A Multi-disciplinary Approach to Assessing the Influence of Facade on Outdoor Thermal Comfort: A Case Study of Milan

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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 study investigates the relationship between microclimatic conditions, thermal sensation, and human preferences to identify the key factors influencing outdoor thermal comfort. Using the Acquabella district in Milan as a case study, the research adopts a cross-examination approach that integrates qualitative and quantitative assessments to evaluate outdoor thermal conditions. The methodology combines user-centered participatory approaches, including a workshop and an online survey, to identify critical intervention areas and factors contributing to thermal discomfort. Thermal Sensation Votes (TSV) are collected and analyzed in QGIS, highlighting significant environmental and psychological factors influencing user perception. Preliminary simulations using SOLWEIG are employed to cross-examine the results, identifying spaces with varying levels of thermal comfort. This study underscores the value of combining objective and subjective measures to pinpoint areas of critical environmental quality and optimize decision-making processes. By leveraging user data, the methodology reduces computational demands while offering actionable insights for urban health. The approach is scalable to different urban contexts, fostering the development of resilient and climate-adaptive environments.

Keywords: Outdoor Thermal Comfort · Perception · citizen science · mixed methods · multi-domain

1 Introduction

Please Urbanization significantly alters land cover and structure, creating urban climates characterized by increased air pollution, elevated temperatures, and heightened flood risks. The Urban Heat Island (UHI) effect, caused by impervious surfaces, heat-retaining materials, and reduced vegetation, exacerbates these challenges, resulting in

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thermal discomfort, increased energy demand, and health risks [1]. Understanding urban microclimates and their interactions with urban morphology is crucial for developing sustainable and resilient cities [2].

Outdoor thermal comfort (OTC) is defined as refers to the state of mind where individuals feel satisfied within their thermal environment [3]. Unlike indoor spaces, urban microclimates are highly dynamic, influenced by changing solar radiation, wind, shading, and surface properties, making OTC assessments complex [4]. Factors influencing OTC include environmental parameters such as air temperature, humidity, wind speed, and Mean Radiant Temperature (Tmrt), alongside subjective elements like individual adaptation, activity level, clothing, and psychological expectations [5]. Outdoor models, designed to capture the dynamic nature of outdoor environments, are classified into thermal indices such as Physiologically Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI); empirical indices like Thermal Sensation Vote (TSV); and simpler linear equation-based indices [6]. Among these, this study employs TSV on a 5-point Likert scale (cold to hot) to evaluate subjective thermal comfort and its interaction with urban microclimatic conditions.

Empirical studies on OTC increasingly emphasize the importance of user feedback, combining field surveys with participatory methods to capture subjective perceptions and adaptive behaviors [7]. These approaches have highlighted the interplay of thermal and aesthetic perceptions and the role of greenery and material properties in shaping comfort [2]. Despite these advancements, computational models are limited in their ability to depict the complex, personal experience of thermal environments, as they cannot account for all individual parameters. Simulating actual conditions for entire urban districts is also resource-intensive and time-consuming, making it impractical in many cases.

This study addresses these gaps by applying a participatory, cross-examination approach to assess OTC in Milan's Acquabella district. By combining workshops, surveys, and computational simulations, the methodology leverages user insights to efficiently detect areas with poor environmental quality. This approach ensures faster, more focused interventions, reducing computational demands while aligning urban design with user needs and experiences.

2 Methodology

This study uses a cross-examination approach to evaluate how the built environment affects thermal perception across multiple domains. As illustrated in Fig. 1, a participatory workshop and an online survey first identify critical zones based on four dimensions—thermal, visual, acoustic, and air quality—and highlight areas of high pedestrian activity. These findings guide the selection of key locations for further examination in SOLWEIG, a QGIS-based model used to simulate Mean Radiant Temperature (Tmrt). By comparing these simulation results with the workshop and survey data, the study provides a comprehensive view of a multi-disciplinary approach to evaluate outdoor thermal comfort.

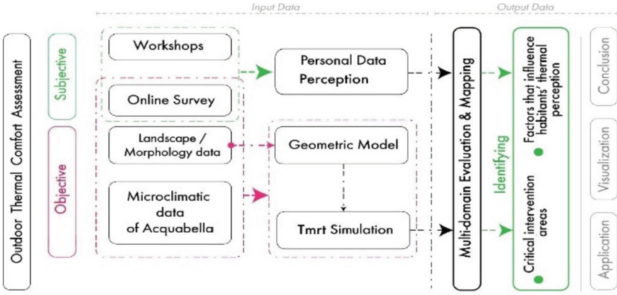

Fig. 1. Workflow of the methodology

2.1 Case Study

The Acquabella district, situated in Milan between Municipality 3 and Municipality 4 (Lat 45° 28′ 5″ N Lon. 9° 13′ 41″ E), represents a residential expansion area east of the city center. It features four to five-story buildings arranged in a north-south orientation. Milan's climate is warm sea climate (type Cfa according to the Köppen climate classification) with reasonably cold winters and warm summers. The city faces significant risks of Sustainable Local Overheating Densities (SLODs) [8], ranking among the top three European cities most vulnerable to overheating due to factors such as high population density, aging demographics, air pollution, and elevated summer temperatures. According to the Local Climate Zone (LCZ) classification, Milan is categorized as Level 2, a compact midrise area with predominantly paved surfaces, minimal vegetation, and buildings constructed from materials like stone, brick, and concrete. This urban configuration amplifies its susceptibility to heat-related challenges.

2.2 Participatory Workshop

The participatory workshop, held on January 17th as a collaboration between TU Delft and Cista, was designed to evaluate outdoor comfort in Milan's Acquabella district. More than 40 community members took part in three main stages: (i) an informative session—featuring interactive mapping and material evaluation—that familiarized participants with outdoor comfort variables and emphasized the importance of pedestrian perception; (ii) an interactive mapping exercise, in which participants marked the district's best and worst locations on printed maps based on four environmental factors (aesthetics, thermal comfort, acoustic quality, and air quality); and (iii) a material evaluation using the Mentimeter app, allowing participants to assess the thermal sensations of common facade and pavement materials on a 5-point scale. During this "Material Evaluation and Feedback" segment, participants also ranked the relative importance of each environmental parameter (thermal, visual, acoustic, air quality and aesthetic), revealing the subjective importance influencing their outdoor comfort experiences. We normalized those rankings into weights to each domain, reflecting participants' perceived significance of thermal, air, acoustic, aesthetic, and visual quality in shaping outdoor comfort. These weighted values were later incorporated into the analysis to better represent user preferences in evaluating environmental conditions.

The collected data were analyzed using QGIS and SPSS, version 25.0. In QGIS, environmental quality perceptions were mapped to produce heatmaps capturing both positive and negative votes. To focus on building-influenced areas rather than open spaces, a 15-m radius buffer was created around points indicating thermal discomfort and aesthetic dissatisfaction, which were then intersected to identify correlations between the two domains. Additionally, a 100-m buffer -representing a short walking distance- was applied around high-traffic locations to highlight areas of significant pedestrian activity. A multi-domain discomfort heatmap was generated based on the weights determined by workshop participants, and a 100 m $\times$ 100 m grid was overlaid on the study area to aggregate and visualize the density of discomfort points per cell. These values were then converted into a raster layer that synthesized participant-prioritized domains, pinpointing zones with the most critical environmental quality concerns.

2.3 Online Survey

Launched on April 17th using Qualtrics XM software and distributed via QR codes in Italian and English, the long-term survey aimed to capture environmental quality perceptions within Milan's Acquabella district. The questionnaire comprised three sections: (i) demographic data, covering gender, age, relationship to the district, and frequency of public space usage; (ii) multi-domain perceptions, where respondents identified specific public locations on a Google Maps interface and rated their comfort or discomfort on the 5-point ASHRAE scale for thermal aspects, and on 5-point Likert scales for aesthetics, acoustics, and air quality; and (iii) open-ended feedback, inviting participants to suggest improvements for enhancing comfort during warm days.

Responses were processed in QGIS using a methodology similar to the workshop analysis, overlaying a 100 m $\times$ 100 m grid on the district to aggregate and visualize perceptions. Heatmaps were generated for negative votes across thermal, air quality, acoustic, and aesthetic domains. A weighted heatmap further refined these results by applying importance weights—determined in the workshop—to the negative votes. DBSCAN clustering was then employed to identify localized clusters of high negative thermal and aesthetic perceptions, using parameters based on Milan's average block size (3.9 ha).

For each cluster, mean thermal and aesthetic votes were calculated to highlight localized environmental quality issues. Finally, one-way ANOVA tests were used to identify statistically significant differences among key variables, while Spearman's Rank Correlation measured relationships between perceptions, demographic factors, and public space usage patterns.

2.4 Simulation in SOLWEIG

To investigate spatial variations in Mean Radiant Temperature (Tmrt) across Milan's Acquabella district, SOLWEIG was employed using updated urban geometry data derived from a field survey. Key spatial inputs, including building footprints and vegetation data (canopy, trunk, and sky-view factor layers), were sourced from the Milano Geoportale and cross-referenced against OpenStreetMap in QGIS for accuracy. A Digital Terrain Model captured the area's topography, while meteorological forcing data from the nearby Juvara weather station (0.54 km away) ensured locally relevant conditions. Based on statistical analysis in SPSS, August third, 2023 was chosen for the simulation, representing a worst-case thermal comfort scenario with maximum temperatures reaching 30.9 °C. Standard emissivity and albedo parameters for walls (0.9 and 0.2, respectively) and ground surfaces (0.95 and 0.15) were used to establish a baseline against which participatory findings could be validated.

Beyond generating district-wide Tmrt maps, the simulation allowed direct comparisons between the mean Tmrt values of two locations previously identified by the citizens as thermal "hotspots" in the workshop and survey heatmaps. Running the model for the entire day on August 3rd facilitated alignment with user-reported discomfort periods; however, the analysis acknowledges that Tmrt is just one component influencing overall outdoor comfort and perception. Future work and multi-parameter indices will be necessary to provide a more holistic view of thermal comfort in the Acquabella district.

3 Results and Discussion

3.1 Participatory Workshop

The negative vote density maps highlight the most concerning areas in the Acquabella district based on subjective environmental quality responses (N = 299) (Fig. 2). Via Beato Angelico (n = 5) was identified as the worst-rated area for thermal comfort, while both Via Beato Angelico and Viale Romagna (n = 3) were ranked lowest for air quality. Aesthetic concerns were most pronounced at the intersection of Via Giuseppe Colombo and Via Beato Angelico (n = 4–5), while Piazzale Paolo Gorini (n = 4) received the biggest number of negative votes for acoustic quality.

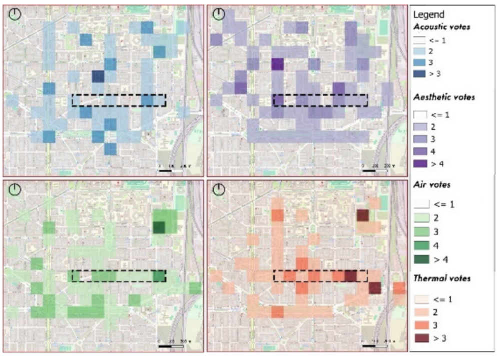

Fig. 2. Heatmaps of number of environmental quality votes. Top-left: Acoustic, top-right: Aesthetic, bottom-left: Air quality, bottom-right: Thermal quality | Highlighted Via Beato Angelico | Workshop

Further analysis using a weighted heatmap reinforced these findings, highlighting the intersection of Via Gaspare Aselli and Via Beato Angelico as a critical intervention area when multi-domain perceptions are considered (Fig. 3). Participant-assigned level of importance weights were normalized to a 0–1 scale, resulting in the following values: Visual (0.80), Thermal (0.875), Air Quality (0.95), Aesthetics (0.775), and Acoustics (0.80). This location, marked by high pedestrian activity, exhibited the poorest multi-domain environmental quality once these weighted factors were applied.

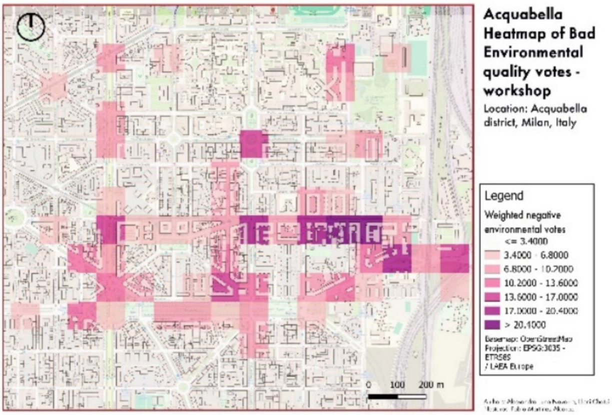

Fig. 3. Density heatmap for perceived environmental quality weighted by domain importance.

Mean thermal sensation scores were calculated for each material, enabling a ranking based on participant evaluations (Fig. 4). This ranking was linked to material properties calculated for simulations. Statistical analysis, including a one-way ANOVA and Spearman correlation, identified emissivity as a significant factor influencing thermal perception ($p = 0.036$). Brick was rated as the warmest material, while marble was perceived as the coolest, highlighting the role of material choice in influencing thermal comfort perception.

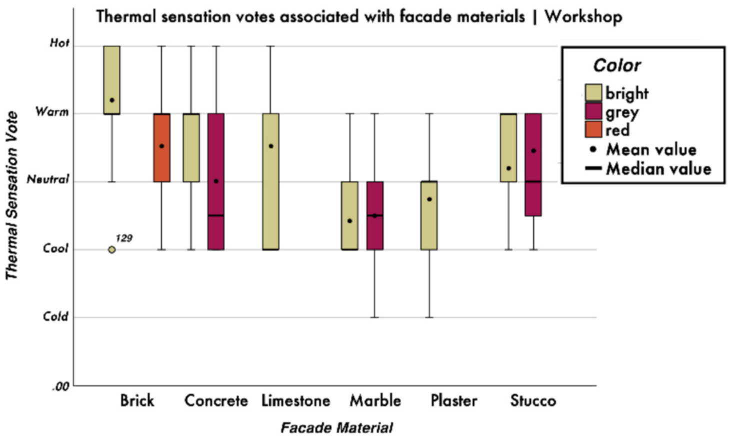

Fig. 4. Boxplot of TSV associated with facade materials during workshop.

3.2 Online Survey

A total of 200 respondents were collected. Among respondents, 70.5% were female, 26.7% male, and 2.9% non-binary. The most common age range was 40–60 years (50.5%), followed by 20–40 years (21.9%), with under 20 years comprising 7.1% of 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. 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 min,' 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%.

The survey weighed heatmap, based on the weights of the workshop, (Fig. 5) collected a total of 572 environmental votes, identifying Via Beato Angelico as the most negatively rated street (average negative weighted votes = 63), with the highest density of low-ranking votes, particularly in the domains of thermal, acoustic, and aesthetic quality. Viale Romagna was primarily rated negatively for acoustic and air quality, while Viale Argonne emerged as the second most critical area (average negative weighted votes = 36), receiving the lowest ratings predominantly for thermal comfort.

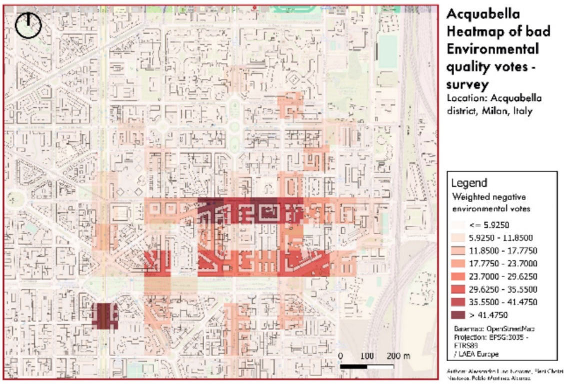

Fig. 5. Density heatmap for perceived environmental quality weighted by domain importance | Survey.

An analysis of the data revealed a significant negative correlation between thermal comfort and the frequency of visits to voted areas ($\rho = -0.198$, $p = 0.007$). Thermal comfort also showed a positive correlation with the presence of vegetation ($\rho = 0.298$, $p < 0.001$). No significant relationships were found for age ($\rho = -0.013$, $p = 0.863$) or gender ($\rho = -0.070$, $p = 0.334$). Cluster analysis indicated a robust negative correlation between thermal and aesthetic comfort ($\rho = -0.281$, $p < 0.001$). Descriptive statistics for clusters in Via Beato Angelico showed that 78.6% of votes were classified as "warm," reflecting consistent thermal discomfort in that location (Fig. 6).

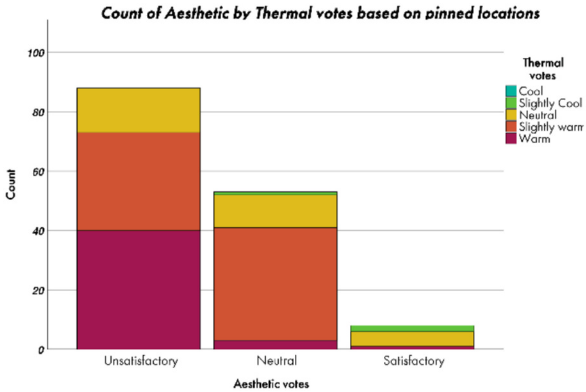

Fig. 6. Stacked bar charts showing the distribution of thermal sensation votes (TSV) for aesthetic perception under three satisfaction levels: Unsatisfactory, Neutral, and Satisfactory.

The mitigation actions (e.g., adding trees, vegetation, water bodies, shading devices, and improving pavement materials) reported in the survey can be found in Fig. 7. For Acquabella district, among the 55 responses, the most frequent recommendations were adding trees (N = 36) and shading devices (N = 23), while, specifically for Via Beato Angelico, among the 15 responses, people also suggested changing the pavement material (n = 3).

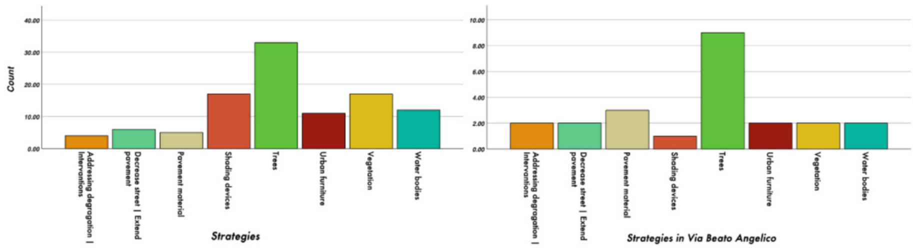

Fig. 7. Community recommendations/heat mitigation strategies in district level (N1 = 55) and in street Via Beato Angelico (N2 = 15) | Survey.

3.3 Simulation in SOLWEIG

The SOLWEIG simulation for August 3, 2023, indicated a district-wide maximum Tmrt of 62.46 °C and an average Tmrt of 51.14 °C in Acquabella. In contrast, the identified Points of Interest showed higher thermal stress, with Via Beato Angelico reaching a mean Tmrt of 59.1 °C and Viale Argonne at 57.5 °C. These results align with survey responses that marked these locations as "worst" areas, underscoring the notably harsher thermal environment in these hotspots compared to the district's average (Fig. 8) and highlighting localized overheating in Via Beato Angelico.

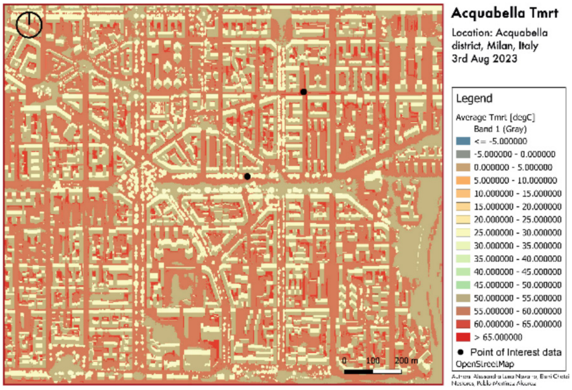

Fig. 8. Map showing the spatial distribution of Tmrt in the Acquabella district. Black dots represent the locations identified in the workshop-survey multi-domain maps.

4 Conclusions

The multi-domain analysis aims to identify areas with poor environmental quality by comparing weighted density maps from the workshop and survey. Overlaying these maps highlights congruences and differences in perceptions, validating findings and aligning survey results with community priorities from the workshop. During the workshop, participants prioritized air and thermal quality as the most important environmental parameters, with visual and acoustic factors receiving less emphasis. Heatmap comparisons revealed Via Beato Angelico as a critical area of concern, consistently rated among the worst streets for environmental quality in both datasets. High-traffic streets such as Viale Romagna and Viale Argonne also ranked poorly, reflecting their frequent use and adverse conditions, reinforcing the importance of targeted interventions in these areas.

The survey and workshop results demonstrate a strong correlation between aesthetic and thermal comfort. Areas perceived as aesthetically appealing 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 Tmrt zones from the simulations. This alignment validates the simulation results and underscores the importance of integrating aesthetic improvements into thermally uncomfortable areas. 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.

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