass percentages (indicative of stores), is not feasible. Instead, old glazing will be replaced with new, well-insulating ones (Abrahem et al., 2020). To improve pedestrian interaction, additional shading devices such as awnings, pergolas, and green walls will be incorporated. These measures provide thermal regulation through shading and evapotranspiration while enhancing visual appeal, as highlighted in workshop feedback.

- Vegetation Enhancements

Buildings with overhangs, terraces, or autonomous lower entrances will integrate hanging or climbing vegetation to improve aesthetic and thermal comfort. The addition of plants on balconies, as requested by residents in thermal walk and workshop, will enhance both the thermal environment and the aesthetic quality of the neighborhood.

- Albedo Adjustments on Vertical and Horizontal Surfaces

While increasing albedo on vertical surfaces does not mitigate heat as effectively as on horizontal surfaces, building roofs will feature higher albedo materials to reduce overall street temperatures. Pavement surfaces, currently grey concrete, are more acceptable than bright concrete or basalt, according to workshop results. The replacement of asphalt in parking spots with permeable pavement is suggested while keeping the existing pavement material. Implementing permeable pavement can significantly improve thermal comfort and potentially increase green surfaces in the street. Studies indicate that this combination effectively reduces all evaluated thermal variables (Haeri et al., 2023).

- Additional Vegetation on Pavements

There is ample space for extra vegetation along pavements, including trees, hedges, and bushes around blocks. These additions will reduce sky view factor (SVF), provide additional shading, and improve aesthetic quality as expressed by respondents in the survey. Increasing green areas aligns with community preferences and offers numerous benefits for thermal comfort. Vegetation can also control the acoustic and air problems identified in the multi-domain analysis.

The design table below, incorporates modifications based on the criteria established for improving thermal comfort and integrating residents' aesthetic preferences. Specific color suggestions have been included to comply with the required albedo and absorption levels.

Table 20. Design proposals.

| Building Code | Upper Facade Material | Ground Floor Material | Proposed Modification (Upper Facade) | Proposed Modification (Ground Floor) | Glass Percenta-ge | Proposed Shading Devices and Glazing Solutions |
|---|---|---|---|---|---|---|
| A1 | Stucco Grey | Stucco Grey | Increase albedo to 0.6, apply low absorption coating (<0.5). Suggested colors: Light Grey (RGB: 200, 200, 200), Off-White (RGB: 245, 245, 245) | Apply low IR emissivity paint, moderate albedo (0.4), specific heat capacity >850 J/(kg·°C). Suggested colors: Pale Yellow (RGB: 255, 255, 224), Light Beige (RGB: 245, 245, 220) | 0% | Add plants on balconies and around the building |
| A2 | Stucco Bright | Stucco Bright | Albedo in desirable levels apply low absorption coating (<0.5)- Thermal Barrier Coatings (TBCs). | Replace with marble, apply low emissivity paint. Suggested colors: Light Grey (RGB: 200, 200, 200), Light Beige (RGB: 245, 245, 220) | 0% | Add plants on balconies and around the building |
| B1 | Plaster Bright | Plaster Bright | Increase albedo to 0.6, apply high-albedo paint or reflective coatings. Suggested colors: Light Beige (RGB: 245, 245, 220), Cream (RGB: 255, 253, 208) | Apply low emissivity paint, moderate albedo (0.4), specific heat capacity >850 J/(kg·°C). Suggested colors: Pale Yellow (RGB: 255, 255, 224), Light Beige (RGB: 245, 245, 220) | 0% | Add overhangs on the façade for shading, or external shading devices |
| C1 | Plaster Bright | Concrete Grey | Increase albedo to 0.6, apply high-albedo paint or reflective coatings. Suggested colors: Light Beige (RGB: 245, 245, 220), Cream (RGB: 255, 253, 208) | Replace with marble, apply low emissivity paint. Suggested colors: Light Grey (RGB: 200, 200, 200), Light Beige (RGB: 245, 245, 220) | 50% | Install awnings, replace glazing with Insulated Glass Units (IGUs) ,Low-Emissivity (Low-E) Glass |
| C2 | Ceramic Bright | Concrete Bright | No change needed | Apply vivid colors with low absorption (0.35) and moderate albedo (0.4-0.5). Suggested colors: Sky Blue (RGB: 135, 206, 250), Mint Green (RGB: 189, 252, 201) | 25% | - |
| D1 | Brick Fireclay | Concrete Grey | Albedo in desirable levels apply low absorption coating (<0.5)- Thermal Barrier Coatings (TBCs). | Apply vivid colors with low absorption (0.35) and moderate albedo (0.4-0.5). Suggested colors: Sky Blue (RGB: 135, 206, 250), Mint Green (RGB: 189, 252, 201) | 45.4% | Install awnings, replace glazing with Insulated Glass Units (IGUs), Low-Emissivity (Low-E) Glass, plants on balconies and |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | around the building |
| **D2** | Brick Red | Concrete Grey | High near-infrared (NIR) reflective paints. Improve the thermal performance while maintaining their visible color and appearance) | Replace with marble, apply low emissivity paint. Suggested colors: Light Grey (RGB: 200, 200, 200), Light Beige (RGB: 245, 245, 220) | 50% | Install awnings, replace glazing with Insulated Glass Units (IGUs) ,Low-Emissivity (Low-E) Glass |
| **D3** | Brick Fireclay | Concrete Grey | Albedo in desirable levels apply low absorption coating (<0.5)- Thermal Barrier Coatings (TBCs). | Apply vivid colors with low absorption (0.35) and moderate albedo (0.4-0.5). Suggested colors: Sky Blue (RGB: 135, 206, 250), Mint Green (RGB: 189, 252, 201) | 54.5% | Install awnings, replace glazing with Insulated Glass Units (IGUs) ,Low-Emissivity (Low-E) Glass |
| **E1** | Plaster Bright | Stucco Bright | Increase albedo to 0.6, apply high-albedo paint or reflective coatings. Suggested colors: Light Beige (RGB: 245, 245, 220), Cream (RGB: 255, 253, 208) | Apply low emissivity paint, moderate albedo (0.4-0.5), specific heat capacity >850 J/(kg·°C). Suggested colors: Pale Yellow (RGB: 255, 255, 224), Light Beige (RGB: 245, 245, 220) | 0% | - |
| **F1** | Brick Fireclay | Marble Bright | Albedo in desirable levels apply low absorption coating (<0.5)- Thermal Barrier Coatings (TBCs). | No change needed | 72.7% | Install awnings, replace Insulated Glass Units (IGUs) ,Low-Emissivity (Low-E) Glass |
| **G1** | Brick Red | Concrete Grey | High near-infrared (NIR) reflective paints. Improve the thermal performance while maintaining their visible color and appearance) | Apply vivid colors with low absorption (0.35) and moderate albedo (0.4-0.5). Suggested colors: Sky Blue (RGB: 135, 206, 250), Mint Green (RGB: 189, 252, 201) | 29.4% | - |
| **G2** | Brick Fireclay | Stucco Bright | Albedo in desirable levels apply low absorption coating (<0.5)- Thermal Barrier Coatings (TBCs). | Apply low emissivity paint, moderate albedo (0.4), specific heat capacity >850 J/(kg·°C). Suggested colors: Pale Yellow (RGB: 255, 255, 224), Light Beige (RGB: 245, 245, 220) | 0% | - |
| **H1** | Stucco Bright | Stucco Bright | Albedo in desirable levels apply low absorption coating (<0.5)- Thermal Barrier Coatings (TBCs). | Apply low emissivity paint, moderate albedo (0.4-0.5), specific heat capacity >850 J/(kg·°C). Suggested colors: Pale Yellow (RGB: 255, 255, 224), Light Beige (RGB: 245, 245, 220) | 25.8% | Install awnings, replace glazing with Insulated Glass Units (IGUs) ,Low-Emissivity (Low-E) Glass |
| **H2** | Plaster Bright | Stucco Bright | Increase albedo to 0.6, apply high-albedo paint or reflective coatings. Suggested colors: Light Beige (RGB: 245, 245, 220), Cream (RGB: 255, 253, 208) | Apply low emissivity paint, moderate albedo (0.4-0.5), specific heat capacity >850 J/(kg·°C). Suggested colors: Pale Yellow (RGB: 255, 255, 224), Light Beige (RGB: 245, 245, 220) | 48.5% | Install awnings, replace glazing with Insulated Glass Units (IGUs) ,Low-Emissivity (Low-E) Glass |

| | | | | | | |
|---|---|---|---|---|---|---|
| I1 | Plaster Bright | Stucco Bright | Increase albedo to 0.6, apply high-albedo paint or reflective coatings. Suggested colors: Light Beige (RGB: 245, 245, 220), Cream (RGB: 255, 253, 208) | Apply low emissivity paint, moderate albedo (0.4-0.5), specific heat capacity >850 J/(kg·° | 0% | - |
| J1 | Brick Fireclay | Concrete Grey | Albedo in desirable levels apply low absorption coating (<0.5)- Thermal Barrier Coatings (TBCs). | Replace with marble, apply low emissivity paint. Suggested colors: Light Grey (RGB: 200, 200, 200), Light Beige (RGB: 245, 245, 220) | 0% | Vegetation on balconies, hanging plants on overhang |
| J2 | Brick Red | Concrete Grey | Albedo in desirable levels apply low absorption coating (<0.5)- Thermal Barrier Coatings (TBCs). | Apply vivid colors with low absorption (0.35) and moderate albedo (0.4-0.5). Suggested colors: Sky Blue (RGB: 135, 206, 250), Mint Green (RGB: 189, 252, 201) | 50% | Install awnings, replace glazing with Insulated Glass Units (IGUs) ,Low-Emissivity (Low-E) Glass |
| J3 | Plaster Bright | Stucco Grey | Increase albedo to 0.6, apply high-albedo paint or reflective coatings. Suggested colors: Light Beige (RGB: 245, 245, 220), Cream (RGB: 255, 253, 208) | Apply low IR emissivity paint, moderate albedo (0.4), specific heat capacity >850 J/(kg·°C). Suggested colors: Pale Yellow (RGB: 255, 255, 224), Light Beige (RGB: 245, 245, 220) | 71.4% | Install awnings, replace glazing with Insulated Glass Units (IGUs) ,Low-Emissivity (Low-E) Glass, add overhangs for shading |
| K1 | Plaster Bright | Marble Grey | Increase albedo to 0.6, apply high-albedo paint or reflective coatings. Suggested colors: Light Beige (RGB: 245, 245, 220), Cream (RGB: 255, 253, 208) | No change needed | 38.5% | Install awnings, replace glazing with Insulated Glass Units (IGUs) ,Low-Emissivity (Low-E) Glass, add vegetation around the building |
| K2 | Plaster Bright | Marble Grey | Increase albedo to 0.6, apply high-albedo paint or reflective coatings. Suggested colors: Light Beige (RGB: 245, 245, 220), Cream (RGB: 255, 253, 208) | No change needed | 46.7% | Install awnings, replace glazing with high-insulation glass, add vegetation around the building |
| K3 | Brick Red | Marble Bright | Albedo in desirable levels apply low absorption coating (<0.5)- Thermal Barrier Coatings (TBCs). | No change needed | 80% | Install awnings, replace glazing with Insulated Glass Units (IGUs) ,Low-Emissivity (Low-E) Glass, |
| K4 | Brick Red | Marble Bright | Albedo in desirable levels apply low absorption coating (<0.5)- Thermal Barrier Coatings (TBCs). | No change needed | 33.4% | Install awnings, replace glazing with high-insulation glass, extend green areas |

## 7.2 Simulation results

Following the design proposal, a new simulation is conducted in ENVI-met to test the impact of changes in material properties on thermal discomfort. The changes are applied directly to the properties of the simulated materials in ENVI-met 'DB Manager', focusing primarily on the outer layer, with a few exceptions for buildings A2, C1, D2, and J1, where the outer layer is replaced with marble or stucco (Table 20). The rest of the simulation settings remain unchanged. The simulation during the most crucial (hottest) hours shows a significant decrease in thermal discomfort:

- PET (Physiological Equivalent Temperature): Decreases by 0.5 - 2 °C in front of the reference facades.

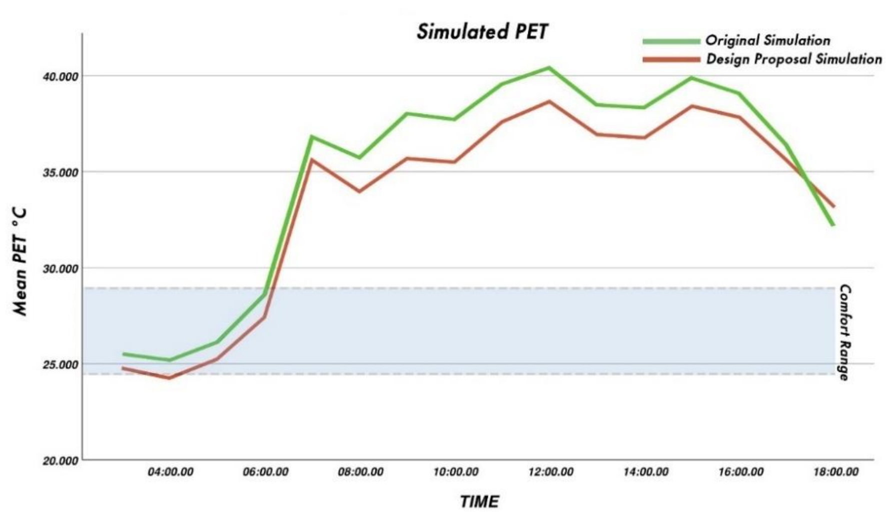



Figure 78. Original Mean PET vs. Mean PET of the design proposal throughout the day hours.

- Tmrt (Mean Radiant Temperature): Decreases by up to 7°C.

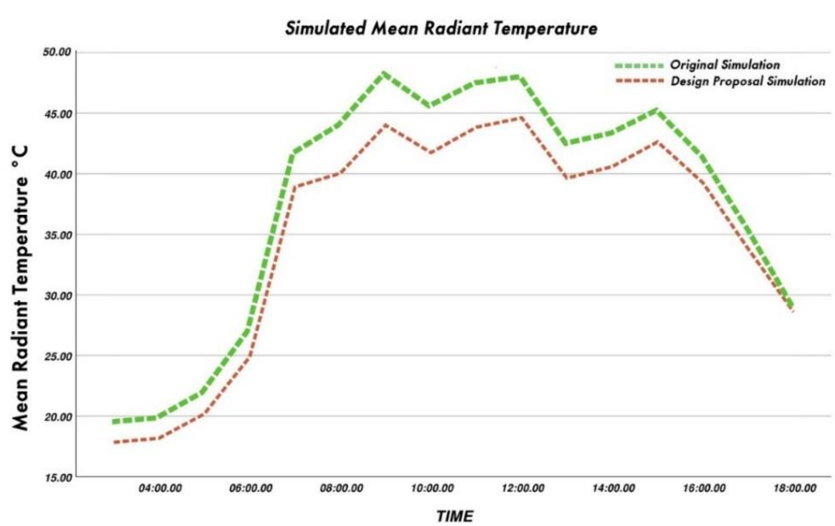



Figure 79. Original  Mean Tmrt vs. Mean Tmrt of the design proposal throughout the day hours.

- Air Temperature: Decreases by up to 1.2°C.

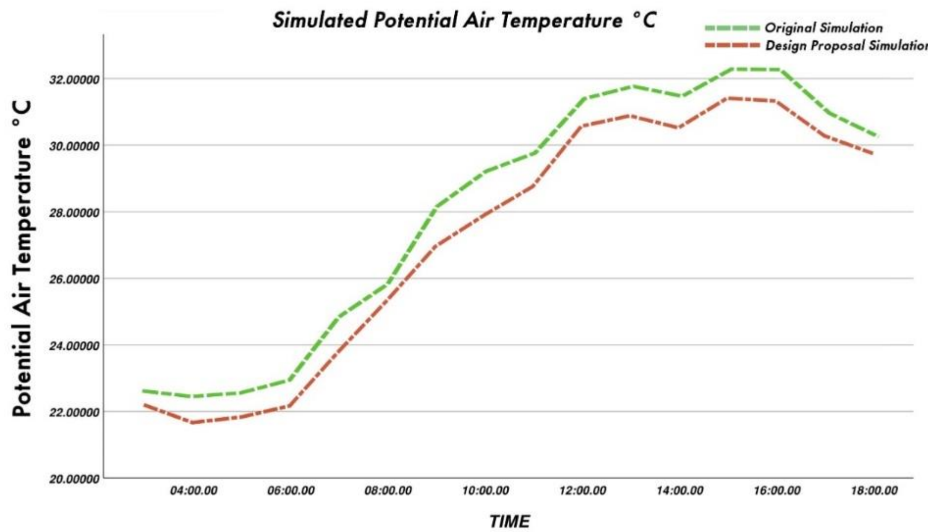



Figure 80. Original Mean Tair vs. Mean Tair of the design proposal throughout the day hours.

The PET is calculated for user profile 3, deemed the most representative user, due to time limitations. The mean PET throughout the simulated hours indicates that an additional 20 minutes of thermal comfort was achieved during the morning hours. It is anticipated that performing simulations for less extreme conditions or on less hot days could result in more hours of comfortable PET values and more significant temperature changes.

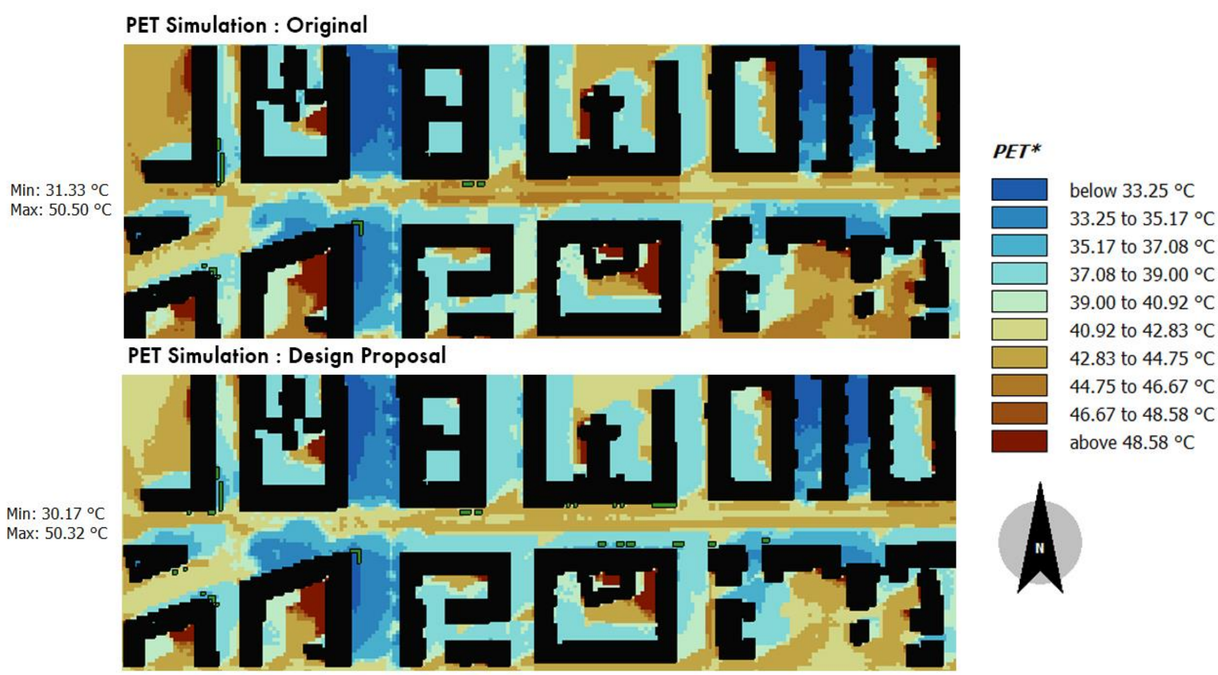



Figure 81.Mapping PET of user3 at 3:00 PM 03/08/2023 ¦Original vs New design.

Table 21. Original vs. New Design analysis of PET, Tmrt and Tair for every building.

| Building Number | Original: PET °C | Design: PET °C | Original: Tmrt °C | Design: Tmrt °C | Original: Tair °C | Design: Tair °C |
|---|---|---|---|---|---|---|
| A1 | 36.62575 | 35.61750 | 42.6469 | 40.3406 | 28.5086088 | 27.2974644 |
| A2 | 35.44554 | 34.34256 | 40.4063 | 37.5094 | 28.3303438 | 27.2347250 |
| B1 | 37.05260 | 35.93263 | 44.0537 | 40.8200 | 28.4706400 | 27.6454037 |
| C1 | 35.27472 | 34.42350 | 39.6856 | 36.3713 | 28.4289544 | 27.6811563 |
| C2 | 34.77856 | 34.09906 | 38.5756 | 36.9256 | 28.4297831 | 27.7945300 |
| D1 | 33.80839 | 33.41506 | 36.9081 | 35.1700 | 27.8633031 | 26.5582444 |
| D2 | 34.78908 | 33.87425 | 40.1331 | 37.2681 | 27.6916919 | 26.9323894 |
| D3 | 33.45549 | 32.85419 | 37.2587 | 35.7206 | 27.3645156 | 27.1171206 |
| E1 | 37.05531 | 35.95344 | 44.1906 | 41.0606 | 28.1050313 | 27.3208063 |
| F1 | 35.57674 | 32.68650 | 37.1494 | 30.0469 | 27.9467725 | 27.1013150 |
| G1 | 32.98768 | 32.22963 | 33.1625 | 30.7288 | 28.0658200 | 27.3101863 |
| H1 | 33.23901 | 32.65706 | 34.2088 | 32.4356 | 27.3767269 | 26.5170450 |
| H2 | 31.81890 | 31.09250 | 32.3556 | 29.9594 | 27.3426319 | 26.5013819 |
| I1 | 34.66753 | 33.82650 | 38.5744 | 35.7100 | 28.2174356 | 27.4387213 |
| J1 | 35.62966 | 34.23775 | 40.9238 | 36.6719 | 28.3951369 | 27.5813213 |
| J2 | 34.55307 | 33.14050 | 37.7631 | 33.2619 | 28.3485525 | 27.4204506 |
| J3 | 33.97785 | 33.30719 | 35.7931 | 33.8494 | 28.3604050 | 27.4616294 |
| K1 | 35.08510 | 34.16744 | 39.0200 | 36.2937 | 28.2800731 | 27.2928663 |
| K2 | 34.01243 | 33.35794 | 36.4563 | 34.3719 | 28.0796256 | 27.1084681 |
| K3 | 33.55484 | 33.17406 | 35.3619 | 33.9231 | 27.9762781 | 27.0744275 |
| K4 | 31.19209 | 30.80350 | 26.2044 | 24.8531 | 27.8279850 | 26.9871375 |

# 9 Conclusion

## 9.1 Revisiting the research questions

### Main Research Question: *How can a multi-domain approach be implemented to assess the influence of facades on outdoor thermal comfort*

The research is structured around this main question, supported by several sub-questions, each addressing critical aspects of the study. Below is a comprehensive conclusion answering each sub-question, detailing the methods and findings of the thesis.

#### Sub-question 1(Literature): *What is outdoor thermal comfort and how is it affected by the built environment?*

Outdoor thermal comfort (OTC) is defined as the state of mind that expresses satisfaction with the outdoor thermal environment. It is measured using various thermal indices, such as the Physiological Equivalent Temperature (PET) and Mean Radiant Temperature (Tmrt). PET is particularly useful as it considers multiple climatic and microclimatic variables, including air temperature, humidity, wind speed, and mean radiant temperature, along with personal factors such as clothing insulation and activity level. These indices provide a comprehensive measure of how comfortable individuals feel in an outdoor setting.

The built environment significantly influences OTC through various factors. Urban configuration elements such as building height, street width, sky view factor (SVF), aspect ratio, vegetation, and facade materials play crucial roles. For instance, taller buildings can provide shading, reducing direct solar exposure and lowering PET. Similarly, the SVF affects how much of the sky is visible, influencing radiation and heat dissipation. Materials with high thermal mass, such as concrete, can store heat during the day and release it at night, impacting thermal comfort. The aesthetic quality of the urban environment also affects thermal perception, as visually appealing areas are often perceived as more comfortable.

Moreover, other personal factors such as age, gender, and psychological adaptation mechanisms significantly influence thermal comfort. For example, older individuals might experience thermal environments differently due to changes in their thermoregulatory systems. Psychological factors, including past experiences and expectations, also play a role in how people perceive thermal comfort. The interplay between these personal and environmental factors underscores the complexity of assessing and improving OTC.

#### Sub-question 2 (Literature): *What are the tools, workflows, and current methods to measure OTC?*

The study reviews various methods to measure OTC, categorized into qualitative, quantitative, and mixed methods. Qualitative methods, such as field surveys, interviews, and workshops, gather subjective data on how individuals perceive their thermal environment. These methods are invaluable for understanding personal comfort levels and identifying specific discomfort areas within a community

Quantitative methods involve numerical simulations, field measurements, and statistical analyses. Tools like ENVI-met, a three-dimensional computational fluid dynamics (CFD) microclimate modeling system, are used to simulate urban climates and assess the impact of different environmental factors on thermal comfort. Other software tools such as SPSS for statistical analysis also play significant roles. Field measurements using portable sensors provide real-time data on air temperature, humidity, and other relevant parameters.

Mixed methods combine qualitative and quantitative approaches to provide a comprehensive assessment. For example, integrating survey data with simulation results can validate and enhance the accuracy of the findings. This combined approach allows for a more holistic understanding of OTC, addressing both subjective perceptions and objective measurements. The thesis highlights the importance of using a combination of these methods to capture the full spectrum of factors influencing thermal comfort.

### Sub-question 3 (Results): *How does facade influence urban inhabitants' thermal perception?*

The influence of facades on thermal perception operates on multiple levels. On a personal level, individuals adapt through physiological, psychological, and behavioral mechanisms. For instance, people might choose shaded routes or adjust their clothing to cope with thermal stress. Psychological adaptation, influenced by past experiences and expectations, also plays a significant role in how individuals perceive thermal comfort.

Urban geometries such as building height, block size, SVF, aspect ratio, vegetation, and orientation critically affect thermal perception. Taller buildings and narrower streets can provide shading, reducing direct solar exposure and lowering PET. Vegetation, through shading and evapotranspiration, can significantly enhance thermal comfort. The study finds that streets perpendicular to Via Beato Angelico offer better comfort levels due to reduced solar exposure and increased shading from vegetation.

The materiality of facades also has a substantial impact on thermal perception. The study's simulations reveal that materials low emissivity and high specific heat capacity materials, like marble, in lower façade surfaces improve thermal comfort by reducing the mean radiant temperature. The findings highlight the importance of considering both day and night effects, as well as upper and ground floor properties, in designing facades for improved thermal comfort. Comparisons between simulated data and user perceptions from workshops and surveys indicate a degree of alignment, validating the accuracy of the simulation models. However, they also reveal that user thermal sensations associated with certain materials, such as marble and brick, remain consistent across different contexts (workshop and thermal walk). This consistency suggests that psychological factors related to facade materials significantly influence thermal perception. On-site experiments highlight that ground floor materials greatly affect thermal perception, whereas objective simulations indicate that upper facade materials have the most significant impact on PET. This discrepancy underscores the complex interplay between objective material properties and subjective thermal experiences.

### Sub-question 4 (Results): *To what extent can the perceptual aesthetics of facades influence pedestrians' perception of the thermal environment?*

The survey and workshop results demonstrate a strong correlation between aesthetic and thermal comfort. Areas perceived as visually attractive are often rated as thermally comfortable, highlighting the intertwined nature of these perceptions. Clusters of negative thermal and aesthetic perceptions, identified through heatmaps and participant votes, align well with high PET and MRT zones from the simulations. This alignment validates the simulation results and underscores the importance of integrating aesthetic improvements into thermal comfort strategies.

The survey uses a Likert scale for perceptual aesthetics and an ASHRAE scale for thermal sensation, facilitating a detailed comparison between visual appeal and thermal comfort. The analysis reveals that factors such as frequency of visits and proximity to vegetation significantly influence both aesthetic and thermal perceptions.

Workshop findings indicate that psychological factors, such as visual experience and past encounters, influence thermal sensation. Participants associate specific facade materials with thermal comfort based on their radiative characteristics, suggesting that aesthetic improvements can enhance perceived thermal comfort.

The thermal walk adds further insights, showing that factors beyond facade aesthetics influence thermal perception. Compared to the survey, where aesthetic questions did not specifically address facades, the thermal walk reveals additional factors affecting thermal perception. It also suggests that elements beyond the scope of this study, possibly related to the broader streetscape, impact the negative aesthetic perceptions of the street.

### Sub-question 5 (Methodology): *How can qualitative and quantitative methods be combined to assess Outdoor Thermal Comfort (OTC)?*

The combination of qualitative and quantitative methods to assess OTC is achieved through a meticulously designed workflow that integrates various stages of data collection, analysis, and validation. The workflow integrates multiple methods to provide a comprehensive understanding of the factors influencing outdoor thermal comfort and to develop effective design solutions. Each step contributes unique insights, building upon the previous step and enhancing the overall process.

1. Workshop

The workshop serves as the initial step in this multi-domain approach, crucial for identifying the focus area of the study. By engaging with participants in an interactive manner, the workshop gathers information about the frequency and importance of various locations within the district. This approach provides ease of access to insights that would be computationally expensive to identify, and ensures that the focus areas reflect the opinions and experiences of the community. The workshop not only highlights problematic areas but also captures the qualitative aspects of environmental quality and thermal discomfort, which are essential for a holistic analysis.

2. Long-term Survey:

The survey expands the multi-domain analysis with a larger sample size, offering detailed demographic information and mapping preferences of different populations within the district. This step is essential for identifying the needs of more vulnerable groups. The survey reveals strong correlations between thermal perception and aesthetics, highlighting the interconnectedness of these factors. By incorporating a broader demographic, the survey provides a comprehensive understanding of the district's diverse needs and preferences, informing more inclusive design solutions.

3. Simulations:

The simulations, representative of the district’s population and morphology, allowed for a deeper inspection of materiality and its effects on thermal perception. This step is critical for defining the objective parameters that influence thermal comfort. By utilizing computational models, simulations offer precise data on how various materials and configurations impact PET and Tmrt, providing a scientific basis for the design proposals. This objective analysis complements the subjective data collected from the workshop and survey.

4. Thermal Walk & Field Measurements:

The thermal walk provided real-time measurements and evaluation of thermal perception. This step is invaluable for exploring which parameters affect thermal comfort in practice and for validating PET as a representative index of thermal perception. By comparing real-time data with simulated results, the thermal walk highlights the dynamic nature of thermal comfort and the importance of contextual factors. This step indicates that certain facade properties are more crucial for TSV than identified in simulations and ensures that the design proposals are grounded in both theoretical simulations and practical, on-the-ground observations.

5. Decision Matrix & Design Proposal:

The culmination of the previous steps is the decision matrix and the resulting design proposal. This step synthesizes the findings from workshops, surveys, simulations, and field measurements into actionable design strategies. By integrating community feedback with objective data, the decision matrix provides a comprehensive framework for enhancing thermal comfort.

The applicability and replicability of this workflow make it a valuable tool for urban planners and designers. By systematically incorporating user data and objective measurements, the workflow can be adapted to different contexts and locations.

Design Question: *What facade design solutions can be used to effectively mitigate overheating and improve outdoor thermal comfort for pedestrians in Acquabella district?*

The design solutions proposed in this thesis are derived from a comprehensive decision matrix that considers all research findings. The matrix provides guidelines for resilient and climate-adaptive designs, tailored to the specific needs of Via Beato Angelico in the Acquabella district. The solutions aim to balance thermal comfort improvements while maintaining the architectural integrity of the neighborhood.

Key design solutions include using moderate-albedo for upper facades and permeable pavements to reduce heat absorption. Shading devices, such as awnings and vertical greenery, are proposed to minimize direct solar gain. Increasing greenery on facades and in open spaces is recommended to enhance cooling through evapotranspiration and improve visual appeal. The use of vivid, fresh colors for upper facades is suggested to improve reflectivity and moderately reduce heat absorption, aligning with residents' preferences. Lower façade modifications also include replacement of poorly performing materials like plaster with marble and stucco, and apply low emissivity paints.

Specific modifications for each building are based on the decision matrix and community feedback. For instance, buildings identified as visually unattractive are prioritized for significant material changes, while others receive minor adjustments to preserve their aesthetic value. The design solutions also include replacing old glazing with well-insulated glass and incorporating shading devices on facades with high glass percentages. These comprehensive design strategies aim to create a more thermally comfortable and visually appealing urban environment, reflecting the needs and preferences of the Acquabella district's residents.

## 9.2 Discussion & Limitations

### 9.2.1 Application

The workflow provides a comprehensive guideline for researchers, policymakers, and urban planners to assess the influence of facades on outdoor thermal comfort and thermal perception. It emphasizes the importance of integrating user-oriented participatory approaches with simulations to identify potential confounding variables affecting thermal perception. By incorporating user data, the workflow helps pinpoint focus areas, saving computational time and gaining insights into the effects of various environmental parameters and conditions on thermal comfort.

The initial step involves gathering community insights, which ensures the study reflects local priorities and provides a solid foundation for further analysis. Expanding the sample size and capturing demographic variations in the next phase offers a broader understanding of the district's environmental quality, validating and complementing initial findings. This step also identifies the needs of vulnerable groups, ensuring that interventions are inclusive and equitable.

Objective analysis through simulations follows, providing quantitative evidence of how different design interventions can improve thermal comfort. This phase defines the parameters affecting thermal perception, allowing for data-driven decision-making. The subsequent real-time validation through field measurements and user experiences confirms the effectiveness of the proposed solutions, ensuring they are grounded in actual conditions and user feedback.

Finally, synthesizing all collected data guides the development of targeted interventions. This integration of objective data and subjective experiences ensures a comprehensive, user-centered design approach that addresses both thermal comfort and aesthetic quality.

Each stage of the workflow builds upon the previous one, ensuring continuous validation and integration of community feedback. The use of accessible tools and datasets enhances the replicability and applicability of the methods, making this approach valuable for other urban areas seeking to improve thermal comfort. By keeping the community engaged throughout the process, the workflow not only gathers valuable data but also fosters a sense of resilience among residents.

### 9.2.2 Future research

Future research should focus on several key areas to build upon the findings of this study. Expanding the temporal scope of simulations to include less extreme weather conditions could provide a more nuanced understanding of thermal comfort throughout the year. Additionally, further investigations should explore the long-term impacts of proposed interventions, particularly their effectiveness in different seasons and varying climatic conditions. Integrating more advanced simulation tools and real-time data analytics could enhance the precision of thermal comfort assessments, leading to more targeted and efficient design solutions

Research should also delve into the psychological aspects of thermal perception, examining how cognitive factors and previous experiences influence individuals' thermal comfort. This holistic approach would ensure that the proposed interventions address not only the physical but also the psychological dimensions of thermal comfort, leading to more sustainable and user-centered urban environments.

Moreover, future studies should consider the impact of other environmental domains—such as aesthetics, acoustics, and air quality—on thermal comfort. Investigating the factors that affect the aesthetics of a façade and their connection to thermal perception would provide a deeper understanding of how visual appeal and thermal experience interact. Additionally, the role of traffic and air pollutants in influencing thermal comfort should be examined, as these factors contribute to the overall environmental quality and well-being of urban residents.

### 9.2.3 Limitations

The limitations of this study highlight areas for improvement and refinement in future applications. One significant limitation is the accuracy of data collection regarding neighborhood configuration. While the datasets used were relatively accurate, incorporating on-site observations and monitoring campaigns during the initial stages of the workflow would enhance the model's setup. Using sensors and direct measurements could lead to more validated results, ensuring a higher level of precision in the environmental simulations.

Another challenge faced during the study was the collection of user data and engaging with the public. Coordinating with participants, especially over great distances between the researcher and the users, proved difficult. Ensuring timely and accurate data collection required flexible scheduling and considerable effort from the researcher. These logistical challenges underscore the complexity of working with human subjects in environmental research, particularly when remote engagement is necessary.

The timing and conditions under which each step was conducted could lead to varying or even contradictory results. For instance, the workshop and survey were conducted during different times and under different environmental conditions, which might affect the consistency of the findings. Additionally, the limited sample size of the thermal walk and the focus on a specific time period constrain the generalizability of the results.

The reliance on simulated data also presents limitations, as simulations cannot fully capture the complexity of real-world conditions. While the ENVI-met model provides valuable insights, its predictions may not always align with actual experiences, highlighting the need for ongoing validation and adjustment of simulation parameters.

Despite these limitations, the multi-step workflow offers a comprehensive approach to understanding and enhancing outdoor thermal comfort. Future research should aim to address these limitations by incorporating more diverse and extensive data sources, ensuring that the findings are robust and applicable across different contexts and conditions.

# 11 APPENDIX

## Thermal walk survey no.1:

Please indicate your age range:

- ≤20
- 20< years old ≤40
- 40< years old ≤ 60
- 60<

Please indicate your gender:

- Female
- Male
- Non binary
- Prefer not to answer
- ________ Not listed

Please indicate your weight (in kg) :

- < 50 kg
- 51 - 60 kg
- 61 - 70 kg
- 71 - 80 kg
- 81 -90 kg
- 90 kg <

Please indicate your height ( in cm) :

- < 150 cm
- 151 - 160 cm
- 161 - 170 cm
- 171 - 180 cm
- 181 - 190 cm
- 190 cm <

**Clothing**

Please indicate the clothing combination you are wearing right now:

| | Shirt or Tshirt | | | Jacket | | | Trousers | | | | Head | | | Other |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Short sleeves | Long Sleeves | Sleeveless | Sweater | Jacket | Coat | Shorts | Pants | Skirt | Sweatpants | Hat | Scarf | Parasol | |
| Clothing | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | |

What's your major activity for the past 20 minutes?

- Seating
- Standing relaxed
- Walking (slowly)
- Walking fast
- ________ Other

Powered by Qualtrics

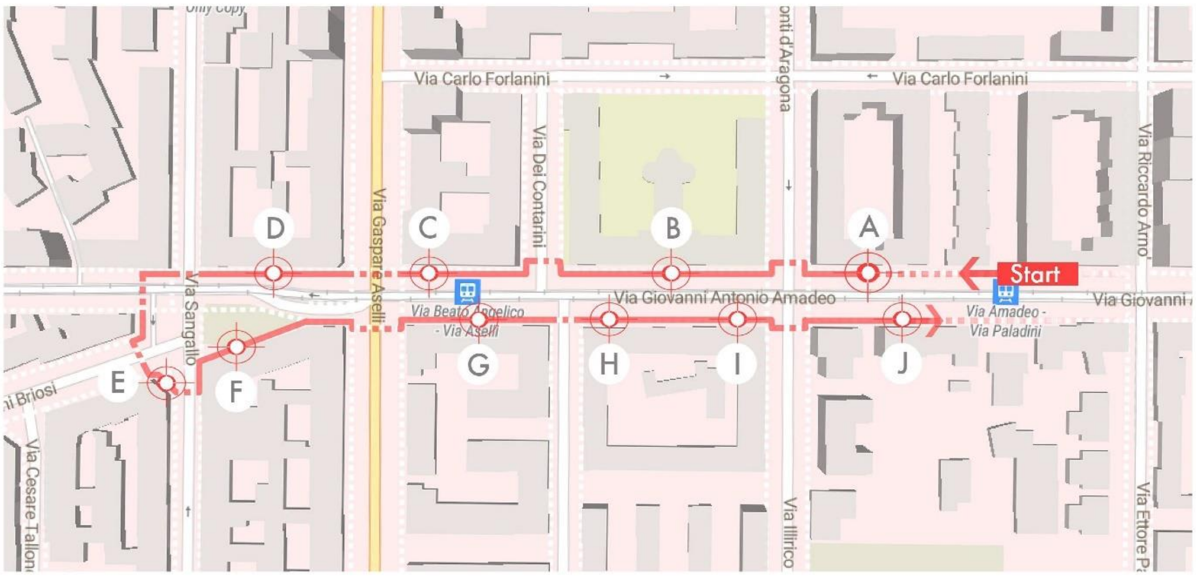
Thermal walk survey no.2:

English

**Thermal Perception Spot no1**

Please indicate your ID.

Click to write the question text




Please indicate your current location according to the map above:

- ○ A
- ○ B
- ○ C
- ○ D
- ○ E
- ○ F
- ○ G
- ○ H
- ○ I
- ○ J

The questionnaire is accomplished:

- ○ Under the shade
- ○ Exposed to sun
- ○ Cloudy weather

What is your overall level of satisfaction with the thermal environment?

| | Very dissatisfied | Dissatisfied | Slightly dissatisfied | Neutral | Slightly satisfied | Satisfied | Very satisfied |
|---|---|---|---|---|---|---|---|
| Thermal Comfort | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

How do you perceive the wind in this moment?

- ○ I don't feel any wind
- ○ I feel wind and makes me feel cold
- ○ I feel wind and makes me feel warm

What thermal sensation do you associate to the material on the building?

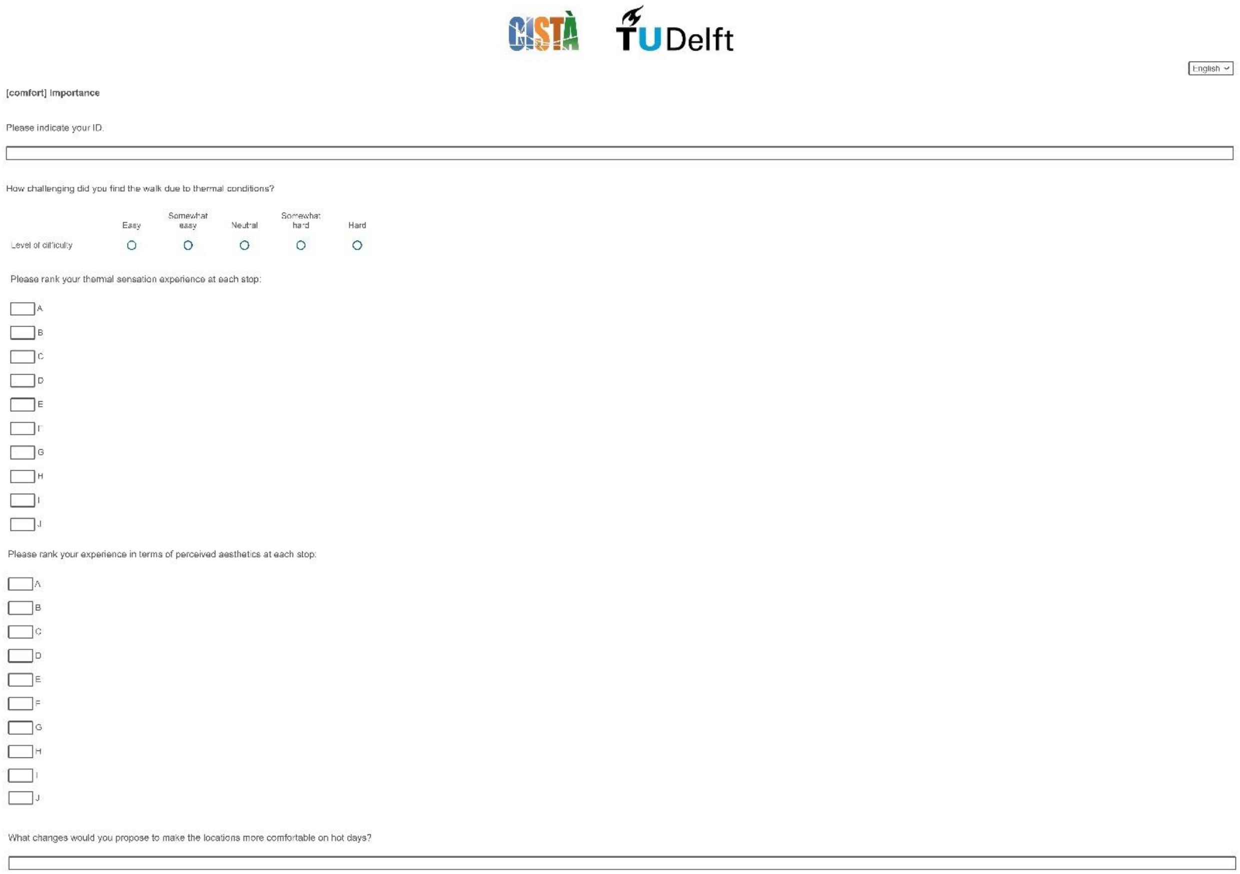
| | Cold | Cool | Slightly cool | Neutral | Slightly warm | Warm | Hot |
|---|---|---|---|---|---|---|---|
| Thermal sensation | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

How do you evaluate the perceived aesthetics of the nearest building?

| | Very dissatisfied | Dissatisfied | Somewhat dissatisfiedd | Neutral | Somewhat satisfied | Satisfied | Very satisfied |
|---|---|---|---|---|---|---|---|
| Visual satisfaction | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

Please upload a photo of the nearest building surface.

Thermal walk survey no.3:



English

[comfort] Importance

Please indicate your ID.

How challenging did you find the walk due to thermal conditions?

| | Easy | Somewhat easy | Neutral | Somewhat hard | Hard |
|---|---|---|---|---|---|
| Level of difficulty | ○ | ○ | ○ | ○ | ○ |

Please rank your thermal sensation experience at each stop:

A
B
C
D
E
F
G
H
I
J

Please rank your experience in terms of perceived aesthetics at each stop:

A
B
C
D
E
F
G
H
I
J

What changes would you propose to make the locations more comfortable on hot days?

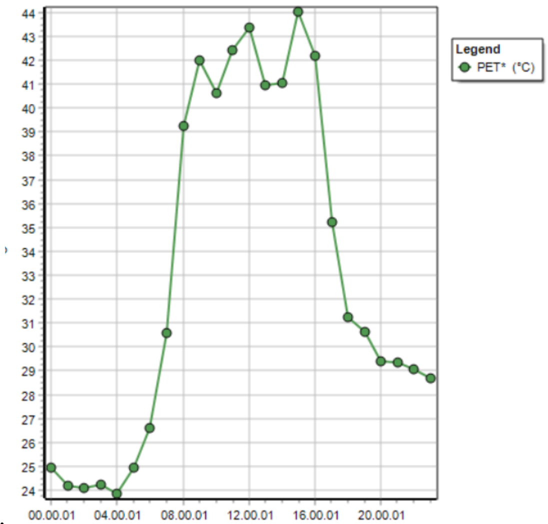
Clothing insulation of user profiles according to ASHRAE 55-2013:

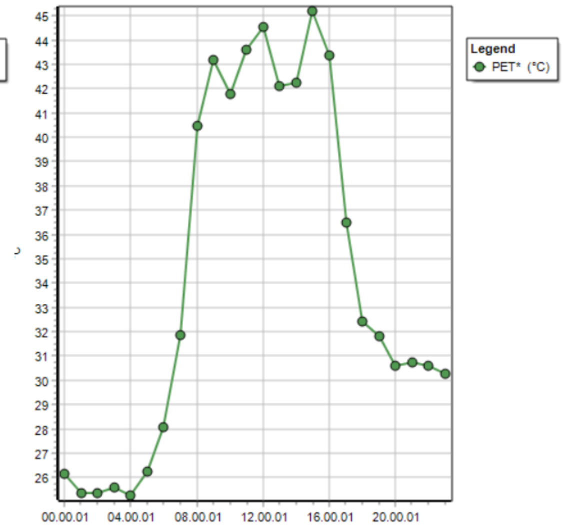
| | |
|---|---|
| Woman | User 3 |
| Bra | 0.01 |
| T-shirt | 0.08 |
| Panties | 0.03 |
| Straight trousers (thin) | 0.15 |
| Ancle length shocks | 0.02 |
| Shoes | 0.02 |
| **Total** | **0.31** |
| Man | User 6 |
| Men's briefs | 0.04 |
| Shirt | 0.12 |
| Straight trousers (thin) | 0.15 |
| Ancle length shocks | 0.02 |
| Shoes | 0.02 |
| **Total** | **0.35** |
| Woman | User 1 |
| Sleeveless blouse | 0.12 |
| Panties | 0.03 |
| Skirt thin | 0.14 |
| Shoes | 0.02 |

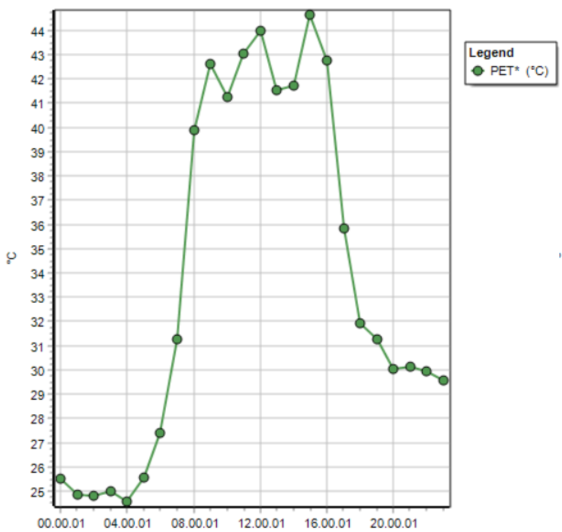
| | |
|---|---|
| **Total** | **0.31** |
| Man | User 2 |
| Men's briefs | 0.04 |
| Short sleeve knit sport shirt | 0.17 |
| Shorts | 0.06 |
| Ancle length shocks | 0.02 |
| Sandals | 0.02 |
| **Total** | **0.31** |
| Girl | User 5 |
| Panties | 0.03 |
| Dress Short-sleeve | 0.19 |
| Ancle length shocks | 0.02 |
| Shoes | 0.02 |
| Hat | 0.01 |
| **Total** | **0.29** |

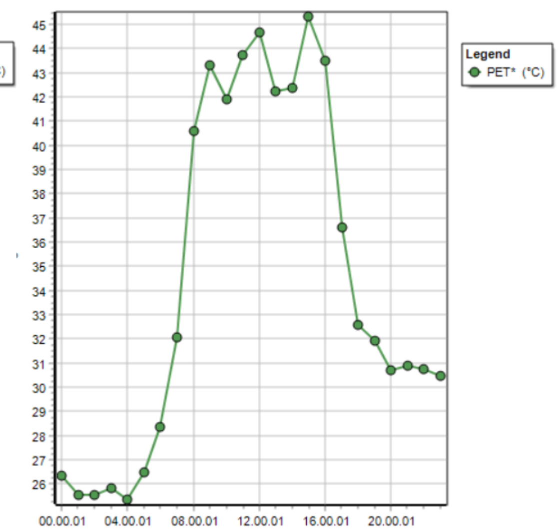
Original simulation results 1) PET of user profiles during the day in front of receptors in building A1, 2) PET simulations for every user profile - User 1 at 4.00AM an 3.00PM:

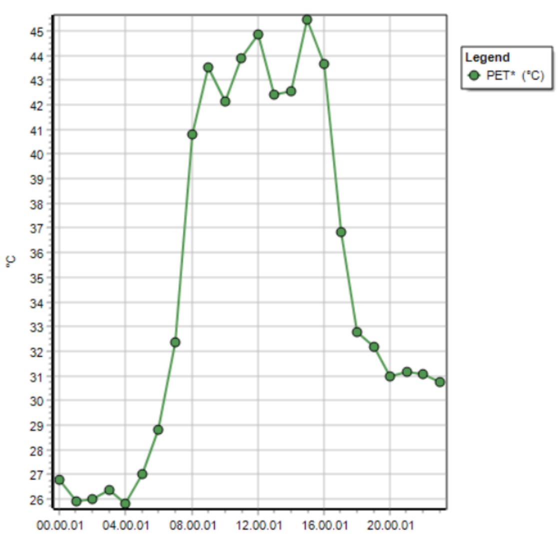
1.

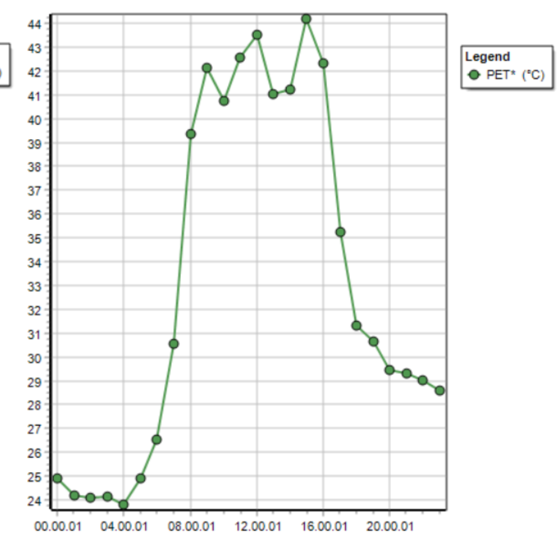

Legend
PET* (°C)
00.00.01
04.00.01
08.00.01
12.00.01
16.00.01
20.00.01


Legend
PET* (°C)
00.00.01
04.00.01
08.00.01
12.00.01
16.00.01
20.00.01


°C
Legend
PET* (°C)
00.00.01
04.00.01
08.00.01
12.00.01
16.00.01
20.00.01


Legend
PET* (°C)
00.00.01
04.00.01
08.00.01
12.00.01
16.00.01
20.00.01


°C
Legend
PET* (°C)
00.00.01
04.00.01
08.00.01
12.00.01
16.00.01
20.00.01


Legend
PET* (°C)
00.00.01
04.00.01
08.00.01
12.00.01
16.00.01
20.00.01

2.

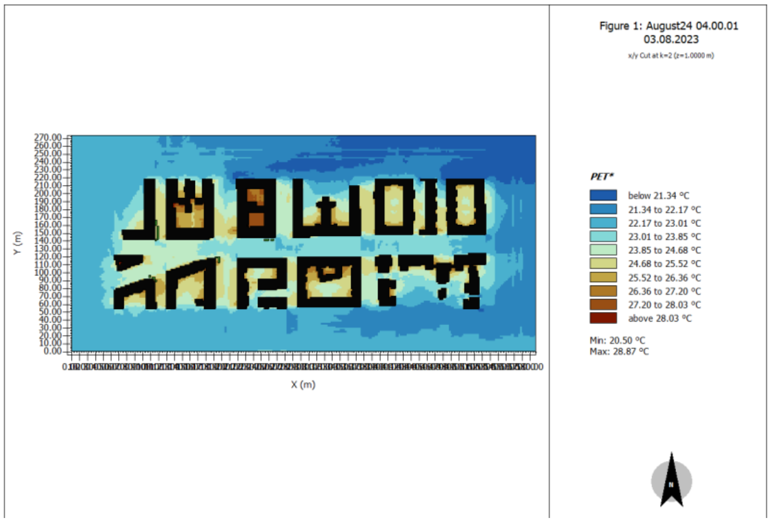


Figure 1: August24 04.00.01
03.08.2023
x/y Cut at k=2 (z=1.0000 m)
PET*
below 21.34 °C
21.34 to 22.17 °C
22.17 to 23.01 °C
23.01 to 23.85 °C
23.85 to 24.68 °C
24.68 to 25.52 °C
25.52 to 26.36 °C
26.36 to 27.20 °C
27.20 to 28.03 °C
above 28.03 °C
Min: 20.50 °C
Max: 28.87 °C
Y (m)
X (m)

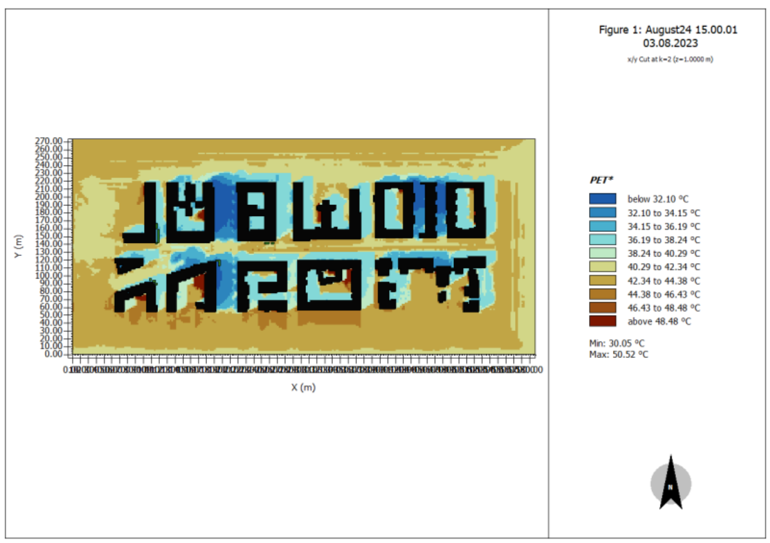


Figure 1: August24 15.00.01
03.08.2023
x/y Cut at k=2 (z=1.0000 m)
PET*
below 32.10 °C
32.10 to 34.15 °C
34.15 to 36.19 °C
36.19 to 38.24 °C
38.24 to 40.29 °C
40.29 to 42.34 °C
42.34 to 44.38 °C
44.38 to 46.43 °C
46.43 to 48.48 °C
above 48.48 °C
Min: 30.05 °C
Max: 50.52 °C
Y (m)
X (m)
ENVI-met
<Right foot>

Workshop exports including a) the maps for environmental quality , 2) the votes from the Mentimeter for improving the attractiveness of the neighborhood and perception associated with façade 3) the maps of frequency and importance:

1.

2.


LUXOTTICA
Mentimeter
Quale sensazione termica associ a questo materiale della facciata?
0
10
1
4
1
Molto freddo
Freddo
Neutro
Caldo
Molto caldo
16

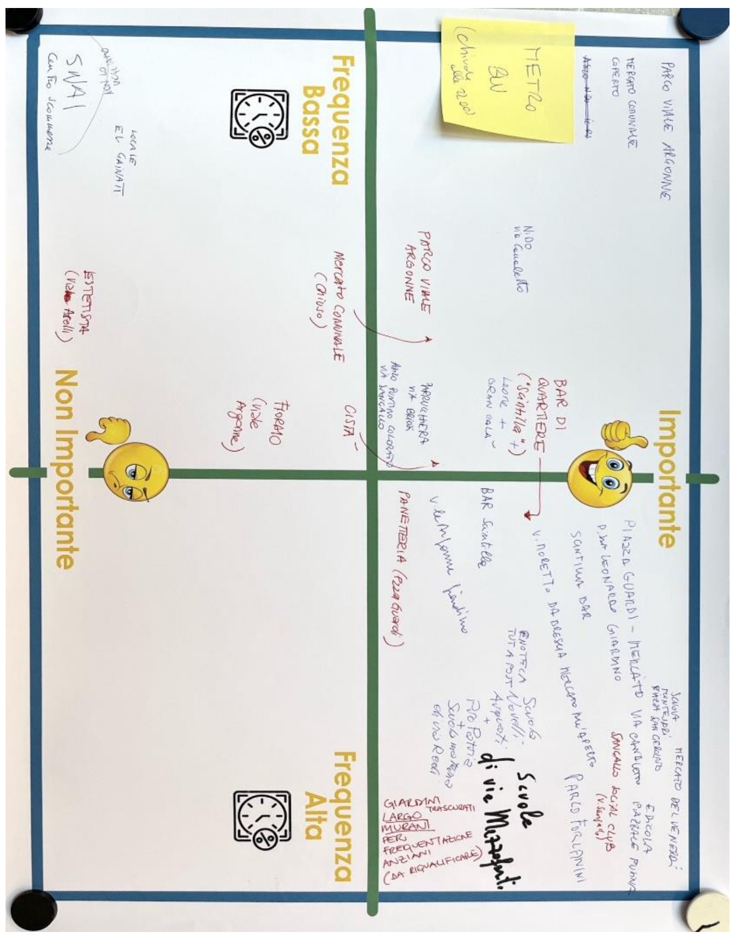

Mentimeter
Quale sensazione termica associ a questo materiale della facciata?
0
1
6
8
1
Molto freddo
Freddo
Neutro
Caldo
Molto caldo
16


Mentimeter
Quale sensazione termica associ a questo materiale della facciata?
0
3
3
10
0
Molto freddo
Freddo
Neutro
Caldo
Molto caldo
16


Mentimeter
Quale sensazione termica associ a questo materiale della facciata?
0
10
5
1
0
Molto freddo
Freddo
Neutro
Caldo
Molto caldo
16

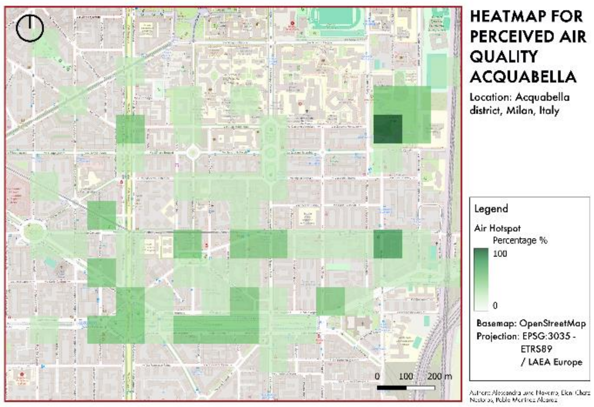
Cosa rende esteticamente piacevole o bella una facciata nel tuo quartiere?
49 responses

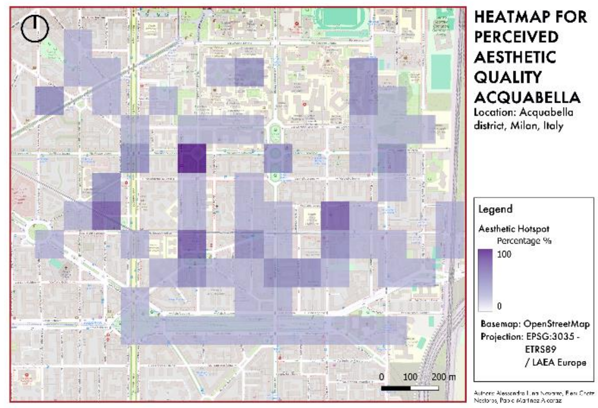

1.

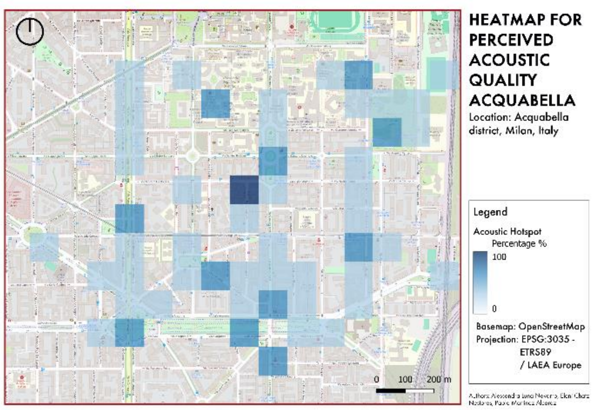


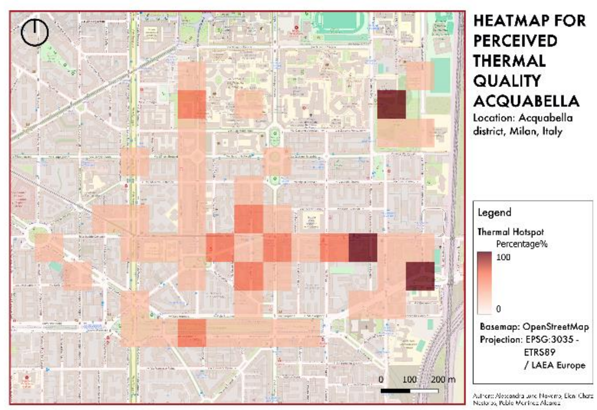
QGIS 1)density maps for all the domains (workshop results) and 2)mapping materiality , storeys of buildings and U-value around the neighborhood:

1.

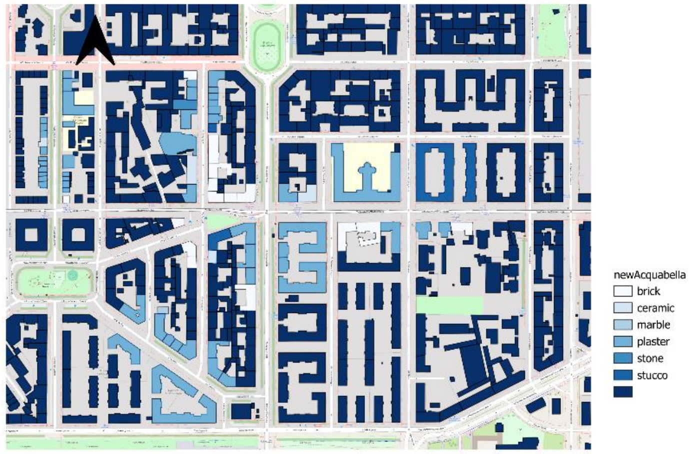


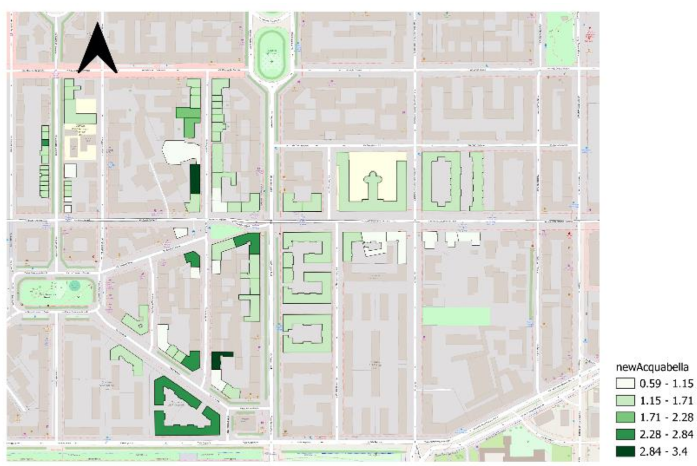



2.


newAcquabella
brick
ceramic
marble
plaster
stone
stucco


newAcquabella
1
2
3
4
5
6
7
8
9


newAcquabella
0.59 - 1.15
1.15 - 1.71
1.71 - 2.28
2.28 - 2.84
2.84 - 3.4

New material dataset for Design proposal:

| Material | Color | Thermal properties | | Optical properties | | | | Physical properties |
|---|---|---|---|---|---|---|---|---|
| | | Thermal Conductivity W/(m·°C) | Specific Heat Capacity J/(kg·°C) | Absorption | Albedo | Emissivity | LRF (%) | Density (kg/m^3) |
| Stucco | Bright | 0.8 | 850 | 0.60 | 0.6 | 0.90 | 75 | 2275 |
| | Grey | 0.8 | 850 | 0.65 | 0.3 | 0.90 | 35 | 2275 |
| plaster | Bright | 0.6 | 1000 | 0.6 | 0.5 | 0.86 | 45 | 1500 |
| | Dark | 0.6 | 1000 | 0.5 | 0.25 | 0.86 | 25 | 1500 |
| marble | Bright | 2.9 | 880 | 0.55 | 0.50 | 0.9 | 60 | 2600 |
| | Grey | 2.9 | 880 | 0.6 | 0.4 | 0.9 | 60 | 2600 |
| Concrete heavyweight | Bright | 0.72 | 890 | 0.56 | 0.54 | 0.8 | 25 | 2000 |
| | Grey | 0.72 | 890 | 0.7 | 0.3 | 0.8 | 20 | 2000 |
| brick | Red | 1.3 | 800 | 0.7 | 0.3 | 0.75 | 10 | 1700 |
| | Bright | 1.3 | 800 | 0.6 | 0.4 | 0.75 | 15 | 1700 |
| ceramic | Bright | 0.8 | 840 | 0.55 | 0.45 | 0.85 | 40 | 1700 |
| granite | Dark | 4,61 | 790 | 0.55 | 0.47 | 0.96 | 25 | 1700 |
| limestone | Bright | 1.5 | 900 | 0.35 | 0.4 | 0.96 | 0.55 | 2550 |
| | Dark | 1.5 | 900 | 0.5 | 0.25 | 0.96 | 0.35 | 2550 |

# 12 Index of figures

## 13 Index of Tables

# 14 Reference Table


*ABACO DELLE STRUTTURE COSTITUENTI L'INVOLUCRO OPACO*. (n.d.).

Abrahem, S. A., Hassan, S. A., & Khamees, W. A. (2020). Impact of Facade Material of Mass Housing on Outdoor Thermal Comfort in Hot-arid Climate. *IOP Conference Series: Materials Science and Engineering*, *881*(1). https://doi.org/10.1088/1757-899X/881/1/012006

Ali-Toudert, F., & Mayer, H. (2006). Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. *Building and Environment*, *41*(2), 94–108. https://doi.org/10.1016/j.buildenv.2005.01.013

*ANSI/ASHRAE Addendum h to ANSI/ASHRAE Standard 55-2012*. (2013). www.ashrae.org

*ATLAS OF URBAN EXPANSION*. (n.d.).

Azarnejad, A., & Mahdavi, A. (2018). Implications of façades' visual reflectance for buildings' thermal performance. *Journal of Building Physics*, *42*(2), 125 – 141. https://doi.org/10.1177/1744259117731287

Barnstorf, P. A., Alves, F. B., & Vale, C. P. Do. (2023). Reflexions on an ENVI-met operation-methodology case study. *U.Porto Journal of Engineering*, *9*(2), 16–99. https://doi.org/10.24840/2183-6493_009-002_001949

Blanco Cadena, J. D., Salvalai, G., Bernardini, G., & Quagliarini, E. (2023). Determining behavioural-based risk to SLODs of urban public open spaces: Key performance indicators definition and application on established built environment typological scenarios. *Sustainable Cities and Society*, *95*, 104580. https://doi.org/10.1016/j.scs.2023.104580

Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., & Tinz, B. (2012). Comparison of UTCI to selected thermal indices. *International Journal of Biometeorology*, *56*(3), 515–535. https://doi.org/10.1007/s00484-011-0453-2

Bracale, R., Milani, L., Ferrara, E., Balzaretti, C., Valerio, A., Russo, V., Nisoli, E., & Carruba, M. O. (2013). Childhood obesity, overweight and underweight: A study in primary schools in Milan. *Eating and Weight Disorders*, *18*(2), 183–191. https://doi.org/10.1007/s40519-013-0036-9

Castaldo, V. L., Pisello, A. L., Pigliautile, I., Piselli, C., & Cotana, F. (2017). Microclimate and air quality investigation in historic hilly urban areas: Experimental and numerical investigation in central Italy. *Sustainable Cities and Society*, *33*, 27–44. https://doi.org/10.1016/j.scs.2017.05.017

Chatzipoulka, C., Compagnon, R., & Nikolopoulou, M. (2016). Urban geometry and solar availability on façades and ground of real urban forms: using London as a case study. *Solar Energy*, *138*, 53 – 66. https://doi.org/10.1016/j.solener.2016.09.005

Coccolo, S., Kämpf, J., Scartezzini, J. L., & Pearlmutter, D. (2016). Outdoor human comfort and thermal stress: A comprehensive review on models and standards. In *Urban Climate* (Vol. 18, pp. 33–57). Elsevier B.V. https://doi.org/10.1016/j.uclim.2016.08.004

Comune di Milano. (2014). *RE Building Regulations*.

Corrado, V., Ballarini, I., & Corgnati, S. P. (2014). *Building Typology Brochure-Italy Fascicolo sulla Tipologia Edilizia Italiana nuova edizione*.

Dietrich, U. (2018). Urban street canyons - Impact of different materials and colours of facades and ground and different positions of persons on outdoor thermal comfort. *International Journal of Sustainable Development and Planning*, *13*(4), 582 – 593. https://doi.org/10.2495/SDP-V13-N4-582-593

Dogan, T., Kastner, P., & Mermelstein, R. (2021). Surfer: A fast simulation algorithm to predict surface temperatures and mean radiant temperatures in large urban models. *Building and Environment*, *196*. https://doi.org/10.1016/j.buildenv.2021.107762

Eliasson, I., Knez, I., Westerberg, U., Thorsson, S., & Lindberg, F. (2007). Climate and behaviour in a Nordic city. *Landscape and Urban Planning*, *82*(1–2), 72–84. https://doi.org/10.1016/j.landurbplan.2007.01.020

Eslamirad, N., Sepúlveda, A., De Luca, F., & Sakari Lylykangas, K. (2022). Evaluating Outdoor Thermal Comfort Using a Mixed-Method to Improve the Environmental Quality of a University Campus. *Energies*, *15*(4). https://doi.org/10.3390/en15041577

Fahed, J., Kinab, E., Ginestet, S., & Adolphe, L. (2020). Impact of urban heat island mitigation measures on microclimate and pedestrian comfort in a dense urban district of Lebanon. *Sustainable Cities and Society*, *61*. https://doi.org/10.1016/j.scs.2020.102375

Fiala, D., Lomas, K. J., & Stohrer, M. (2001). Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions. *International Journal of Biometeorology*, *45*(3), 143–159. https://doi.org/10.1007/s004840100099

Golasi, I., Salata, F., de Lieto Vollaro, E., Coppi, M., & de Lieto Vollaro, A. (2016). Thermal perception in the mediterranean area: Comparing the mediterranean outdoor comfort index (moci) to other outdoor thermal comfort indices. *Energies*, *9*(7). https://doi.org/10.3390/en9070550

Haeri, T., Hassan, N., & Ghaffarianhoseini, A. (2023). Evaluation of microclimate mitigation strategies in a heterogenous street canyon in Kuala Lumpur from outdoor thermal comfort perspective using Envi-met. *Urban Climate*, *52*. https://doi.org/10.1016/j.uclim.2023.101719

Huang, B., Hong, B., Tian, Y., Yuan, T., & Su, M. (2021). Outdoor thermal benchmarks and thermal safety for children: A study in China's cold region. *Science of The Total Environment*, *787*, 147603. https://doi.org/10.1016/j.scitotenv.2021.147603

Jamei, E., Rajagopalan, P., Seyedmahmoudian, M., & Jamei, Y. (2016). Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort. In *Renewable and Sustainable Energy Reviews* (Vol. 54, pp. 1002–1017). Elsevier Ltd. https://doi.org/10.1016/j.rser.2015.10.104

Johansson, E. (2006). Influence of urban geometry on outdoor thermal comfort in a hot dry climate: A study in Fez, Morocco. *Building and Environment*, *41*(10), 1326–1338. https://doi.org/10.1016/j.buildenv.2005.05.022

Johansson, E., Spangenberg, J., Gouvêa, M. L., & Freitas, E. D. (2013). Scale-integrated atmospheric simulations to assess thermal comfort in different urban tissues in the warm humid summer of São Paulo, Brazil. *Urban Climate*, *6*, 24–43. https://doi.org/10.1016/j.uclim.2013.08.003

Khraiwesh, M. M., & Genovese, P. V. (2023). Outdoor Thermal Comfort Integrated with Energy Consumption for Urban Block Design Optimization: A Study of the Hot-Summer Mediterranean City of Irbid, Jordan. *Sustainability (Switzerland)*, *15*(10). https://doi.org/10.3390/su15108412

Klemm, W., Heusinkveld, B. G., Lenzholzer, S., & van Hove, B. (2015). Street greenery and its physical and psychological impact on thermal comfort. *Landscape and Urban Planning*, *138*, 87–98. https://doi.org/10.1016/j.landurbplan.2015.02.009

Kousis, I., Pigliautile, I., & Pisello, A. L. (2021). Intra-urban microclimate investigation in urban heat island through a novel mobile monitoring system. *Scientific Reports*, *11*(1). https://doi.org/10.1038/s41598-021-88344-y

Kumar, P., & Sharma, A. (2020). Study on importance, procedure, and scope of outdoor thermal comfort –A review. In *Sustainable Cities and Society* (Vol. 61). Elsevier Ltd. https://doi.org/10.1016/j.scs.2020.102297

Lama Idrees. (2021). *LIVING WALL SYSTEM As a strategy to mitigate the Urban Heat Island effect in Damascus Faculty of Architecture and the Built Environment*.

Lassandro, P., & Di Turi, S. (2019). Multi-criteria and multiscale assessment of building envelope response-ability to rising heat waves. *Sustainable Cities and Society*, *51*. https://doi.org/10.1016/j.scs.2019.101755

Lau, K. K. L., & Choi, C. Y. (2021a). The influence of perceived aesthetic and acoustic quality on outdoor thermal comfort in urban environment. *Building and Environment*, *206*. https://doi.org/10.1016/j.buildenv.2021.108333

Lau, K. K. L., & Choi, C. Y. (2021b). The influence of perceived environmental quality on thermal comfort in an outdoor urban environment during hot summer. *Journal of Physics: Conference Series*, *2042*(1). https://doi.org/10.1088/1742-6596/2042/1/012047

Liu, Z., Cheng, W., Jim, C. Y., Morakinyo, T. E., Shi, Y., & Ng, E. (2021). Heat mitigation benefits of urban green and blue infrastructures: A systematic review of modeling techniques, validation and scenario simulation in ENVI-met V4. In *Building and Environment* (Vol. 200). Elsevier Ltd. https://doi.org/10.1016/j.buildenv.2021.107939

*Milan, Italy - The study of city pattern _ PPT*. (n.d.).

Milano Leonardo, C., Juan Diego Blanco Cadena Thesis Authors, I., & Vittoria Borghesi Alessia Cannone, M. (n.d.). *AIMING FOR OUTDOOR THERMAL COMFORT WHILE MITIGATING THE RISK OF INCREASING TEMPERATURES SLOD THROUGH BUILT ENVIRONMENT RESILIENCE. A case study in Milan*.

N. de Waard. (2021). *Development of a parametric PET assessment model for the early design stage and evaluation of building-related heat mitigation measures for extreme heat events in the Netherlands*.

Nikolopoulou, M., & Lykoudis, S. (2006). Thermal comfort in outdoor urban spaces: Analysis across different European countries. *Building and Environment*, *41*(11), 1455–1470. https://doi.org/10.1016/j.buildenv.2005.05.031

OERCO2. (n.d.). *.2.1. STUDY OF MOST USED MATERIALS IN ITALIAN CONSTRUCTION SECTOR OERCO2 ONLINE EDUCATIONAL RESOURCE FOR INNOVATIVE STUDY OF CONSTRUCTION MATERIALS LIFE CYCLE*.

Ouis, A., Benhassine, N., & Canan, F. (2023). Outdoor thermal perception in the semi-arid climate of Constantine, Algeria: A field survey during the post-COVID-19. *Building and Environment*, *245*. https://doi.org/10.1016/j.buildenv.2023.110920

Palusci, O., Laurino, V., Barbieri, V., & Buccolieri, R. (2023). Identifying and monitoring the Urban Heat Island in the compact Mediterranean city using satellite imagery and in-situ measurement data. *Journal of Physics: Conference Series*, *2600*(9). https://doi.org/10.1088/1742-6596/2600/9/092006

Perini, K., & Magliocco, A. (2014). Effects of vegetation, urban density, building height, and atmospheric conditions on local temperatures and thermal comfort. *Urban Forestry and Urban Greening*, *13*(3), 495–506. https://doi.org/10.1016/j.ufug.2014.03.003

Pierre-Alain, C. (n.d.). *Politecnico di Milano 2037: A Space Odyssey-Dynamic Intervention in Città Studi*.

Pigliautile, I., D'Eramo, S., & Pisello, A. L. (2021). Intra-urban microclimate mapping for citizens' wellbeing: Novel wearable sensing techniques and automatized data-processing. *Journal of Cleaner Production*, *279*. https://doi.org/10.1016/j.jclepro.2020.123748

Piselli, C., Castaldo, V. L., Pigliautile, I., Pisello, A. L., & Cotana, F. (2018). Outdoor comfort conditions in urban areas: On citizens' perspective about microclimate mitigation of urban transit areas. *Sustainable Cities and Society*, *39*, 16–36. https://doi.org/10.1016/j.scs.2018.02.004

Prieto, A., & Oldenhave, M. (2021). What makes a façade beautiful? *Journal of Facade Design and Engineering*, *9*(2), 21–45. https://doi.org/10.7480/jfde.2021.2.5540

*Regolamento edilizio previgentetrans.it.en*. (n.d.).

Rosso, F., Golasi, I., Castaldo, V. L., Piselli, C., Pisello, A. L., Salata, F., Ferrero, M., Cotana, F., & de Lieto Vollaro, A. (2018). On the impact of innovative materials on outdoor thermal comfort of pedestrians in historical urban canyons. *Renewable Energy*, *118*, 825–839. https://doi.org/10.1016/j.renene.2017.11.074

Rosso, F., Pioppi, B., & Pisello, A. L. (2022). Pocket parks for human-centered urban climate change resilience: Microclimate field tests and multi-domain comfort analysis through portable sensing techniques and citizens' science. *Energy and Buildings*, *260*. https://doi.org/10.1016/j.enbuild.2022.111918

Salata, F., Golasi, I., Vollaro, E. de L., Bisegna, F., Nardecchia, F., Coppi, M., Gugliermetti, F., & Vollaro, A. de L. (2015). Evaluation of different urban microclimate mitigation strategies through a PMV analysis. *Sustainability (Switzerland)*, *7*(7), 9012 – 9030. https://doi.org/10.3390/su7079012

Salvati, A., Kolokotroni, M., Kotopouleas, A., Watkins, R., Giridharan, R., & Nikolopoulou, M. (2022). Impact of reflective materials on urban canyon albedo, outdoor and indoor microclimates. *Building and Environment*, *207*. https://doi.org/10.1016/j.buildenv.2021.108459

Shaffer, J. P. (1995). Multiple hypothesis testing. *Annual Review of Psychology*, *46*(1), 561–584. https://doi.org/10.1146/annurev.ps.46.020195.003021

*SPAZIO PUBBLICO SPAZIO PUBBLICO linee guida di progettazione*. (n.d.).

Stazi, F., Tomassoni, E., & Di Perna, C. (2017). Super-insulated wooden envelopes in Mediterranean climate: Summer overheating, thermal comfort optimization, environmental impact on an Italian case study. *Energy and Buildings*, *138*, 716–732. https://doi.org/10.1016/j.enbuild.2016.12.042

Tabatabaei, S. S., & Fayaz, R. (2023). The effect of facade materials and coatings on urban heat island mitigation and outdoor thermal comfort in hot semi-arid climate. *Building and Environment*, *243*. https://doi.org/10.1016/j.buildenv.2023.110701

Taleghani, M., Tenpierik, M., van den Dobbelsteen, A., & Sailor, D. J. (2014). Heat in courtyards: A validated and calibrated parametric study of heat mitigation strategies for urban courtyards in the Netherlands. *Solar Energy*, *103*, 108 – 124. https://doi.org/10.1016/j.solener.2014.01.033

*Town Planning Scheme Regulatory plan*. (n.d.).

*URBAN HISTORY FROM MEDIOLANUM TO MILAN – EVOLUTION OF MILAN'S URBAN PLANNING AND MORPHOLOGY - Issuu*. (n.d.).

Wang, Y., Bakker, F., de Groot, R., Wörtche, H., & Leemans, R. (2015). Effects of urban green infrastructure (UGI) on local outdoor microclimate during the growing season. *Environmental Monitoring and Assessment*, *187*(12), 1 – 14. https://doi.org/10.1007/s10661-015-4943-2

Wu, H., Sun, X., & Wu, Y. (2020). Investigation of the relationships between thermal, acoustic, illuminous environments and human perceptions. *Journal of Building Engineering*, *32*. https://doi.org/10.1016/j.jobe.2020.101839

Yang, F., Qian, F., & Lau, S. S. Y. (2013). Urban form and density as indicators for summertime outdoor ventilation potential: A case study on high-rise housing in Shanghai. *Building and Environment*, *70*, 122–137. https://doi.org/10.1016/j.buildenv.2013.08.019

*Atlas of Urban Expansion - Milan*. (n.d.). http://atlasofurbanexpansion.org/cities/view/Milan

*Milano Lombardia - Walk score*. (n.d.). Walk Score. https://www.walkscore.com/score/acquabella-milan

*Search - Geoportale della Lombardia*. (n.d.). Geoportale Della Lombardia. https://www.geoportale.regione.lombardia.it/en-GB/ricerca?p_p_id=gptadvancedsearch_WAR_gptmetadataportlet&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&_gptadvancedsearch_WAR_gptmetadataportlet_selectedSpatialRel=grid

Elnahas, M. M. (2003). The effects of urban configuration on urban air temperatures. *Architectural Science Review*, *46*(2), 135–138. https://doi.org/10.1080/00038628.2003.9696975

*Spearman's Rank Order Correlation using SPSS Statistics - A How-To Statistical Guide by Laerd Statistics*. (n.d.). https://statistics.laerd.com/spss-tutorials/spearmans-rank-order-correlation-using-spss-statistics.php

ENVI-met. (2024, May 13). *ENVI-met high-resolution 3D modeling for Climate Adaption*. https://www.envi-met.com/

*history+ ¦ Weather History & Archive*. (n.d.). Meteoblue. https://www.meteoblue.com/en/historyplus

dilium.com. (n.d.). *Dilium ¦ ARPA Meteo Lombardia - Find out weather forecasts*. https://www.dilium.com/projects/ARPA-meteo-lombardia

*CAMS radiation service - SoDa*. (n.d.). SoDa. https://www.soda-pro.com/web-services/radiation/cams-radiation-service

*Home ¦ ashrae.org*. (n.d.). Web Starter Kit. https://www.ashrae.org/

Matzarakis, A., Rutz, F., & Mayer, H. (2006). Modelling radiation fluxes in simple and complex environments—application of the RayMan model. *International Journal of Biometeorology*, *51*(4), 323–334. https://doi.org/10.1007/s00484-006-0061-8

Matzarakis, A., Rutz, F., & Mayer, H. (2009). Modelling radiation fluxes in simple and complex environments: basics of the RayMan model. *International Journal of Biometeorology*, *54*(2), 131–139. https://doi.org/10.1007/s00484-009-0261-0

*Thermohygrometer TC100*. (n.d.). TROTEC. https://en.trotec.com/shop/thermohygrometer-tc100.html