Outdoor comfort conditions in urban areas: On citizens’ perspective about microclimate mitigation of urban transit areas

Outdoor comfort conditions in urban areas: on citizens' perspective about microclimate mitigation of urban transit areas

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Abstract

Understanding citizens' environmental perception is a crucial issue to improve outdoor environmental and landscape quality. This paper is aimed at investigating the perspective of travelling citizens about local microclimate conditions in a transportation open-air hub of an urban district in central Italy, to propose effective mitigation strategies. Therefore, a survey was submitted to pedestrians while crossing the area to understand their actual perception of visual-thermal-acoustic conditions characterizing the outdoor environment, with varying weather and personal characteristics. Simultaneously, the continuous in-situ monitoring of the main environmental parameters was performed. Finally, the benefits generated by selected microclimate mitigation and landscape improvement strategies were quantitatively assessed by means of validated microclimate district models. Results of the field survey highlighted the minor tolerance of the local environment by local citizens compared to tourists, especially those coming from denser and more polluted cities. Moreover, the simulations confirmed the capability of selected microclimate mitigation strategies to improve pedestrians' outdoor thermal comfort conditions in summer, without winter penalties. In particular, the vegetation increase, according to pedestrians' request for additional green areas, combined to other solutions for sustainable landscape change, showed the most significant impact in summer overheating mitigation and urban resilience to anthropogenic climate change.

Keywords Urban Heat Island; Microclimate mitigation; Outdoor comfort; Human perspective; Continuous monitoring; Population survey; Urban resilience.

1. Introduction

Urbanization represents the most visible and pervasive modification to the Earth system accomplished by man (D. Zhou, Zhang, Li, Huang, & Zhu, 2016). In last decades, people moved to live and work in cities and, in 2014, 54% of the world's population was residing in urban areas (United Nations, 2014). In 2007, for the first time in history, the global urban population exceeded the global rural population, and, thereafter, the world population has remained predominantly urban (United Nations, 2014). Various environmental issues can be associated to urbanization, such as air pollution (Clifford, Lang, Chen, Anstey, & Seaton, 2016; Knibbs, Cole-Hunter, & Morawska, 2011) and noise pollution, mainly due to the road traffic noise (Lipfert & Wyzga, 2008; Meng & Kang, 2016), in urban areas and climate change (Oke, 1982; Souza, Alvalá, & Nascimento, 2016). In particular, the knowledge about the role played by urbanization in the Earth-climate system processes is incomplete (Shepherd & Shepherd, 2005). Recently, several studies have focused on the mutual connection between urban environment and climate system, namely how land cover is linked to climate change and weather (Arnfield, 2003; Emmanuel & Fernando, 2007; Rosenfeld, Akbari, Romm, & Pomerantz, 1998; Taha, 1997). Landscape alteration through urbanization involves the transformation of the radiative and aerodynamic characteristic of the land surface and results in change of the water cycle and planetary boundary layer (Arnfield, 2003).

Accordingly, with more people living in urban areas than in rural areas, urban open spaces become increasingly important. Therefore, urban spaces, such as squares, green spaces, or parks can provide environmental, ecological, social, and economic benefits to cities and are indispensable for healthy urban living (Nouri & Costa, 2017). The greatest problem of urban areas associated to climate change is the urban heat island (UHI) effect (Akbari et al., 2016). Urban heat islands refer to higher air temperatures in urban areas compared to their rural surroundings. Firstly documented in 1883 (Howard, 1883), this phenomenon is the most validated phenomenon of climate change associated to urbanization (Akbari & Kolokotsa, 2016). Oke (Oke, 1988) suggested that the annual mean air temperature of a city with one million or more people can be 1 K to 3 K warmer than its surroundings, and on a clear, calm night, this temperature difference can be up to 12 K. UHI is the mutual response to many controllable and uncontrollable factors, which could be clustered as (i) temporary effect variables, such as air speed and cloud cover (Hsieh & Huang, 2016), (ii) permanent effect variables, such as green areas, building and urban materials and geometry, and sky view factor (Synnefa, Dandou, Santamouris, Tombrou, & Soulakellis, 2008; Zoulia, Santamouris, & Dimoudi, 2009), and (iii) cyclic effect variables, such as weather conditions, solar radiation, and anthropogenic heat sources (Taha, 1997). Although the effect often decreases with city size, even smaller cities are affected by the heat island phenomenon (Castaldo, Pisello, Pigliautile, Piselli, & Cotana, 2017; Vardoulakis, Karamanis, Fotiadi, & Mihalakakou, 2013) also exacerbated by heat waves (Pyrgou, Castaldo, Pisello, Cotana, & Santamouris, 2017; A. Pyrgou, Castaldo, Pisello, Cotana, & Santamouris, 2017). In fact, in urban areas, open land and vegetation are replaced with buildings, roads, and other infrastructures. Therefore, surfaces turn from permeable to impermeable, dry and with low solar reflectance (Emmanuel & Fernando, 2007). The same authors performed outdoor microclimate monitoring in different areas of the case study small-sized historical city, i.e. Perugia, in Italy (Castaldo et al., 2017). Results showed up to 5 °C air temperature increase in the historical urban neighborhood during nighttime with respect to the suburban green area.

Moreover, the newly developed urban neighborhood, where the case study area investigated in the present study is located, was found to be up to 2 °C hotter compared to the same suburban area.

The associated urban overheating during summer can significantly affect outdoor environment and, therefore, quality of life. In fact, high summertime temperatures in urban areas deteriorate the outdoor comfort conditions and produce negative effects on citizens health, increasing the stress to vulnerable populations (Santamouris et al., 2017). Moreover, the increase of ambient temperatures increases the energy demand for cooling, adding pressure to the electricity grid during peak periods of demand (Andri Pyrgou et al., 2017). Therefore, examining the urban microclimate is really important to establish the life quality of an urban context and to act against urban overheating (Busato, Lazzarin, & Noro, 2014; van Hove et al., 2015).

Since ancient times, suitable public spaces have been designed to make cities attractive and livable. In order to counteract the impact of urban warming, specific mitigation and adaptation technologies have been proposed by the scientific community (Norton et al., 2015). The two major clusters of promising mitigation technologies are cool materials, i.e. characterized by high solar reflectance and high thermal emittance capability aimed at decreasing the absorption of solar radiation in the urban environment (Rosso et al., 2015; Santamouris et al., 2017), and green infrastructures, i.e. aimed at increasing evapotranspiration and shading in the urban environment (Gunawardena, Wells, & Kershaw, 2017; Hoelscher, Nehls, Jänicke, & Wessolek, 2016; Rahman, Moser, Rötzer, & Pauleit, 2017). The role of vegetation, e.g. parks, green roofs, vertical greeneries, etc., is to reduce the temperature gap between urban and surroundings areas. Considering that pavements constitute over 30% of typical urban areas (Akbari & Matthews, 2012) and most of these surfaces are either paved with asphalt or cement, they represent suitable urban components to be modified by implementing green or cool materials (Salata, Golasi, Vollaro, & Vollaro, 2015). Focusing on street greenery, Klemm et al. (Klemm, Heusinkveld, Lenzholzer, & van Hove, 2015) demonstrated its clear impact on outdoor thermal comfort from a physical and psychological perspective in moderate climates, by creating thermally comfortable and attractive living environments. Similarly, in Mediterranean climate, Saaroni et al. (Saaroni, Pearlmutter, & Hatuka, 2015) showed a largely favorable perception of thermal comfort among individuals in urban parks due to their satisfaction with the park aesthetic attractiveness and in fact its very existence. When considering urban green infrastructures, Derkzen et al. (Derkzen, van Teeffelen, & Verburg, 2017) investigated people’s views on climate change adaptation and benefits deriving from such strategies in temperate climate. Morakynio et al. (Morakinyo, Kalani, Dahanayake, Ng, & Chow, 2017) focused on the role of green roofs for outdoor temperature and cooling demand reduction in various climates and with different urban densities. Results of numerical analysis showed that green roofs are mainly effective in hot-dry climate, while the least efficiency was found in the temperate climates. Instead, in hot-humid climate, Morakynio et al. (Morakinyo, Lai, Lau, & Ng, 2017) demonstrated that the greening of 30–50% of facades in high-density urban settings can potentially produce daytime pedestrian thermal comfort improvement by at least one thermal class.

Accordingly, one of the main aims of outdoor microclimate mitigation strategies is to improve pedestrians comfort perception and living quality (Acero & Herranz-Pascual, 2015; Chen & Ng, 2012; Lee, Mayer, &

Chen, 2016). Current research works aim at providing information about appropriate microclimate interventions to improve pedestrians' comfort to be used by urban designers (Huang, Li, Xie, Niu, & Mak, 2017). Studies have demonstrated that human outdoor thermal perception and well-being is affected by both meteorological and morphological factors (Jamei & Rajagopalan, 2017) and personal characteristics, i.e. anthropometric variables (Kruger & Drach, 2017), income (Scopelliti et al., 2016), and personal background (A.L. Pisello et al., 2017). Nouri and Costa (Nouri & Costa, 2017) investigated, through coupled experimental and numerical analysis, the principal microclimatic risk factors that can affect pedestrian thermal comfort within a square and how they can be translated into opportunities for public space design. On the other hand, Chatzidimitrioua and Yannas (Chatzidimitriou & Yannas, 2016) studied the influence of specific urban morphologies and design parameters, e.g. street and building geometry, landscape elements, etc., on pedestrian thermal comfort in cities in summer. The high impact of trees and soil humidity and the contrasting effects of pavement albedo was specifically highlighted. Switching to mitigation strategies, Kleerekoper et al. (Kleerekoper, Taleghani, van den Dobbelsteen, & Hordijk, 2017) compared the effect of different urban modifications on pedestrians' thermal comfort in terms of PET. They found that strategies influencing wind speed and mean radiant temperature can lead to large temperature effects, yet localized. On the contrary, strategies influencing air temperature and relative humidity are effective on a wider scale.

2. Purpose of the study

Based on the outlined background, the purpose of the present work is to investigate (i) the local microclimate in a passage area located in the case study urban district and, (ii) the perception of the pedestrians travelling in the area about the quality of the surrounding outdoor environment. Therefore, the aim is to select the most appropriate microclimate mitigation strategies for the case study area. To this aim, a combined experimental and numerical approach involving in-situ monitoring campaigns, questionnaires submission to the pedestrians, and microclimate simulations is used to:

- assess personal characteristics mostly affecting perception of travelling citizens about the local environmental conditions of the surrounding environment. The so-defined "travelling citizens" are pedestrians crossing the case study area, considered as a public hub in the city. They are meanly travelers, commuting people or locals moving through logistic nodes of the public transportation network in the urban area;
- correlate pedestrians' perceptions about visual, thermal, acoustic, and air quality of the urban area, gathered by means of dedicated questionnaires, with the environmental parameters measured in-situ;
- select the most appropriate mitigation strategies for the case study urban area, according to the citizens' perspective and existing knowledge;
- evaluate the yearly outdoor microclimate benefits deriving from the application of the selected mitigation strategies in the area compared to its current configuration through numerical analysis.

The perspective of citizens travelling toward a new city or through their own city was selected as original contribution of the work and by considering that this citizenship category is mostly affected by landscape and outdoor microclimate conditions. Therefore, mitigation strategies and urban design play a key role in enhancing urban resilience to climate-change hazards, since it may be indeed hugely responsible for their wellbeing and for driving their decision making process (Taylor, 2017; M. Zhou et al., 2015).

3. Description of the case study

The case study area (Figure 1), named Fontivegge, is located in the South-West part of the city of Perugia, Italy (43°10’45” N, 12°37’50”E) and it hosts the train and bus station hub of the city. Perugia is a medium size city located in central Italy with about 165000 inhabitants and it is characterized by a typical Mediterranean climate, with mild and warm temperatures during spring and fall. Summer season is usually hot, humid, and characterized by low precipitation rate, whereas winter tends to be mild-to-cold and wet with isolated phenomena of low temperatures and snowfall. Most rainfall occurs in spring and fall, in particular during the months of November and April. The selected area within the city is important due to the presence of the city main railway station and urban sky-train connecting the station to the city center on one side and to the suburbs on the other side. The projects of master plans of 60’s and 80’s influence even today the area distribution. In fact, in the area there are mostly 70’s residential buildings and offices, in addition to a square located on the North of the station. Furthermore, this area is the core of urban infrastructures. Besides sky-train and railway stations, there are three bus stops in the area: one in front of the railway station, one in front of the square, and a third one next to the urban sky-train stop. Therefore, the area is a passage zone, continuously crossed by citizens and tourists moving in/out the urban district during the whole day. For this reason, the selected case study area is almost completely paved or asphalted. Accordingly, the zone lacks of green areas, which are just a few and relatively small.

Figure 1. Case study area as seen from Google Earth.

4. Methodology

In order to evaluate (i) travelers' comfort levels, (ii) the urban heat island intensity, and (iii) the effectiveness of the selected mitigation techniques, the following steps were carried out:

- experimental continuous in-situ monitoring of the main local microclimate parameters;
- in-situ survey campaign by means of questionnaires to pedestrians crossing the area;
- validated microclimate simulation of the case study urban area and comparative analysis of microclimate mitigation scenarios;
- results analysis and comparison.

Figure 2 shows a scheme of the implemented methodology.

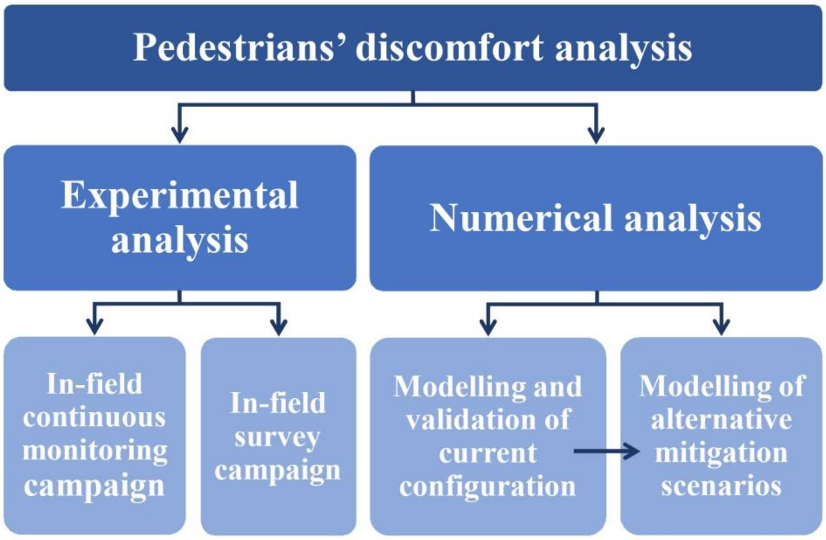


Figure 2. Scheme of the applied methodology.

4.1. Experimental in-situ continuous monitoring

To experimentally characterize the local microclimate in the case study area and validate the numerical model, an in-situ continuous monitoring campaign was carried out during some days in spring and summer 2016. Different monitoring setups were used during the experimental campaign (Figure 3), i.e. portable microclimate stations coupled with local weather stations. Most of the data were acquired thanks to portable stations based on Wireless Sensor Network (WSN) technology. Nevertheless, a separate thermo-hygrometer TGP-4500 and an albedometer were used for further data acquisition. Additionally, measurements by means of infrared camera were carried out during days with peak summer conditions to assess the superficial temperature of outdoor pavements (highlighted area in Figure 3b). Therefore, the main environmental parameters, namely air temperature [°C] and relative humidity [%], surfaces temperature [°C], illuminance [lux], global solar radiation [W/m^2], reflected radiation by pavements [W/m^2], CO_2 concentration [ppm], wind speed [m/s] and main direction [°] were measured in the case study area (black dots in Figure 3b). The continuously monitored data, aimed at validating the numerical model, were collected from 9:00 a.m. to 6:00 p.m. during summer days. Moreover, air temperature and relative humidity were measured through a separate sensor during 24 hours in another point of the area (Figure 3a on the top left and white dot in Figure 3b). These data, in addition to wind speed and wind direction, were used as input for the numerical model for being calibrated. The thermo-hygrometers were shielded from the solar radiation thanks to polystyrene semi-circular screens to avoid sensor overheating and measurement corruption.

Figure 3. In-situ monitoring equipment: (a) monitoring setup and (b) monitoring stations location.

4.2. Experimental in-situ survey campaign

Data related to personal characteristics and perception about the local thermal comfort, air pollution, and noise pollution levels were collected from pedestrians while crossing the area with the aim of correlating the local microclimate conditions with the pedestrians' perceptions. Moreover, personal and external parameters affecting pedestrians' sensations were evaluated. Therefore, tailored questionnaires were submitted to 367 persons crossing the area (Figure 4), i.e. travelling and moving through the nodes of the public transportation connection urban area. More in detail, the questionnaires were submitted to those pedestrians during different seasons, i.e. spring (102), summer (181), and winter (84), by paying particular attention to the data collected during periods characterized by extreme summer temperatures in consecutive days. The questionnaires were designed according to existing examples in literature (Huebner, Cooper, & Jones, 2013; Santamouris et al., 2014), in order to consider possible environmental parameters and personal characteristics affecting pedestrians' thermal comfort and air/noise pollution perception. Among key personal characteristics, information about age, gender, height, weight, origin, and time of stay were asked to the respondents. Moreover, the citizens were investigated about the preferable mitigation strategies to be designed in the area to improve the local environmental and landscape condition or the energy and security efficiency. In particular, the following strategies and technologies were proposed:

- increase of greenery, i.e. grass-land and trees;
- PV tech-trees;
- air purification systems;
- S.O.S. stations, i.e. multimedia stations operating as help and information points for the people in the area.

In addition, respondents could propose their own ideas or suggestions. The data requested through the questionnaire are summarized in Table 1.

Figure 4. Survey among pedestrians in various seasons.

Thereafter, the collected data were statistically analyzed and compared by dividing them as:

- Independent variables (IVs): respondents' personal characteristics and environmental data;
- Dependent variables (DVs): respondents' answers concerning personal perceptions and sensations.

Firstly, the sample distribution was analyzed to assess its composition and to verify the representativeness of the collected data. Therefore, the monitored environmental parameters and the moving pedestrians' answers in terms of comfort levels were correlated. Linear regression analyses were carried out to study the dependence of DVs on IVs. In particular, the influence of each considered independent variables on comfort levels was defined as statistically significant or not significant by considering a confidence interval of 95% and a significance level of 0.05 (J.Kiefer, 1977).
In order to evaluate which parameters mostly influence pedestrians' comfort perception, the DVs collected through the questionnaire procedure were statistically analyzed and correlated to:

- respondent's origin and visiting time;
- personal physical characteristics;
- survey period (i.e. season).

The number of respondents was verified to be consistent with the number of users of the area and the number of considered variables (Austin & Steyerberg, 2015; Cappa, Laut, Nov, Giustiniano, & Porfiri, 2016). Furthermore, the composition analysis (Figure 5) showed that the sample was balanced in terms of gender, while the most of respondents were (i) shorter than 1.70 m with weight between 50 and 65 kg, accordingly, and (ii) middle aged, i.e. between 20 and 40 years old. Moreover, the most of respondents were from Perugia, Italy, i.e. the case study city. Finally, the survey showed that most of the citizens crossed the case study area mainly during lunch time and spent less than 15 minutes there.

Table 1. Information asked to pedestrians by means of questionnaires and values assigned to the DVs.

INFORMATION TYPE	DATA	OPTIONS	VALUES
Personal information	Date	-	-
	Time	-	-
	Age	≤ 20 years old 20 ≤ years old < 40 40 ≤ years old < 60 ≥ 60 years old	-
	Gender	M F	-
	Height	≤ 1.70m 1.70 ≤ m < 1.80 1.80 ≤ m < 1.90 ≥ 1.90m	-
	Weight	50 ≤ kg < 65 65 ≤ kg < 80 ≥ 80kg	-
	Clothing	Spring clothing Summer clothing Winter clothing	-
	Origin	Perugia Umbria region Other	-
	Long-time visit	≤ 15minutes 15 ≤ minutes < 30 30 ≤ minutes < 45 ≥ 45 minutes	-
Thermal comfort	Perception	Cold Cool Neutral Warm Hot	2 1 0 -1 -2
	Comfort	Very comfortable Slightly uncomfortable Neutral Uncomfortable Very uncomfortable	0 1 2 3 4
	Tolerability	Perfectly tolerable Slightly difficult to tolerate Fairly difficult to tolerate Intolerable Absolutely intolerable	0 1 2 3 4

Air pollution	Perception	Very polluted	4
		Polluted	3
		Slightly polluted	2
		Pollution-free	1
		Absolutely pollution-free	0
	Comfort	Very comfortable	0
		Slightly uncomfortable	1
		Neutral	2
		Uncomfortable	3
		Very uncomfortable	4
	Tolerability	Perfectly tolerable	0
		Slightly difficult to tolerate	1
		Fairly difficult to tolerate	2
		Intolerable	3
		Absolutely intolerable	4
Noise pollution	Perception	Very polluted	4
		Polluted	3
		Slightly polluted	2
		Pollution-free	1
		Absolutely pollution-free	0
	Comfort	Very comfortable	0
		Slightly uncomfortable	1
		Neutral	2
		Uncomfortable	3
		Very uncomfortable	4
	Tolerability	Perfectly tolerable	0
		Slightly difficult to tolerate	1
		Fairly difficult to tolerate	2
		Intolerable	3
		Absolutely intolerable	4
Design of the area	Preference	Additional greenery	-
		PV tech-trees	
		Air purification systems	
		S.O.S. stations	
		Others	

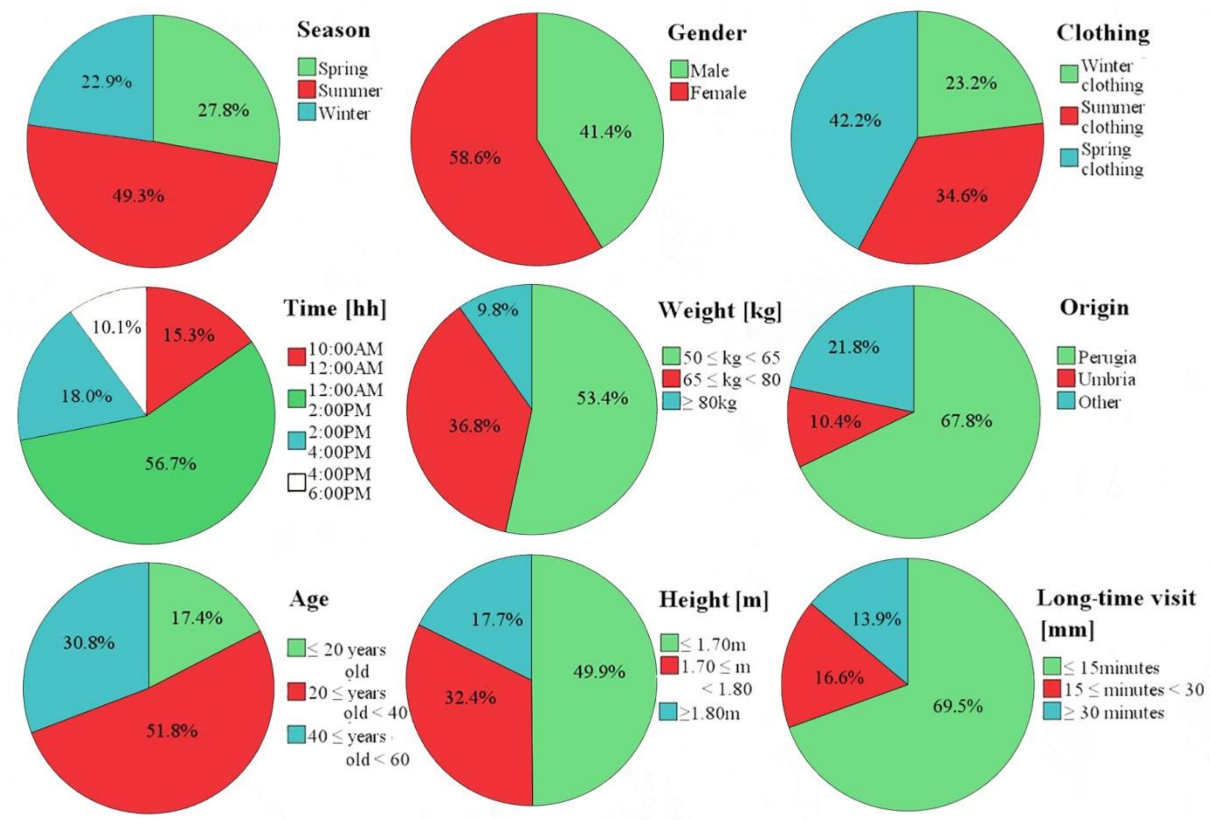


Figure 5. Survey sample composition.

4.3. Microclimate modeling

The numerical simulations were performed through ENVI-met V4, i.e. a three-dimensional validated microclimate modeling system (Bruse & Fleer, 1998). Such tool is the most suitable for carrying out urban canopy microclimate simulations for its high accuracy in space allowed by the use of the orthogonal Arakawa C-grid numerical discretization scheme. Moreover, the software allows to model both short and long-wave radiation and to determine the outdoor air temperature and relative humidity based on the calculated 3D wind field and sensible heat and vapor sources or sinks. The model of the wind field is based on the Reynolds-averaged non-hydrostatic Navier-Stokes equations (RANS), which are solved for each grid in space and each time step of the simulation. The heat interchanged by built surfaces with atmosphere is also considered. Additionally, all the thermo-physical properties of the building components are taken into account in the calculations (i.e. thickness, solar reflectance, thermal emissivity, absorption capability, transmission capability, heat transfer coefficient, and heat capacity). The calculation of façades surface temperature is based on a 3-node transient state model, and the finite difference method is used to solve partial differential equations.

Finally, turbulence in the air is considered thanks to the Turbulence Kinetic Energy (TKE) model describing the distribution of kinetic energy and its dissipation rate.

For the present study, a preliminary reference model (i.e. Scenario 0) representing the current configuration of the case study area was elaborated and validated through the collected experimental data. Therefore, the model of the case study area was used as a baseline for the microclimate analysis. Starting from Scenario 0, multiple strategies for the mitigation of the local urban microclimate and the redevelopment of the area were proposed and additional scenarios (i.e. Scenarios 1-5) were elaborated. The main strategies were considered according to the Public Authority in charge of the landscape improvement of the studied area, for both touristic and safety issues. They concern the modification of the amount of vegetation and albedo of coating materials (Table 2) and the implementation of renewable energy systems, included into the questionnaire submitted to pedestrians. The five mitigation scenarios were developed as follows:

- Scenario 1: inclusion of cool materials in the pavements;
- Scenario 2: conscious increase of greenery in the area;
- Scenario 3: inclusion of PV tech-trees (eight modules);
- Scenario 4: inclusion of photovoltaic asphalt in the roads;
- Scenario 5: combination of the above-mentioned strategies, including cool pavements, vegetation increase, and PV tech-trees (seven modules).

The realistic urban morphology of the case study area and the surrounding buildings were implemented into the model and considered in the calculations. In fact, both the nearby buildings and the urban configuration can considerably affect the local microclimate parameters especially in terms of wind speed and direction, as well as sky-view factor (Anna Laura Pisello, Castaldo, Taylor, & Cotana, 2016). Therefore, a grid based on a matrix of 159×159 cells on the horizontal plane and with 30 cells high was elaborated to build the model (Figure 6). The horizontal and vertical spacing among the calculation points were of 2 m and 3 m, respectively. In this way, a 318 m×318 m horizontal and 90 m vertical real space was simulated, for a total modeled area equal to more than 100000 m^2. With this pattern size, a space equal to twice the height of the tallest building was modeled between the study area and the edge of the map. Additionally, 10 nesting grids were added on each side. The addition of nesting grids allows improving the stability of the mathematical models used by the microclimate simulation tool, by avoiding outliers in final results (Castaldo et al., 2017). Afterwards, the ground elevation map, the type of soil, and the geographical position, the height, and the main materials of the buildings were inputted to the model. Moreover, the characteristics of the vegetation were defined thanks to the dedicated ENVI-met model (Morakinyo, Kong, Lau, Yuan, & Ng, 2017). The ground elevation was discretized with a stepped profile, since ENVI-met does not allow to model sloping surfaces. It must be pointed out that the grid sensitivity and model dimension were selected in order to balance the simulation effort in terms of computational time and accuracy of the results, which were validated by means of the in-situ collected experimental data as already mentioned.

In this case study, clay tiles sloped roof, concrete flat roof, and concrete walls were used. Glass walls were modeled in buildings characterized by large fenestrated areas. Regarding pavements profiles, the reference scenario has a high percentage of surfaces covered by asphalt, in addition to a small permeable surface and other low-albedo pavements. Trees of type Acer Negundo were used to represent the trees alongside roads presenting a LAD profile of 2 with a foliage albedo equal to 0.5, while grass was used in the parts with low-height vegetation. In general, 175 Acer Negundo trees were modeled. Every tree occupies 241 m^3, therefore the volume occupied by trees is equal to 0.46%.

As concerns the mitigation scenarios, the following landscape modifications were implemented in each scenario (Figure 7):

- Scenario 1: increase of the pavements albedo in front of the train station, i.e. up to 0.7 and 0.8 in vehicular and pedestrian areas, respectively;
- Scenario 2: increase of the number of trees, i.e. Acer Negundo, in front of the train station and, therefore, implementation of natural sandy soil in that area;
- Scenario 3: inclusion of eight photovoltaic trees within the area modelled as single horizontal surfaces with a specific albedo of 0.08, which simulates the superficial optical properties of a common PV panel;
- Scenario 4: replacement of the reference pavement with the photovoltaic one in front of the train station, characterized by an albedo of 0.08;
- Scenario 5: suitable combination of the above-mentioned strategies, as summarised in Table 2.

The time step for the simulations was defined in order not to have turbulence issues. Therefore, the simulation was initialized during the night, i.e. weak turbulence conditions, and the duration of each simulation was 48 hours, to provide 24 hours of training stage to the model (Zhang et al., 2017). The input data were daily average values for wind speed and direction, while air temperature and relative humidity values were provided on an hourly basis. The “Simple Forcing” ENVI-met tab allows to enter hourly values for the first 24 hours, after that the software continues running without forcing.

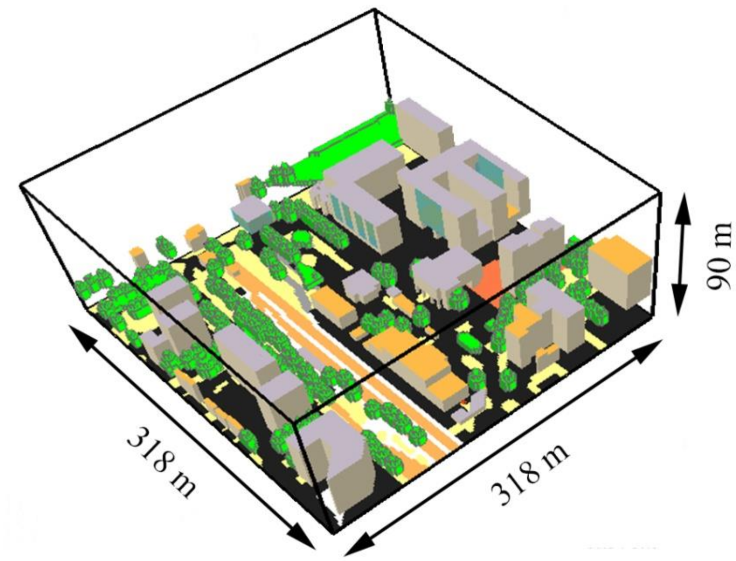
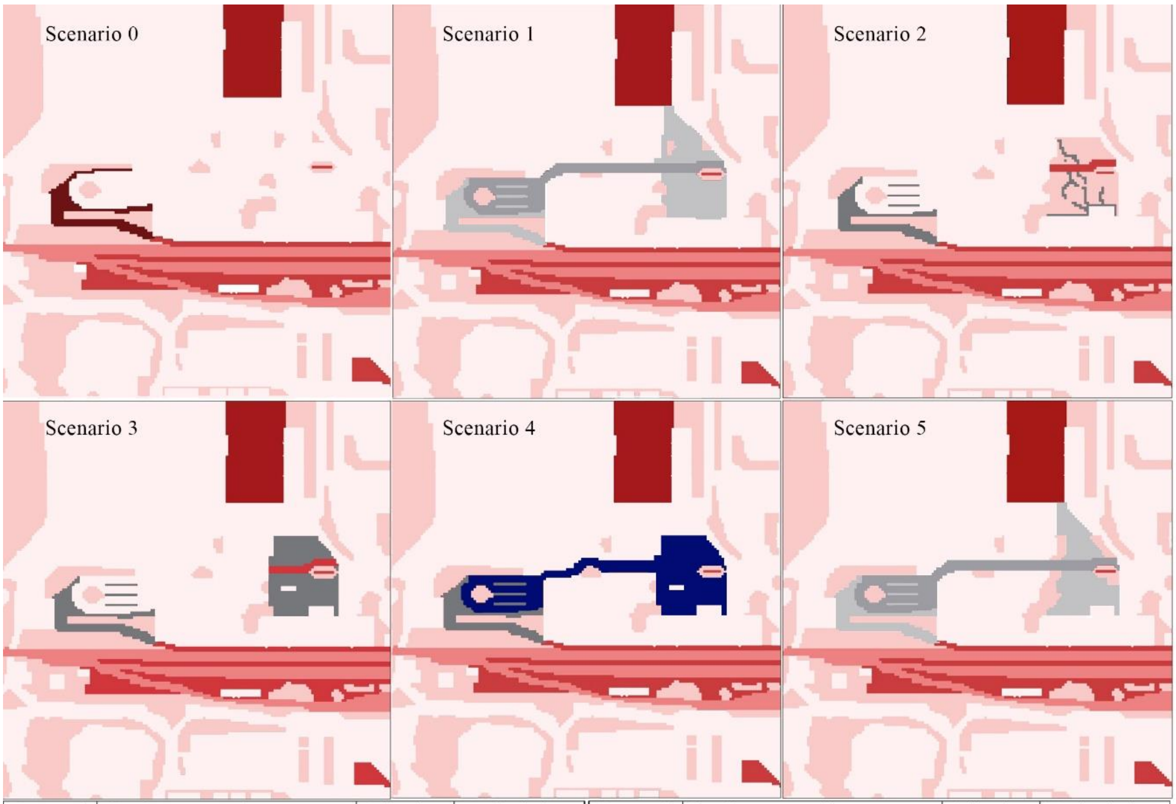


Figure 6. ENVI-met model of the case study area.

Table 2. Simulated reference and mitigation scenarios for the case study area.

SCENARIO	0	1	2	3	4	5
Amount of vegetation	21.93%	21.93%	**23.82%**	21.93%	21.93%	**22.51%**
High albedo surface (0.8)	-	**4.07%**	-	-	-	**4.07%**
High albedo surface (0.7)	-	**2.53%**	-	-	-	**2.53%**
Concrete surface	5.01%	5.01%	**5.34%**	**5.34%**	**5.34%**	5.01%
PV asphalt	-	-	-	-	**6.60% (250kWp)**	-
PV trees	-	-	-	**7.20kWp**	-	**6.30kWp**



Legend Colour	Surface covering typology	Albedo	Emissivity	Legend Colour	Surface covering typology	Albedo	Emissivity
	Asphalt Road	0.1	0.9		Granit Pavement	0.4	0.9
	Sandy Soil	0.0	0.9		Granit Pavement	0.5	0.9
	Smashed Brick	0.3	0.9		Granit Pavement	0.8	0.9
	Concrete pavement grey	0.4	0.9		Granit pavement	0.7	0.9
	Brick Road, red stone	0.3	0.9		PV asphalt road	0.08	0.9

Figure 7. Landscape modification in each mitigation scenario.

4.4. Simulation results analysis

To assess the performance of outdoor microclimate mitigation strategies, the simulation results for the different scenarios were compared in terms of the main environmental parameters. In particular, air

temperature and relative humidity in the area, outdoor surfaces temperature, mean radiant temperature, and wind speed were considered. Moreover, two outdoor thermal comfort indexes, i.e. PET and MOCI, were evaluated within the investigated area. For the present analysis, only area influenced by the local microclimate mitigation strategies was investigated, i.e. smaller compared to the whole modeled area (as shown in the following section 5.2). Simulations were performed in both hot and cold weather conditions, i.e. during a summer and a winter day. However, results were mainly focused on summer analysis, since mitigation strategies were designed with the aim of counteracting summer overheating related issues.
The PET (Physiological Equivalent Temperature) (Höppe, 1999) is defined as the air temperature in a standardized indoor setting at which the heat balance of the human body is balanced at the same core and skin temperature as under the outdoor conditions being assessed. It is based on the Munich Energy-balance Model for Individuals (MEMI). On the other hand, the MOCI (Salata, Golasi, de Lieto Vollaro, & de Lieto Vollaro, 2016a) is a recently developed thermal index specifically elaborated for the evaluation of Mediterranean outdoor areas. It defines the mean vote expressed by Mediterranean people to judge the thermal quality of an outdoor environment. This index is based on the ASHRAE 7-point scale and is expressed as follows (Eq. (1)):

$$MOCI = -4.068 - 0.272 \cdot w_s + 0.005 \cdot RH + 0.083 \cdot MRT + 0.058 \cdot T + 0.264 \cdot I_{cl} \qquad (1)$$

where wind speed (w_s), relative humidity (RH), mean radiant temperature (MRT), air temperature (T), and clothing insulation (I_{cl}) are the parameters affecting the MOCI index value.

Previously, the accuracy of the model was verified by comparing the predicted (P) and observed (O) values of the above mentioned environmental parameters. Additionally, validation indexes frequently adopted for the evaluation of such models were calculated. Such indexes are the following:

- Mean Bias Error (MBE), which describes the bias between predicted and observed values and is defined as in Eq. (2):

$$MBE = N^{-1} \sum_{i=1}^{N} (P_i - O_i) \qquad (2)$$

- Systematic Root Mean Square Error ($RMSE_s$), which is the RMSE due to model construction and should approach zero. The index is defined by Eq. (3):

$$RMSE_s = \sqrt{N^{-1} \sum_{i=1}^{N} \left(\widehat{P_i} - O_i\right)^2} \qquad (3)$$

  where $\widehat{P_i}$ is the predicted variable according to the least-squares regression, $\widehat{P_i} = a + b \cdot O_i$.
- Unsystematic Root Mean Square Error ($RMSE_u$), which is equal to the difference between RMSE and $RMSE_s$.
- Willmott index of agreement (*d*) (Willmott, 1982), which represents a descriptive measure varying between 0 and 1 and is defined as in Eq. (4):

$$d = 1 - \left[\sum_{i=1}^{N}(P_i - O_i)^2 / \sum_{i=1}^{N}(|P'_i| + |O'_i|)^2\right] \quad (4)$$

where $P'_i = P_i - \bar{O}$ and $O'_i = O_i - \bar{O}$.

5. Discussion of the results

5.1. Experimental social campaign

In the analysis of survey results, the personal characteristics of respondents and the survey period were set as Independent Variables (IVs), while participants' answers in terms of thermal comfort, air pollution, and noise pollution were considered as Dependent Variables (DVs). The travelling pedestrians' perception, comfort, and tolerability of thermal conditions, air pollution, and noise pollution were investigated. Additionally, the perspective of the respondents about possible design strategies aimed at improving the surrounding environment in the passage area were asked. As previously mentioned, the considered confidence interval (CI) for each analysis was set as 95%.

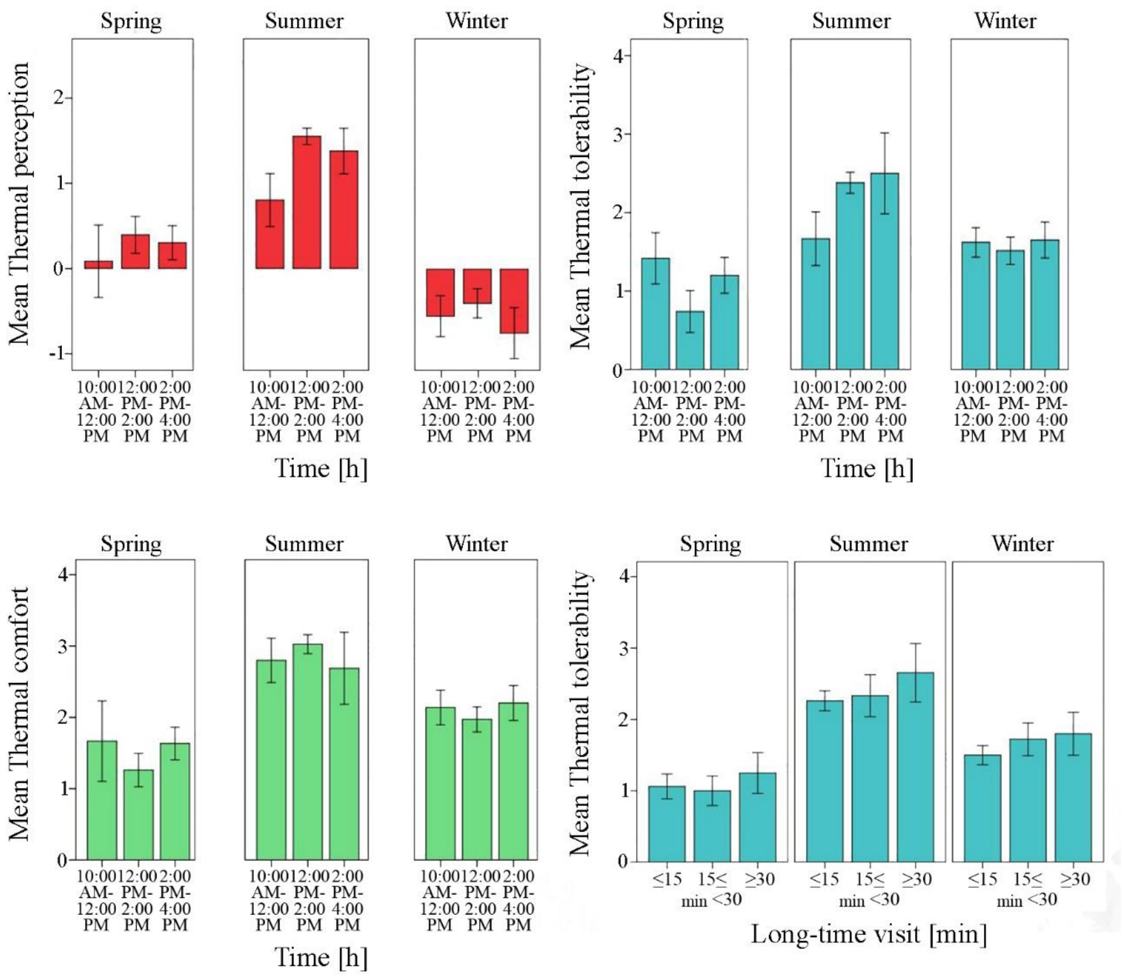


Figure 8. Influence of survey period and long-time visit (IVs) on respondents' thermal comfort (DV).

Thermal comfort was the first investigated DV (Figure 8). The IVs showing a significant impact on its perception, tolerability, and comfort level were the survey period, in terms of season and time of the day. Moreover, the long-time visit (IV) showed a significant impact only on tolerability. More in detail, in spring participants were closer to a neutral thermal sensation, while in summer the thermal perception was the farthest from the neutral sensation. Accordingly, in spring, about the 68% of participants replied "neutral" to question "What is your thermal perception?", while in summer, around the 75% of participants considered uncomfortable or very uncomfortable the thermal conditions. As expected, in summer, the time of the day with the highest thermal discomfort was 12:00 p.m. - 2:00 p.m. On the contrary, the time period 12:00 a.m.-2:00 p.m. was one with most comfortable conditions in winter. Nevertheless, in all assessed seasons the thermal tolerability was found to increase with increasing long-time visit, thanks to the human body adaptation capability, which is rarely achievable during short stays.

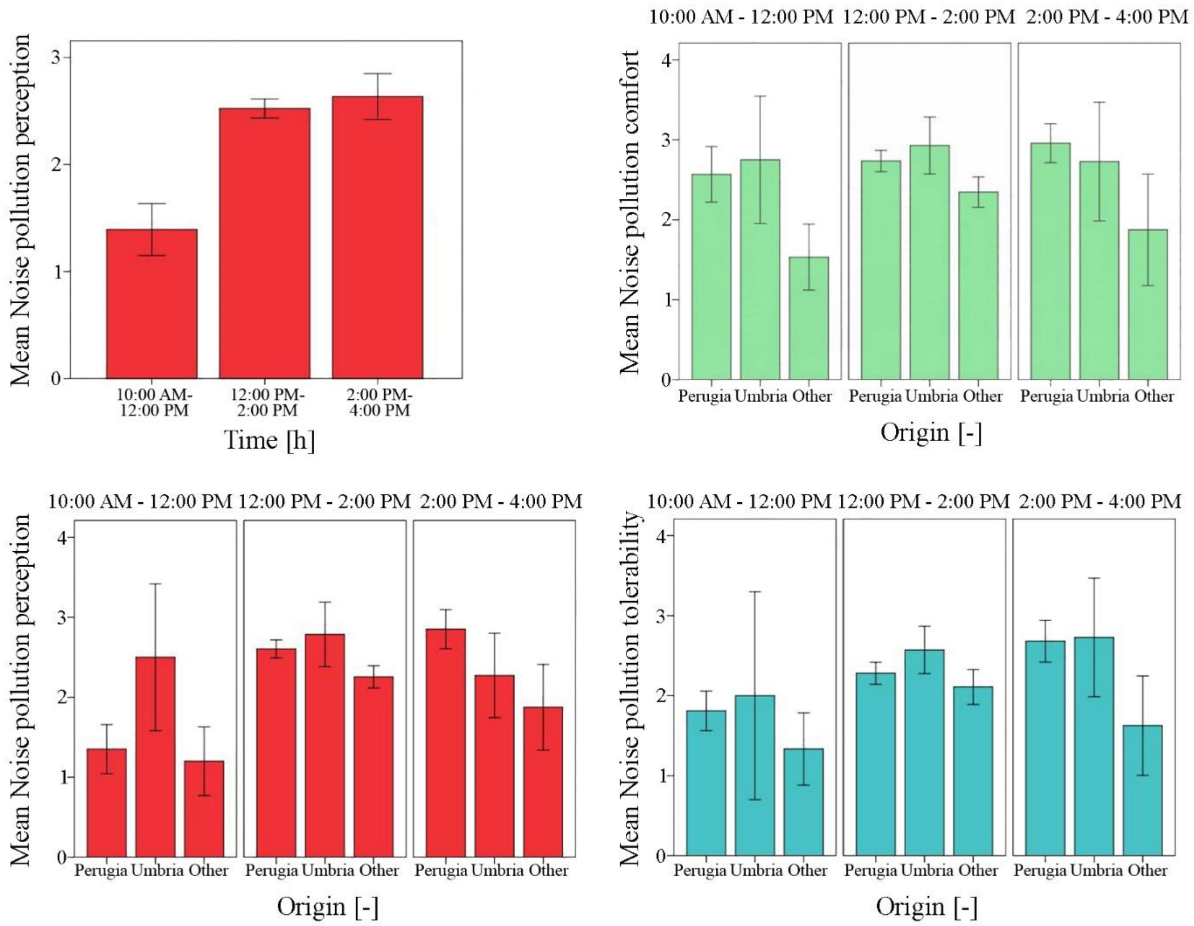


Figure 9. Influence of survey time and respondents' origin (IVs) on noise pollution perception (DV).

Afterwards, the noise pollution (DV) of the case study area was investigated (Figure 9). The IVs showing a significant impact on noise pollution perception, tolerability, and comfort were the survey time period and participants' origin. In particular, the noise pollution perception was found to be lower during morning, i.e. 10:00 a.m. - 12:00 p.m. Accordingly, about the 36% and 53% respondents considered intolerable or very intolerable the noise pollution during late morning (12:00 p.m. - 2:00 p.m.) and early afternoon (2:00 p.m. - 4:00 p.m.), respectively, when car traffic is denser in the studied area. As regards the influence of participants' origin, citizens living in the case study city and region consider the area more polluted and less tolerable and, therefore, less comfortable than foreign people, i.e. coming from probably noisier and more polluted areas.

Finally, air pollution was investigated as DV (Figure 10). The IVs showing a significant impact on its perception, comfort, and tolerability were again the survey time period and participants' origin. However, the air pollution perception was found to be lower during early and late morning, i.e. 10:00 a.m. - 2:00 p.m. In fact, during afternoon, 32-45% of respondents found the air pollution in the area intolerable or very intolerable. Concerning respondents' origin, results were consistent with the noise pollution analysis, since local citizens were shown to be stricter about the air pollution perception and tolerability in the case study area. Foreign respondents, indeed, appear to be used to even worst environmental conditions. Also, the reason for the pedestrians' transit in the area, e.g. working-day schedule vs. holiday, can play a significant role in influencing their comfort perception.

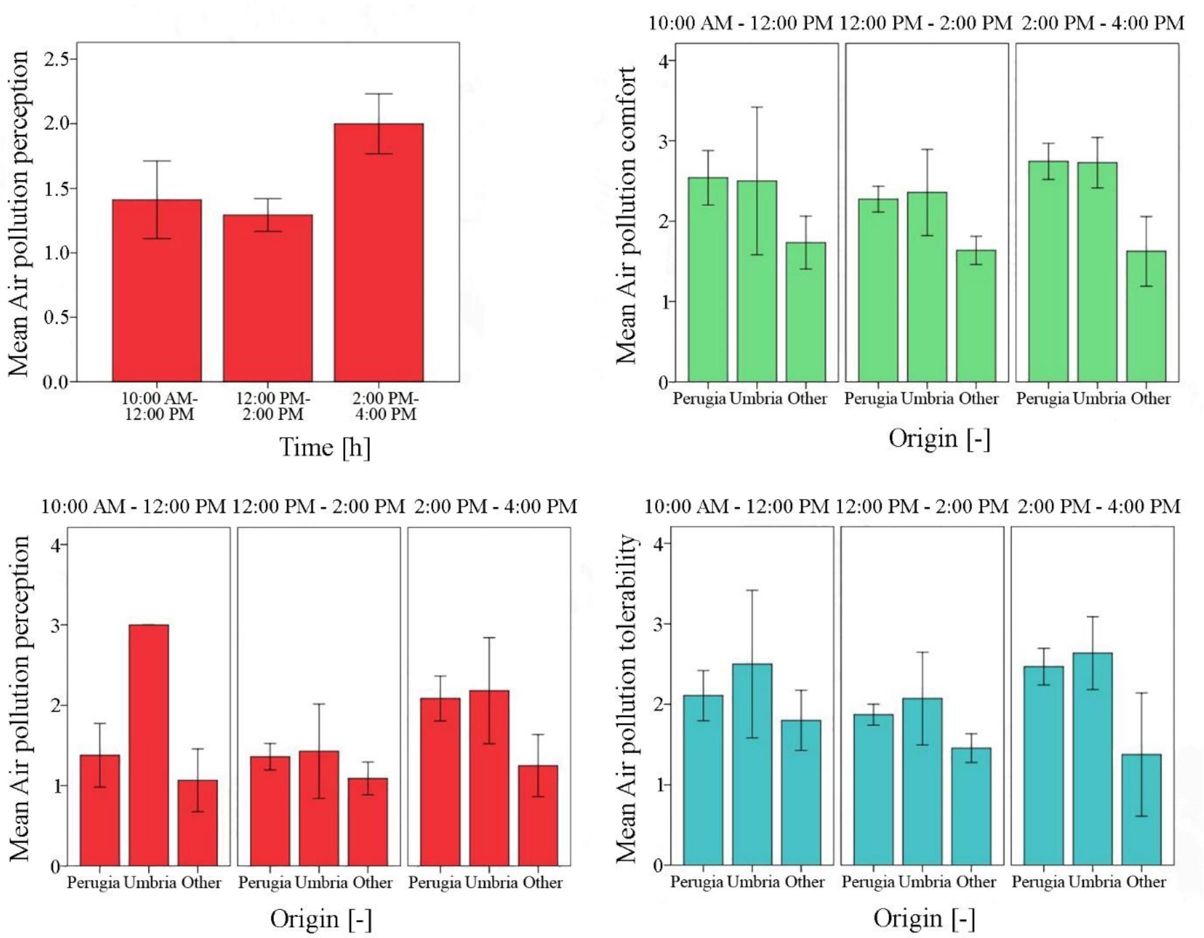


Figure 10. Influence of survey time and respondents' origin (IVs) on air pollution perception (DV).

After assessing their sensations about the case study area, participants were asked to give their preferences about the mitigation strategies to be possibly implemented in the case study passage area to improve its environmental perception through participated landscape design techniques. In particular, strategies aimed at improving local microclimate and air pollution, the security, the esthetical value, or the renewable energy production in the area were proposed. All the proposed technologies were favorably judged by more than half of the respondents, as depicted in Figure 11. Nevertheless, the analysis of personal preferences results showed that almost all participants would appreciate additional greenery in the area, which is able to improve both the environmental conditions and the esthetical value of the area. In fact, the perspective of the travelling pedestrians, who take few minutes to cross the area, is mainly aimed at achieving immediate rather than long-term benefits.

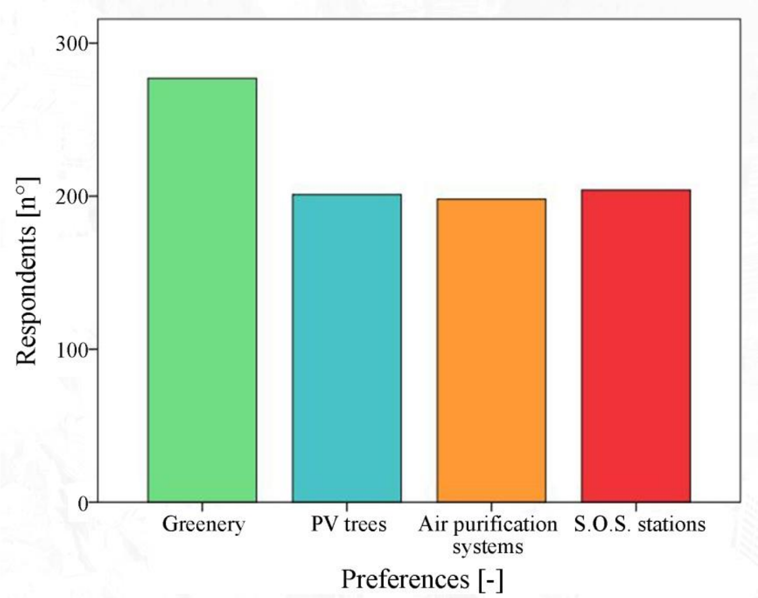


Figure 11. Pedestrians' preferences about the design strategies for the case study area.

5.2. Microclimate modeling

5.2.1. Model validation

In order to develop a reliable and representative model of the case study area, the results obtained through the numerical simulations were compared against the experimentally measured parameters. In particular, five microclimate variables, i.e. air temperature and relative humidity, global solar radiation, reflected short-wave radiation, and surface temperature were taken into account. The wind speed was not taken into consideration during the model validation since ENVI-met uses constant values as input for this variable.

Table 3 presents the average and maximum difference between the measured and the simulated parameters and the obtained values for the validation indexes MBE, $RMSE_u$, $RMSE_s$, and *d*. Although discrepancies were observed between simulation outputs and measured parameters, the values of the indexes were in line with the validation processes that can be found in literature for ENVI-met models (Salata, Golasi, de Lieto Vollaro, & de Lieto Vollaro, 2016b). Moreover, the correlation between the predicted and the observed environmental variables is shown in Figure 12. Good values of the coefficient of determination R^2 were obtained for both air and surface temperature (Figure12a), i.e. 0.63 and 0.91, respectively, and relative humidity (Figure 12b), i.e. 0.96. Conversely, the accordance between the predicted and the observed values of global solar radiation and reflected radiation was weaker (Figure 12c). Nevertheless, the coefficient R^2

assumed high values, i.e. 0.92 and 0.86 for global solar and reflected radiation, respectively, because the linear correlations were affected by the presence of data characterized by different orders of magnitude, i.e. almost 100 and 1000 W/m^2. Therefore, the time trend of observed and predicted incoming global solar radiation is plotted in Figure 12d. The graph clearly highlights the gap between the two curves. However, since the version of the software ENVI-met used does not allow to force the incoming solar radiation, these discrepancies were due to time-dependent overcast sky conditions of the real environment which could not be reproduced within the model. Taking into account this limitation of the software and the calculated values presented in Table 3, the model validation was considered acceptable.

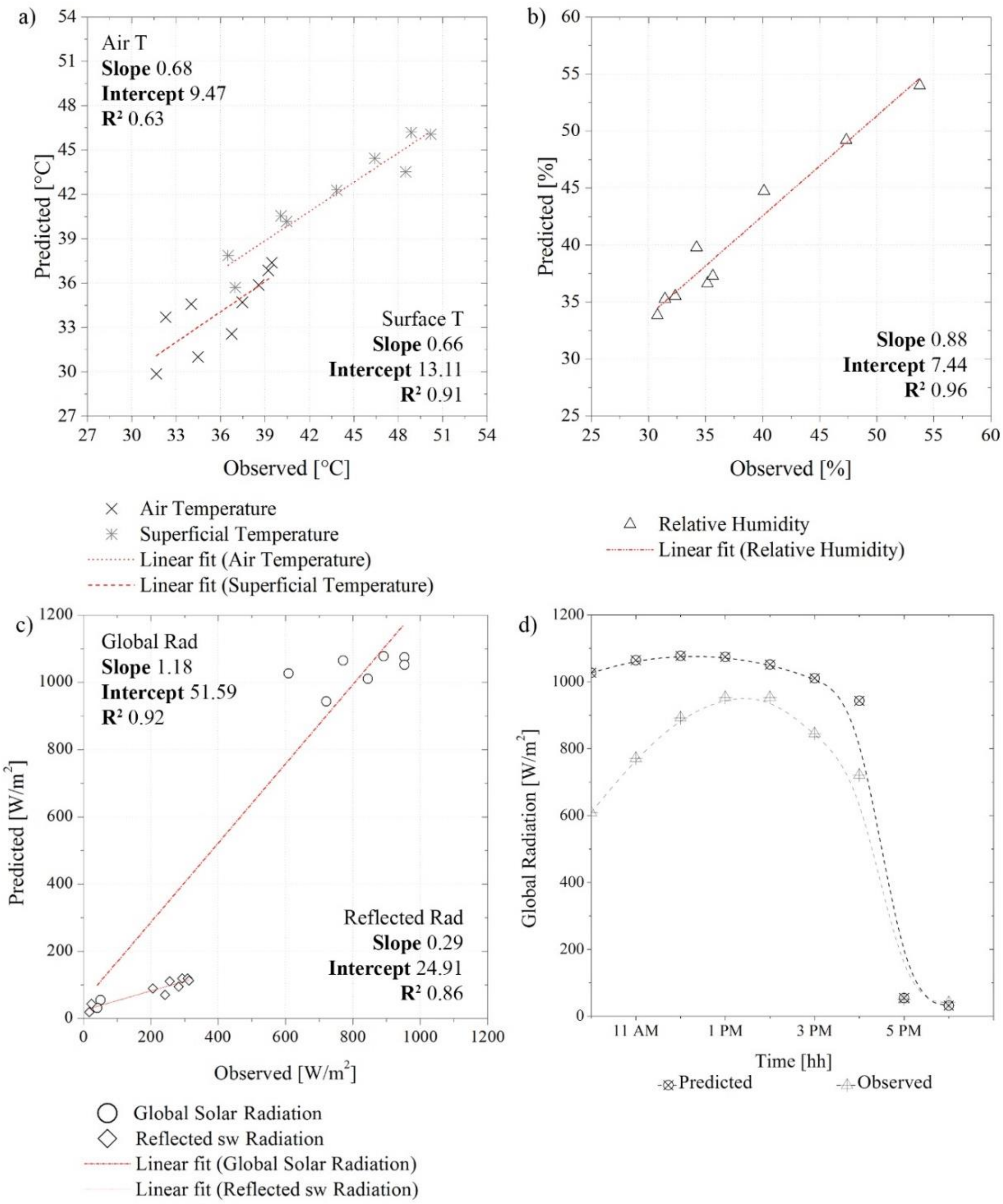


Figure 12. Linear correlation between predicted and observed values of (a) surface and air temperature, (b) relative humidity, and (c) global solar and reflected radiation; (d) comparison of predicted and observed global solar radiation trend.

Table 3. Experimental validation of the numerical model.

VALUE	Δave	Δmax	MBE	$RMSE_u$	$RMSE_s$	*d*
Air temperature	2.36 °C	4.19 °C	-1.93 °C	2.23 °C	0.35 °C	0.74
Relative humidity	2.81 %	5.57 %	2.81 %	3.03 %	0.20 %	0.95
Surface temperature	2.09 °C	4.99 °C	-1.68 °C	2.39 °C	0.18 °C	0.90
Global solar radiation	113.49 W/m^2	336.89 W/m^2	-	-	-	-
Reflected short-wave radiation	133.90 W/m^2	200.04 W/m^2	-	-	-	-

5.2.2. Microclimate analysis in summer

The microclimate analyses are presented for the hottest monitored summer day, i.e. July 29th, 2016. Most of the selected mitigation strategies were specifically designed to face summer overheating. Accordingly, previously reported results of the survey campaign showed that summer was the most uncomfortable season according to pedestrians crossing the case study passage area. Results were analyzed at two different times of the day, namely at 8:00 a.m. and at 2:00 p.m. However, maps representing the distribution of the assessed microclimate parameters in the area are reported only at 2:00 p.m.

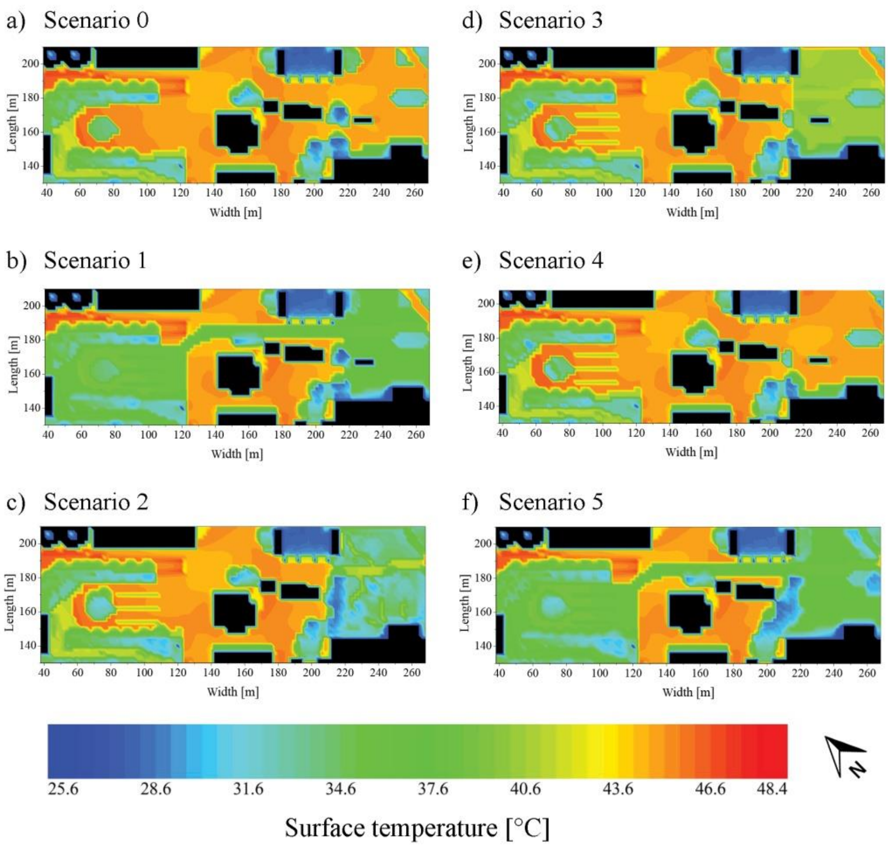


Figure 13. Surface temperature distribution in summer at 2:00 p.m.

Firstly, the distribution of surfaces temperatures within the area was analyzed. Figure 13 shows the distribution of surfaces temperatures at 2:00 p.m. for the current and the five mitigation scenarios. By analyzing the maps, it is possible to notice how the most advantageous configurations in terms of surface temperature were the green and combined scenarios (i.e. Scenario 2 and 5). Such scenarios generated a drop in the surface temperature, up to about 9°C and 20°C in the early morning and at midday (Figure 13c and f), respectively, compared to the reference configuration, i.e. Scenario 0 (Figure 13a). It is also possible to notice a decreasing of surface temperature when using cool coverings (Scenario 1). Such solution determined a reduction of the surface temperature with respect to the reference configuration up to 4°C at 8:00 a.m. and 10°C at 2:00 p.m. (Figure 13b). On the other hand, Scenario 3 showed a surface temperature reduction with respect to the reference configuration of about 2°C and 6°C, in the early morning and at midday (Figure 13d), respectively, while scenario 4 (Figures 13e) showed the same distribution in term of surface temperature of Scenario 0. As expected, the highest contribution of mitigation strategies in terms of surface temperature reduction was found when mostly required, i.e. at 2:00 p.m., which is the hottest time of the day.

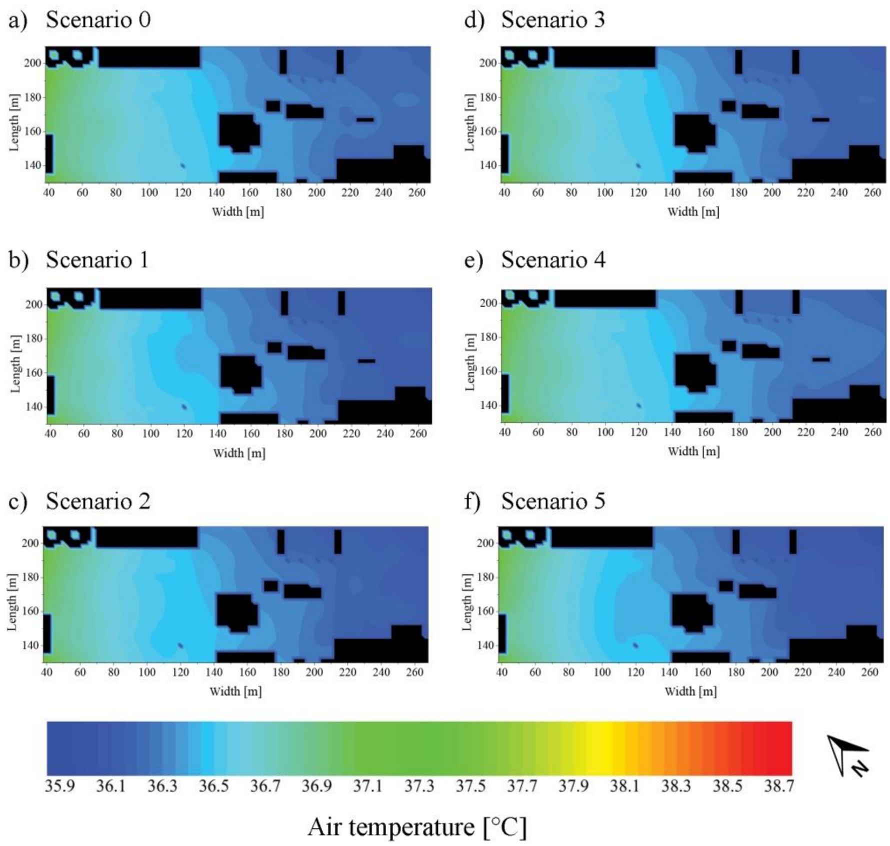


Figure 14. Air temperature distribution in summer at 2:00 p.m.

Figure 14 shows the distribution of air temperature at pedestrians' height, i.e. 1 m from the ground, in the same summer day at 2:00 p.m. Consistently with the previous results, Scenario 2 and 5 were the best performing in terms of overheating mitigation potential. In fact, at midday the increase of green areas generated a temperature decrease of up to 0.9°C (Figure 14c) compared to the current configuration of the case study urban area, i.e. Scenario 0 (Figure 14a), due to the passive shading of the underlying area and the active evapotranspiration from the added greenery. In the early morning, instead, the temperature reduction was slightly dampened up to 0.7°C with respect to Scenario 0. Moreover, Scenario 1 generated a reduction of the air temperature of about 0.2°C and 0.4°C at 8:00 a.m. and 2:00 p.m. (Figure 14b), respectively, compared to the reference scenario, thanks to the reduced solar absorptance of the paved surfaces. Again, Scenario 3 (Figures 14d) and Scenario 4 (Figures 14e) showed almost the same distribution of Scenario 0 in term of air temperature. This means that the selected renewable energy technologies, i.e. PV tech-trees and PV asphalt, which were not aimed directly at improving the environmental conditions of the area but at producing clean energy, did not have a negative effect in terms of local microclimate.

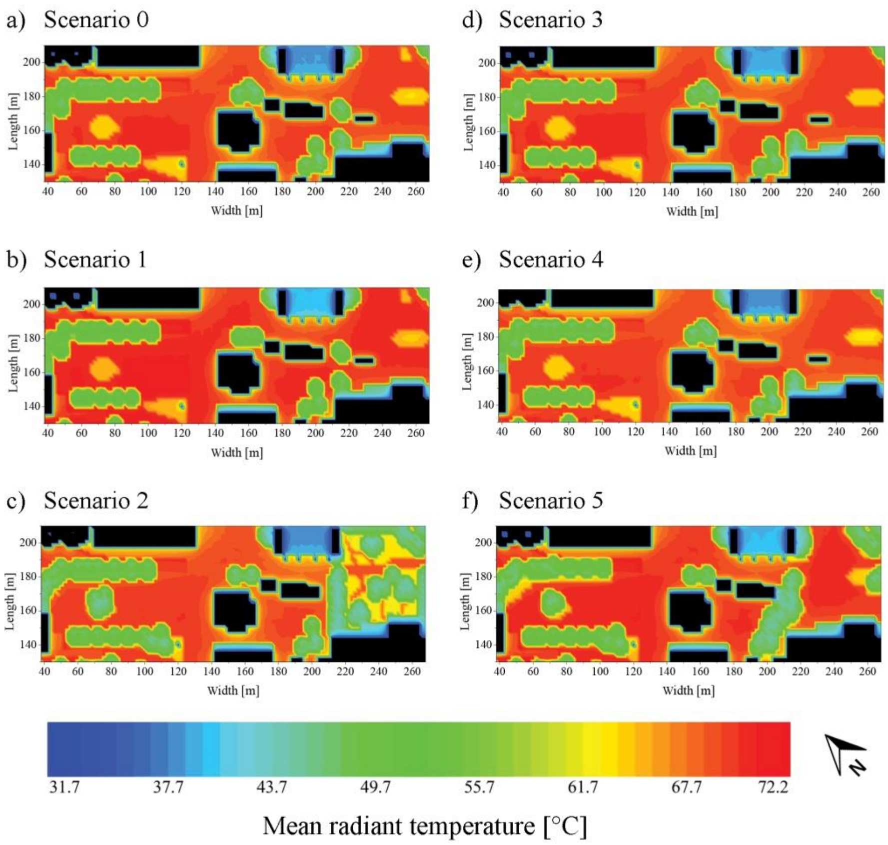


Figure 15. Mean radiant temperature distribution in summer at 2:00 p.m.

A third variable that significantly influences the thermal perception is the mean radiant temperature. Figure 15 shows that the configuration characterized by the highest values of mean radiant temperature was the scenario with cool materials, i.e. Scenario 1, where the mean radiant temperature increased up to 0.5°C at midday (Figure 15b) compared to Scenario 0 (Figure 15a). On the contrary, Scenario 2 (Figure 15c) and Scenario 5 (Figure 15f), where vegetation was increased within the area, showed a decrease of mean radiant temperature, especially in proximity of the green areas, up to more than 20°C with respect to the reference scenario. Finally, Scenario 3 (Figure 15d) and Scenario 4 (Figure 15e) presented again negligible differences compared to Scenario 0 (Figure 15a).

The wind speed distribution maps at 2:00 p.m. are shown in Figure 16. Low variations were noticed during the course of the day. Scenario 2 and 5, both characterized by a significant vegetated surface percentage, showed the lowest values even in terms of wind speed. The effect was perceived mainly in the area where trees are more densely concentrated, but also in the surrounding area. In fact, the presence of trees can modify, sometimes even considerably, the wind speed in a certain location, by obstructing its main directions. In this study, the difference between the configurations with and without the addition of greenery was up to 0.5 m/s (Figure 16c and f). Although mitigating high local flows, this air change reduction negatively affected the cooling off due to the increase of vegetation. Nevertheless, trees shading and cooling effect overtopped this phenomenon and provided more thermally comfortable conditions in summer.

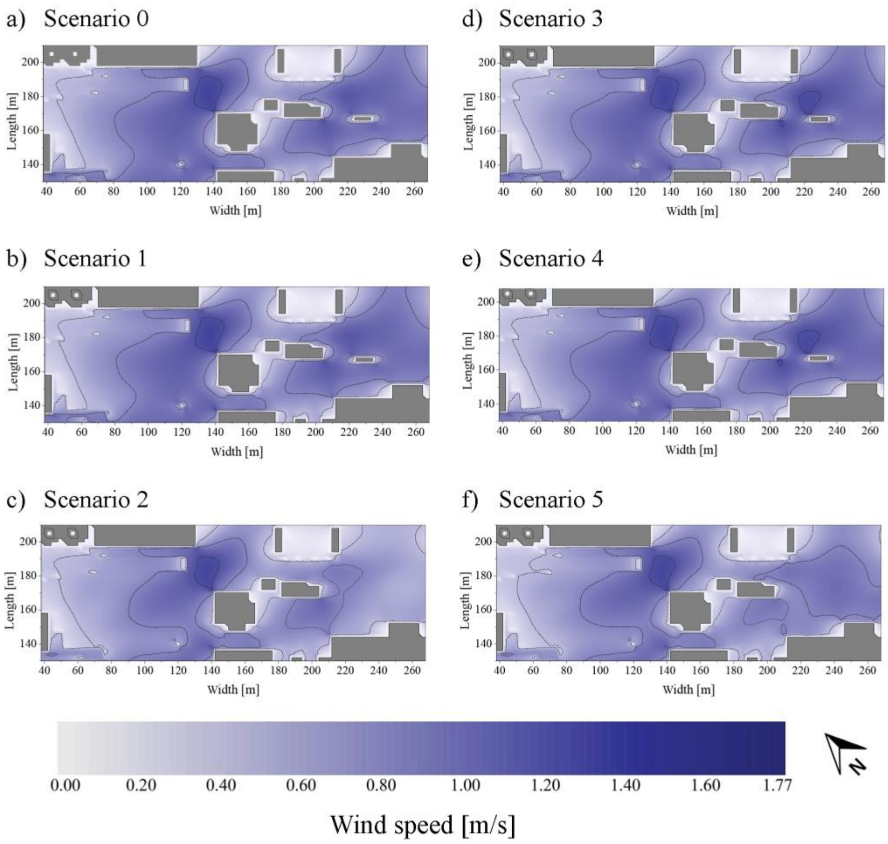


Figure 16. Wind speed distribution in summer at 2:00 p.m.

Finally, Figure 17 shows the distribution of air relative humidity at 2:00 p.m., whose trend is strictly correlated to the one of air temperature. Therefore, the configurations presenting the lowest air temperature values, i.e. Scenario 2 and 5 (Figures 17c and f), were those ones characterized by higher values of air relative humidity. In fact, in such scenarios the increase of surfaces covered by vegetation increased the air relative humidity, due to vegetation activity in terms of soil evaporation and plants transpiration phenomena. Nevertheless, discrepancies were mainly perceived in the early morning, due to nighttime activity, while all scenarios appeared similar at midday (Figure 20). Moreover, the relative humidity variation between the different scenarios appeared to be negligible, since differences were rather lower than 10 %. Accordingly, the increase of vegetation is expected not to affect the thermal comfort conditions in the area due to the occurrence of high relative humidity. The other scenarios presented no differences with respect to the reference Scenario 0.

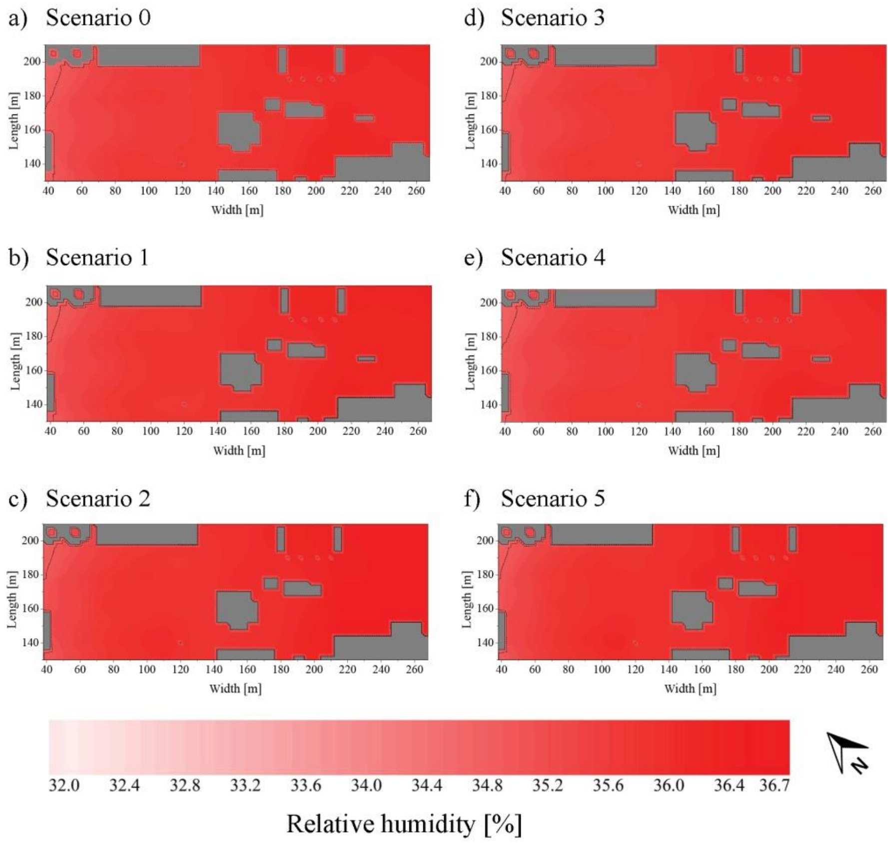


Figure 17. Air relative humidity distribution in summer at 2:00 p.m.

5.2.3. Microclimate analysis in winter

Although the study focuses on strategies for urban overheating mitigation, winter analyses were also carried out to assess possible year-round effects. Figure 18 reports the air temperature distribution in the case study area at 2:00 p.m. in a winter day, i.e. December 31st, 2015. Only the modeled scenarios involving local microclimate mitigation strategies were considered, i.e. Scenario 1, Scenario 2, and Scenario 5. The comparison against the reference scenario, namely Scenario 0, showed that differences in terms of outdoor air temperature were negligible. Similar results were found also for the other analyzed parameters. Therefore, no additional analysis are discussed concerning winter analysis results.

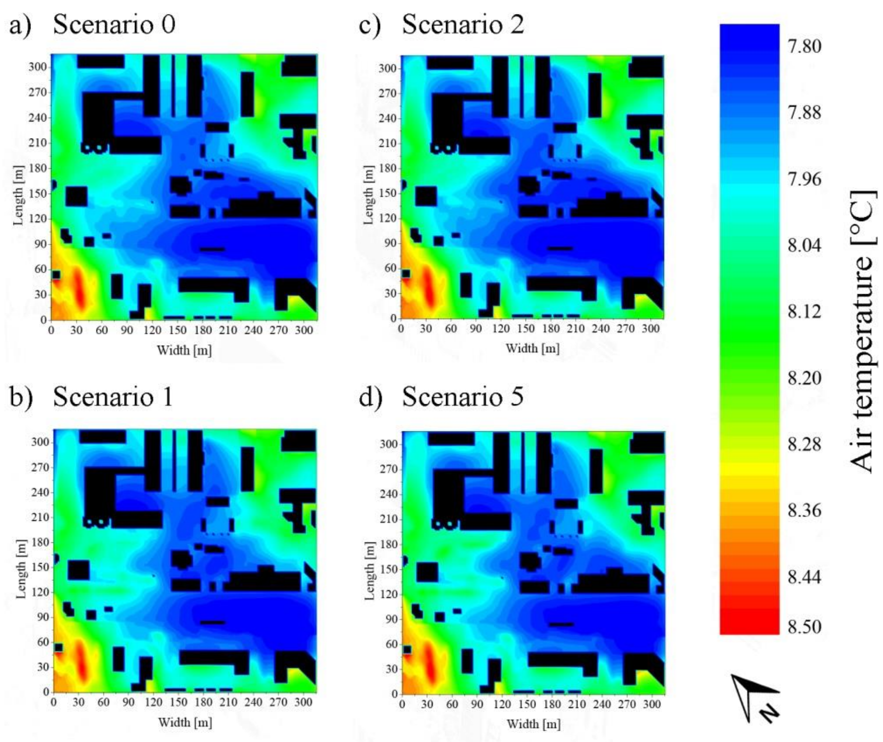


Figure 18. Air temperature distribution in winter at 2:00 p.m.

5.2.4. Outdoor thermal comfort assessment

Figures 19 and 20 depict the distribution of the analyzed thermal comfort indexes within the case study area at 2:00 p.m. in the considered summer day, i.e. July 29th, 2016, since negligible differences among the scenarios were found in winter. It can be notice how only the scenarios where additional vegetation was implemented (Scenario 2 and Scenario 5) experienced a decrease of both indexes, meaning more comfortable conditions. The effect in terms of PET reduction was mainly perceived at midday (Figure 19), when temperatures were generally higher in the whole case study area. On the contrary, MOCI variations at 2:00 p.m. (Figure 20) were shorter and significant mainly in confined areas. However, in the early morning the implementation of greenery allowed the neutralization of MOCI in those points, namely the achievement of thermally comfortable conditions for the pedestrians crossing the area. According to previous findings, the other mitigation scenarios did not present significant variations with respect to the reference scenario, i.e. Scenario 0 (Figure 19a and 20a).

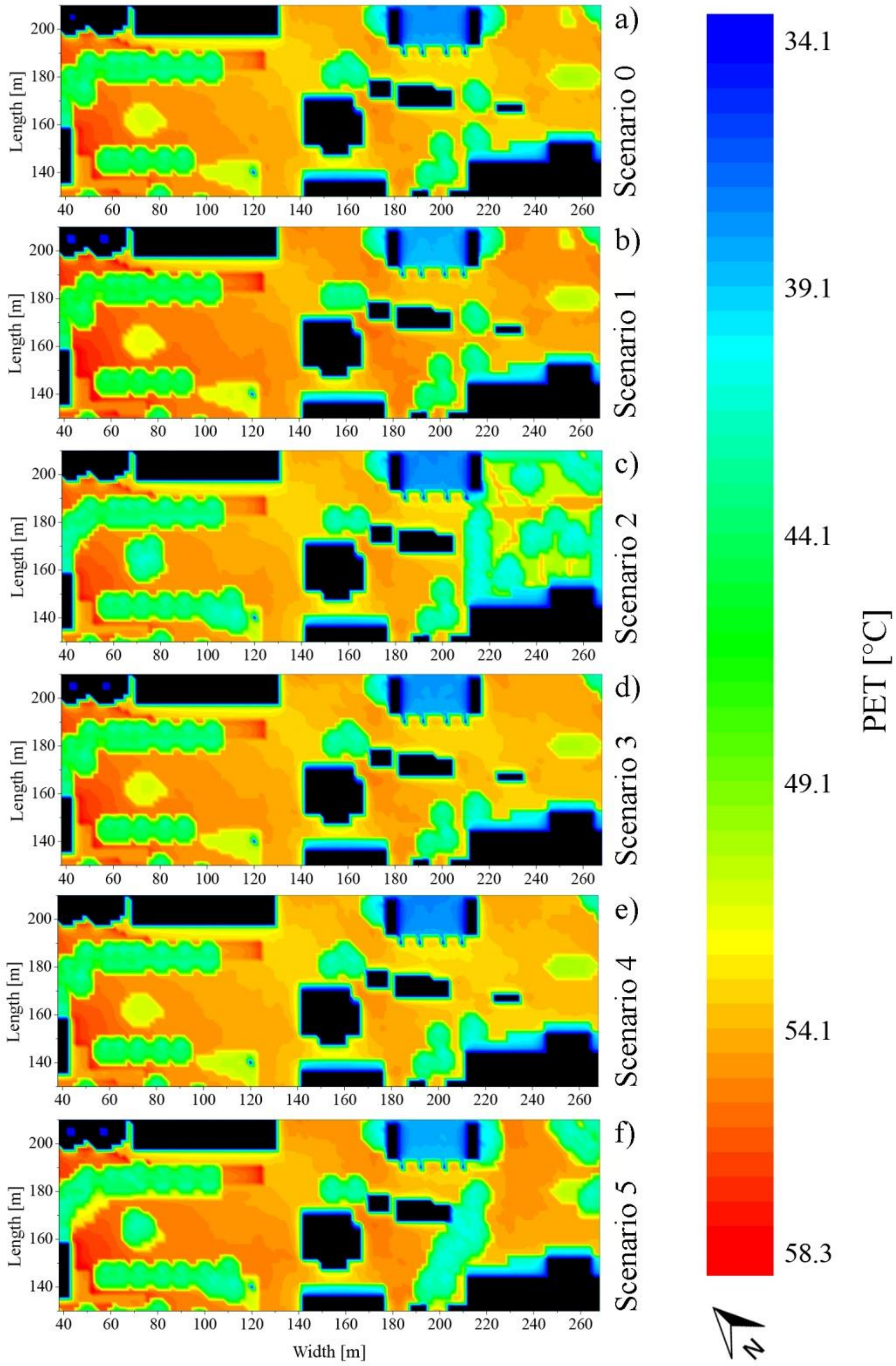


Figure 19. PET (Physiological Equivalent Temperature) distribution in summer at 2:00 p.m.

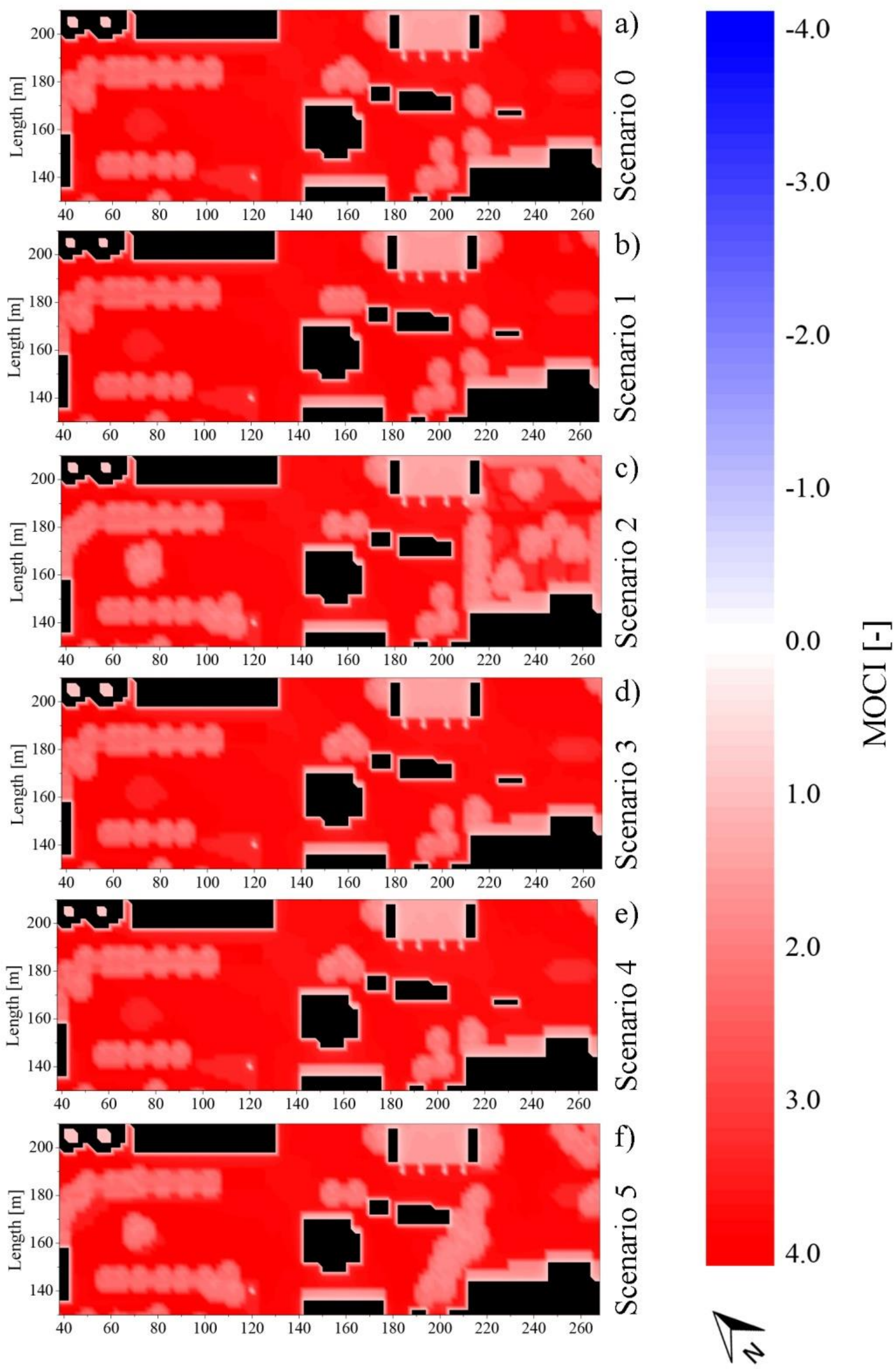


Figure 20. MOCI (Mediterranean Outdoor Comfort Index) distribution in summer at 2:00 p.m.

Based on the above-mentioned results of microclimate simulations, the implementation of additional greenery in the case study area appears to be the most performing strategy in mitigating summer overheating and, therefore, improving the travelling pedestrians comfort in terms of thermal conditions and air quality. Moreover, negligible penalties were observed in winter. Therefore, the most comfortable conditions are found in the green scenario, Scenario 2, and in the scenario combining all the considered strategies, Scenario 5, which provides also renewable energy production. In fact, the increment of shady zones and permeable surface and the active evapotranspiration from vegetation allow the decrease of air temperature, mean radiant temperature, surface temperature, and, therefore, the improvement of comfort indexes. Moreover, the added shady zones arrange sun-shelter areas for the travelling pedestrians. On the other hand, the improvements associated to the cool scenario, i.e. Scenario 1, are generally poor. This effect seems to be associated to the generation of convective phenomena that cause remixing between cold and hot air in the area. Moreover, the higher values of reflected radiation associated to cool materials negatively affect the mean radiant temperature close to the ground, which highly influences comfort indexes. Findings are consistent with the preferences expressed by the respondents in the survey, who mostly asked for the increment of green areas and vegetation in the case study area.

6. Conclusions and Future Developments

The present work analyzes the local microclimate and comfort conditions in outdoor pedestrians' passage areas within urban districts in temperate climates. In-situ monitoring campaigns, questionnaires to the travelling and moving pedestrians, and microclimate simulations, were carried out to assess their perception about the local microclimate conditions of the passage urban area. To this aim, the effects of selected mitigation strategies on outdoor thermal comfort and air quality perception were investigated. Particular attention was paid on the assessment of the influence of tailored microclimate mitigation strategies, i.e. implementation of vegetation and high albedo materials, for urban heat island mitigation.

Firstly, the in-situ monitoring of the main environmental parameters was performed. In the meantime, personal questioners were submitted to pedestrians, to investigate their perceptions about thermal comfort, noise pollution, and air pollution while crossing the case study area. Also, external and personal respondent's characteristics influencing their comfort conditions were evaluated. Therefore, six different scenarios of the case study passage area, i.e. current and mitigation scenarios, were simulated, based on the experimental campaigns. The comparison of all configurations was carried out in terms of outdoor microclimate parameters and outdoor thermal comfort index, namely PET and MOCI, in both summer and winter conditions.

Outcomes of the survey campaign among pedestrians, showed that participants find the air pollution and noise pollution in the case study area generally quite tolerable. However, local citizens were shown to be stricter about noise pollution and air pollution perception and tolerability, due to non-physical influences. On the contrary, in summer, around the 75% of respondents considered uncomfortable the thermal conditions, in particular in the central hours of the day, i.e. 12:00 p.m. - 2:00 p.m. Accordingly, citizens asked for a greener area, which is able to improve both the environmental conditions and the esthetical value of the urban passage area with a sudden perception for travelling pedestrians. The results of the numerical analysis were found to be consistent with such request. In fact, the scenarios with additional vegetated areas, i.e. Scenario 2, and the one combining all the mitigation and renewable energy production strategies, i.e. Scenario 5, are those ones providing the higher mitigation potential. The additional trees and green surfaces are able to decrease the air temperature up to about 1°C and the mean radiant temperature up to more than 20°C with respect to the reference scenario at midday in summer. Therefore, in such scenarios pedestrians comfort conditions are improved both in terms of PET, up to 15°C, and MOCI, up to discomfort neutralization in the areas characterized by greenery implementation. On the other hand, negligible penalties are found in winter. Future developments of this study may concern the enlargement of the scale of the analysis to include the major effects related to convection phenomena. In fact, natural convection typically generates the attenuation of the mitigation strategies effectiveness (in particular in the case of cool materials application). Moreover, longer simulations, from 24 h analysis to 72 h, could allow more accurate and reliable results. Finally, it would be appropriate to measure the impact of urban heat island effect in the case study area with respect to the surrounding areas.

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