Thermal Comfort and Microclimates in Open Spaces

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ABSTRACT

Microclimatic conditions in urban open spaces are characterized by the morphology of the urban pattern and by the properties of urban surfaces. In this paper a variety of ground surface materials and vegetation located in typical open spaces, in a historical city in central Italy (Ascoli Piceno), are examined in order to evaluate the influence of surfaces on the microclimatic variations of the study area. In street canyons, public places, and open spaces, the local microclimate depends directly on the physical properties of the surrounding surfaces and objects, producing well-known effects such as wind speed decrease, local jets, increased turbulence, or increased thermal loads. All these phenomena can greatly influence the comfort of a city or of pedestrians.

Urban climate assessment requires different methods, from numerical climate models that provide meteorological parameters, to a set of models that simulate the comfort level. The tools used in the simulation are the numerical microclimate model ENVI-met and the COMFA+ thermal model, which aim at calculating comfort conditions.

Several techniques based on bioclimatic architectural criteria and energy conservation principles have been analyzed in order to improve the microclimate in an outdoor space located in a typical Mediterranean area.

INTRODUCTION

There is a strong public interest in creating pleasant open spaces, and in this sense, thermal comfort is as important as acoustic or visual comfort. The liking and use of open spaces are influenced by the microclimatic conditions provided, whereas microclimate and thermal perception definitely depend on urban design and show a high temporal and spatial variation. The outdoor thermal environment, in fact, is impacted by the built environment, through anthropogenic heat (Ichinose et al. 1999), ground surface covering (Lin et al. 2007), evaporation and evapotranspiration of plants (Robitu et al. 2006), and shading by trees or constructed objects (Lin et al. 2010).

Moreover, the climate of the urban outside space influences a city's energy consumption, and the processes that create these climates are very complex. Therefore, the most precise way to calculate or assess the impact of changes is through numerical methods, although there already are several models that can deal with the complexity of urban structures and even take into account human thermal comfort.

The numerical model uses a numerical procedure to solve the conservation equations that govern airflow and heat transfer in an open space. It is a very powerful and efficient methodology of investigating temperature, flow fields, and comfort indices in outdoor urban spaces where many parameters are involved.

This complex thermal environment is relevant to human well-being and health due to a close relationship between thermoregulatory mechanism and circulatory system (Jendritzky et al. 1990). A complete application of thermal indices of the energy balance in the human body gives detailed information on the effect of the thermal environment on humans (VDI 1998).

In the literature, many thermal indices have been reported; common applications are the predicted mean vote (PMV), physiological equivalent temperature (PET)

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(Matzarakis et al. 1999), standard effective temperature (SET*) (Gagge et al. 1986), perceived temperature (Tinz and Jendritzky 2003) and thermal balance (TB, COMFA) (Brown and Gillespie 1986). All these thermal indices are well documented and include important meteorological and thermophysiological parameters (Matzarakis 2001a, 2001b). The advantage of these thermal indices is that they require the same meteorological input parameters: air temperature, air humidity, wind speed, and short- and long-wave radiation fluxes.

Calibration of these predictive models is necessary to verify their applicability in outdoor spaces. Usually, the calibration method adopted is experimental inductive (i.e., field research of microclimatic variables and subjective answers), and deductive with simulation of predictive models (Monteiro and Alucci 2006).

In this study, the COMFA+ model (a comfort evaluation tool) has been used for calibration purpose, because it has been assessed in an Italian urban area (Dessì 2007). This model is an upgrade of COMFA, a comfort evaluation tool based on the energy balance of a person in a given outdoor space, originally developed by Brown and Gillespie (1986) for landscape evaluation.

The city of Ascoli Piceno was chosen as case study because it represents a typical example of a medieval Mediterranean city located in central Italy (Marche region), characterized by long, hot summers and mild winters.

The investigations of this study are almost exclusively limited to the summer period (June to September) of a meteorological data series (1999–2008), because climatic heat stress in the urban open spaces mainly occurs during this season. Conversely, thermal cold stress only occurs in winter for a few days. This study analyzes the lower urban boundary layer where the interaction between different natural and artificial elements produces patterns of varying local climatic conditions, which are very sensitive to structural changes and proper use of materials, ground surface covering and vegetation.

An accurate analysis describes the microclimatic scenario of an existing central area in Ascoli Piceno. It is an urban restoration site that foresees two hypotheses of industrial refurbishment and reuse that are similar in their geometry and orientation, but differ in the use of materials and amount of vegetation.

The local atmospheric conditions have been simulated in ENVI-met and meteorological parameters measured in order to compare the results obtained with calculation results of COMFA+ model. Shading is critically important as an approach for trying to reach an acceptable thermal comfort level in a hot setting such as Ascoli Piceno during summer periods. Consequently, the combination of ENVI-met and COMFA+ model had been assessed to simulate the thermal performance of different external shading devices.

METHODS

Modeling Thermal Comfort Conditions in Outdoor Spaces

Fanger's (1972) equation applies to indoors and assumes comfort conditions. Solving this equation provides the predicted mean vote (PMV), defined as the corresponding thermal index. The PMV indicates comfort when it is around zero (–0.5 to +0.5). Deviation from zero is referred to as thermal stress and varies on a seven-point scale from –3 (cold stress) to +3 (heat stress). Jendritzky et al. (1990) subsequently modified the equation to take into account the complex outdoor radiation conditions, and this approach has increasingly been applied to outdoor conditions.

Efforts were made to use physiologically significant indices which derived from meteorological parameters, and different parameters have been developed to estimate thermal comfort and microclimates in open space. These indices were based either on single or multiple meteorological parameters such as equivalent temperature and wet-bulb temperature.

It is important to remember that outdoor thermal comfort is influenced not only by physiological response to highly variable microclimatic parameters, but also by psychological and cultural adaptation, which sets a wide range of environmental stimuli fluctuation to avoid thermal stress and discomfort. Therefore, there are many possibilities to get a certain value calculated by different parameters without having the same thermophysiological effect. Every climatic region has its own characteristics and meanings of an index. It has to be adjusted to the local situation and cannot be used globally.

In general, thermal indices can be classified in the following four groups (Scudo 2002):

- Empirical thermal indexes correlating only a few climatic parameters and usually elaborated for specific climates, such as the wind chill Index (Siple and Passel 1945) and discomfort index (Thom and Bosen 1959)
- Psycho-sociological-climatic indexes, correlating subjective perception (e.g., actual sensation vote, satisfaction indexes) of microclimatic variables and comfort index (Nikolopoulou et al. 2001)
- Energy balance equation indexes based on a two-node model of the human body and on the assessment of all relevant thermal climatic parameters, coupling the heat balance equation with a simplified model to evaluate Mean Radiant Temperature (Hoppe 1999)
- Energy balance equation based on a one-node model of the human body: perceived temperature (PT) model based on Fanger's (1972) equation plus an outdoor radiant evaluation model (Jendritzki et al. 1990): PVM index and COMfort FormulA-COMFA+ (Brown and Gillespie 1986; Dessì 2007) with a simplified radiant evaluation model

Table 1. Comfort Sensations and Energy Budget

Energy Budget	Sensation
TB < –150 W/m^2	Very cold
–150 W/m^2 < TB < –50 W/m^2	Cold
–50 W/m^2 < TB < 50 W/m^2	Hot
TB > 150 W/m^2	Very hot

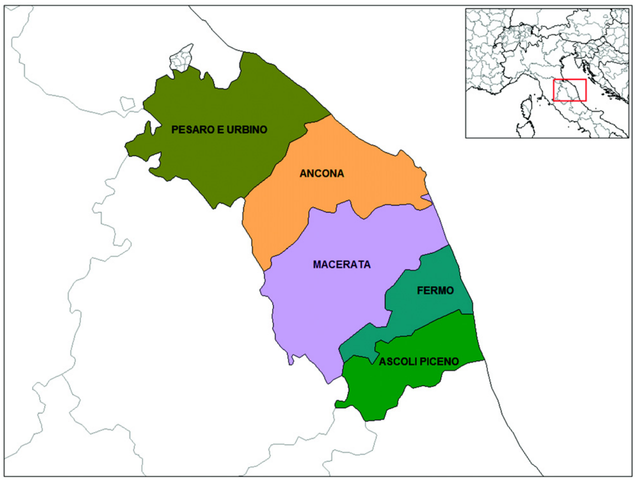

Figure 1 *Location of Ascoli Pieno in Italy.*

In this paper we will briefly review two models used to simulate thermal comfort conditions in outdoor spaces.

The first one is ENVI-met. It is a user-friendly tool that aims at reproducing the major processes in the atmosphere that affect the microclimate on a well-founded physical basis (i.e., the fundamental laws of fluid dynamics and thermodynamics). It is a three-dimensional nonhydrostatic model for the simulation of surface-plant-air interactions in urban environments. It is designed for microscale simulations with a typical horizontal resolution from 0.5 to 10 m and a typical time frame of 24 to 48 h, with a time step of 10 s at maximum. This resolution allows a fine reading of the microclimatic changes, especially sensible to urban geometry and relevant for comfort issues and analysis of small-scale interactions between individual buildings, surfaces, and plants. Vegetation is handled not only as a porous obstacle to wind and solar radiation, but also as a contributor of the physiological processes of evapotranspiration and photosynthesis. Various types of vegetation with specific properties can be used. The soil is also considered as a volume composed of several layers, and the ground can be of various types. The atmospheric model forecasts the evolution of the wind flow (speed and direction), turbulence, temperature, humidity, and short- and long-wave radiation fluxes.

The second model is the COMFA+ method. It is a comfort evaluation tool based on the energy balance of a person in a given outdoor space. It is one of the simplest models of

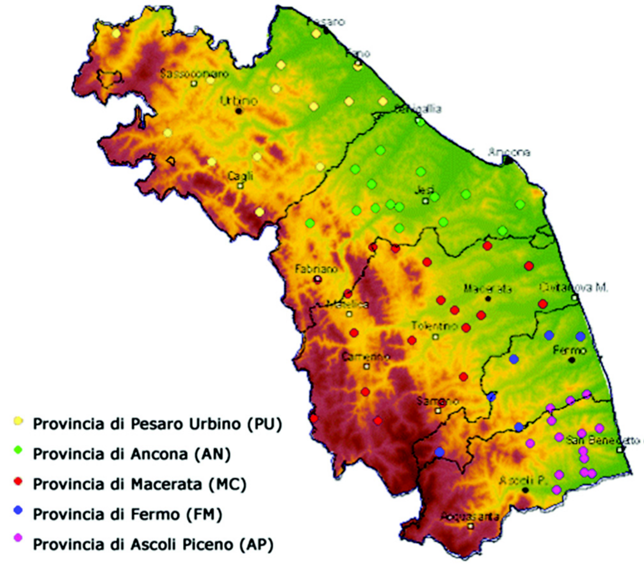

Figure 2 *Colored dots represent meteorological station positions.*

outdoor comfort evaluation, but also sensitive enough to the physical variations to mitigate microclimatic conditions.

The comfort feeling is evaluated through the value of the energy budget thermal balance (TB), which gives comfort conditions as a function of the “amount” of energetic exchanges between a person and the environment (Table 1).

COMFA+ can be used to assess the effects of the presence of vegetation in an urban space, local shading on the person, position of the person in relation to buildings, and albedo of paving materials. The model requires ambient air temperature, horizontal solar radiation, mean wind speed, relative humidity, surrounding ground surface temperature, the buildings’ view factors, their sunlit fraction, and their surface temperatures.

The simulations were carried out for Ascoli Piceno in the Marche region, a location in central Italy at 42°, 50'N, 13°, 37'E, and 154 m (505 ft) above sea level (Figure 1). The Marche climate is categorized as Mediterranean, with hot and humid summers and cool winters.

During the typical summer months (beginning in May and continuing through September), the air temperature T_a can reach 38°C, and the daily T_a amplitude can be relatively wide. The atmospheric moisture content sometimes reaches very high levels (RH = 70%). On the contrary, winters are short and cold, especially at night (reaching freezing point).

Living conditions during summer periods are becoming very difficult because of higher summer temperatures in recent years.

Weather data from 77 meteorological stations belonging to Agenzia Servizi Settore Agroalimentare Marche (ASSAM), shown in Figure 2, have been used to obtain daily and monthly mean values of the main meteorological param-

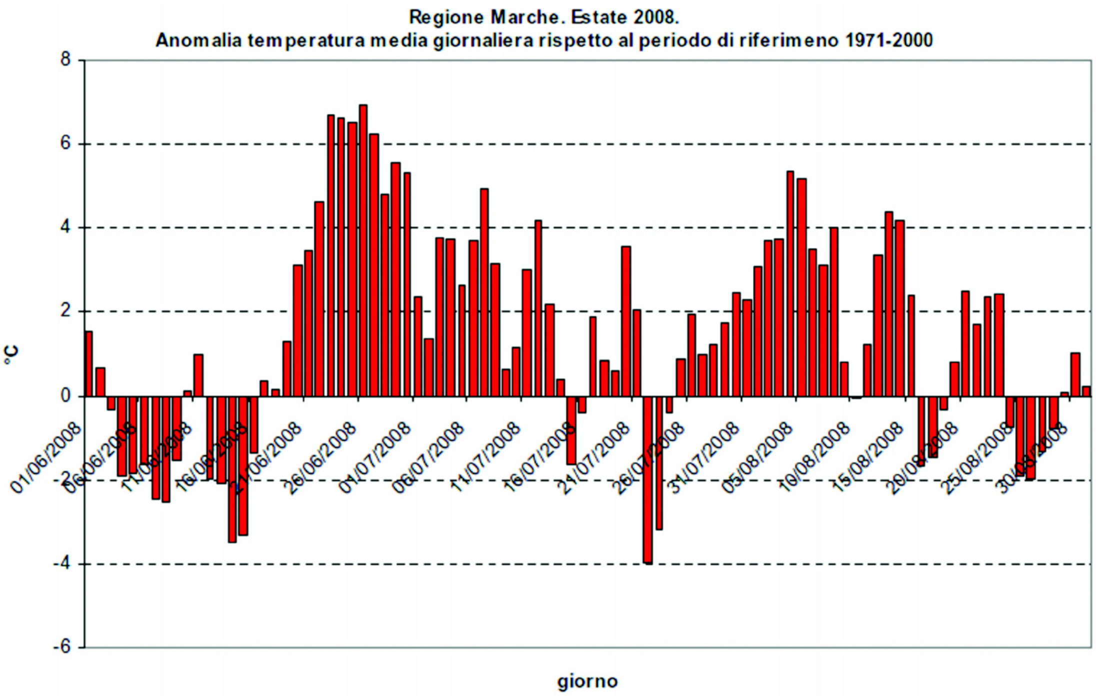

Figure 3 *Mean daily temperature anomalies.*

eters in summer months, to compare with climatic values from 1971–2000. The investigation was performed in the summer of 2008.

In the summer of 2008, the mean daily temperature anomalies showed a generally accentuated warming in the average conditions of July and August, according to the series data 1971–2000. The portion of the region that suffered the main warming was the Adriatic seaside, particularly the coasts of middle to lower Adriatic Sea, where the daily temperature anomalies reached +6 to +7°C with respect to the mean values of the period (Figure 3).

THE ENVI-COM+ UTILITY

The ENVI-COM+ utility is a simple Fortran90 code that aims to bridge information computed by the ENVI-met model dynamic model with the COMFA+ utility.

The COMFA model was originally proposed by Brown and Gillespie in 1995 with the aim of providing a swift comfort index in landscape areas based on a person thermal balance (TB). The TB has been calibrated to compare to a comfort evaluation scale.

The TB equation to be calculated is

$$\mathrm{TB} = M + K_{abs} + L_{abs} - (\mathrm{Conv} + \mathrm{Evap} + \mathrm{TR}_{emitted}) \quad (1)$$

The COMFA approach has been successively enhanced to the COMFA+ version presented by Angelotti et al. (2007), and adaptations to urban environment were introduced. More specifically, among the right-hand member contributions, those related to a person's energy production and loss need no particular examinations, because they are defined by means of well-known governing laws and may easily be found in Brown and Gillespie (1995). Conversely, the absorption terms are strongly affected by the presence of buildings, and every kind of obstacles in general that may be found in urban environments. So, in the enhanced version, they were redefined as follows:

$$K_{abs} = (1 - A_p)(T + D + S + R + B) \quad (2)$$

where A_p is the person's albedo, T is the beam solar radiation incident on the person, D is the diffuse solar radiation incident on the person, S is the diffuse solar radiation reflected by objects in the sky (trees), R is the solar radiation reflected on the person by the ground, and B is the diffuse solar radiation reflected by buildings.

$$L_{abs} = \varepsilon_p(V + G + F + U) \quad (3)$$

where

$$V = \mathrm{SVF}'\sigma\varepsilon_{sky}T_{sky}^4 \quad (4)$$

$$G = \mathrm{GVF}\sigma\varepsilon_g T_g^4 \quad (5)$$

$$F = \mathrm{OVF}\sigma\varepsilon_o T_o^4 \quad (6)$$

$$U = \Sigma_i \mathrm{BVF}_i \sigma\varepsilon_b T_{bi}^4 \quad (7)$$

From Equations 3 to 7, it appears evident that the core information in simulating urban scale radiation interaction is

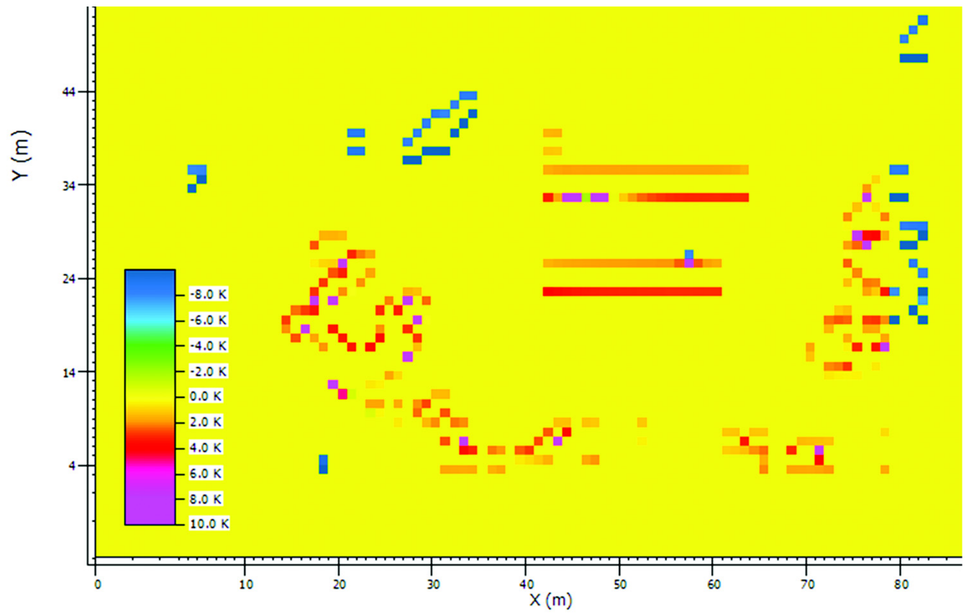

Figure 4 *Map of differential temperature over the south and north faces (Y surfaces) of buildings. The legend shows the temperature difference (in K) between asphalt and green versions of the square.*

the absolute temperature of in-view surface, and more specifically those related to ground, building, and the sky virtual surface (Scudo et al. 2007).

There are two possible approaches to this issue: temperatures can be measured and then representative data can be extrapolated by the observation series, or they can be estimated. In literature, these data are often estimated by means of an external model such as SOLENE (Antoine and Groleau 1998); our aim is to derive them from the ENVI-met simulation.

As previously mentioned, ENVI-met can estimate surface temperature, along with all the other microclimate parameters, for each finite element of the computational domain. All georeferenced data can be extrapolated using the Xtract utility, which results in a XYZ ASCII file. The simple format followed by the file is very common and it presents a very easy way for georeferencing. The coordinates reported are those related to the bottom left corner of each cell: this allows easy creation of an overlapping layer of information with respect to ENVI-met domain.

The ENVI-COM+ utility first launches a parsing routine, which is able to open and interpret ENVI-met output files and store data into a temporary memory.

In a different ASCII file, we have previously stored the coordinates of cells occupied by buildings. This is key information to retrieve the requested wall temperatures.

Successively, the CONFA+ TB equation was routinely solved for each node of the ENVI-met computational grid. The computation was performed for a specific, sufficiently sensitive portion of the domain (even the whole domain), for which the previously retrieved temperature was used.

In this way, the calculation was performed automatically for each point and an output ASCII table was written. Moreover, a referenced map of the comfort index, which is easily graphed with analysis software, can be represented, as in Figure 4.

An issue about the ENVI-met output is that currently the simplest way to obtain the temperature data, and others in the future, is to generate an extrapolation file with the Xtract tool. This implies an interactive phase in the data-flow with no batch approach. For the future, we foresee the possibility to access directly the binary data files produce by ENVI-met (.EDT) in order to extrapolate data within the ENVI-COM+ code.

DISCUSSION

Ascoli Piceno is a medieval town laying at the confluence of Tronto River with Castellano Creek, surrounded by mountains on three sides.

The study area is a central city zone, precisely a redevelopment area where a carbon and graphite industry was formerly located. The domain simulated is made of two long buildings (270 m and 240 m) with height of 15 m, separated by a large square of a constant width of 100 m.

The simulation was started preferably at 6:00 LST, when most atmospheric processes are slow and wind speed is very low (1.5 m/s), according to meteorological data.

Simulations were run during daytime hours, because that is the time of the day with regular, frequent use of outdoor spaces.

The first simulation needed was the calibration of the outdoor thermal comfort models (Figure 5). The procedure for calibrating the models was the following: each index was linguistically compared to seven values, as stated before, the

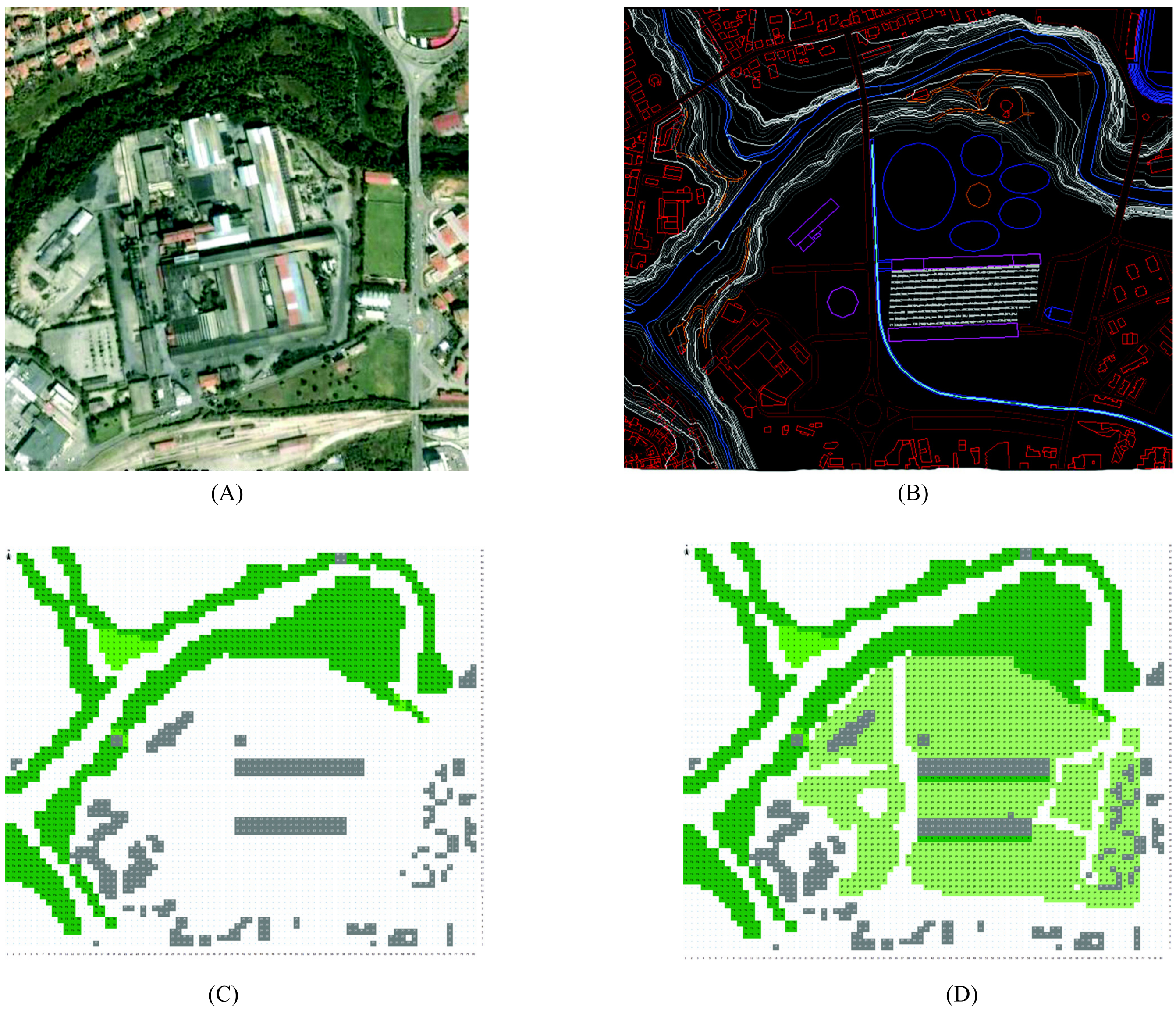

Figure 5 *Setup of first ENVI-met simulation in the study area: (a) aerial photography, (b) CAD map, (c) green area, and (d) asphalt area.*

same used in the field researches: three positive (warm, hot, very hot), three negative (cool, cold, very cold) and one of neutrality (Givoni et al. 2002). The calibration was done using the iterative method, changing the range limits of each index in order to maximize the correlation between its results and those found in literature and field researches, as indicated in Table 2 (RUROS 2004; Dessì 2007). The authors used the regression coefficients, derived for different climates, to calibrate the model minimizing the difference between predictions (simulations) (Monteiro et al. 2006).

For the ENVI-met simulations, the study area was transformed into a model grid measuring 80 × 68 × 20 cells with a resolution of 10 m ×10 m × 2 m, resulting in a total area of 800 m × 680 m in the horizontal extension (Figure 5).

Calculations were performed during the summer period, and two different scenarios (asphalt paved area and grassed open space) were considered

Figure 6 represents the ENVI-met output (PMV index) for the first simulated scenario (asphalt paving), and Figure 7 shows the calculated thermal comfort condition values for the 216 different considered points of the selected outdoor area in its existing situation (i.e., asphalt cement) using the COMFA+ method. From these color maps can be observed the high values for thermal balance (TB) index and for PMV index in all points, resulting in quite poor thermal comfort conditions (very hot).

Similarly, for the second simulated scenario (i.e. lawn grass), color maps in Figures 8 and 9 show lower values for TB

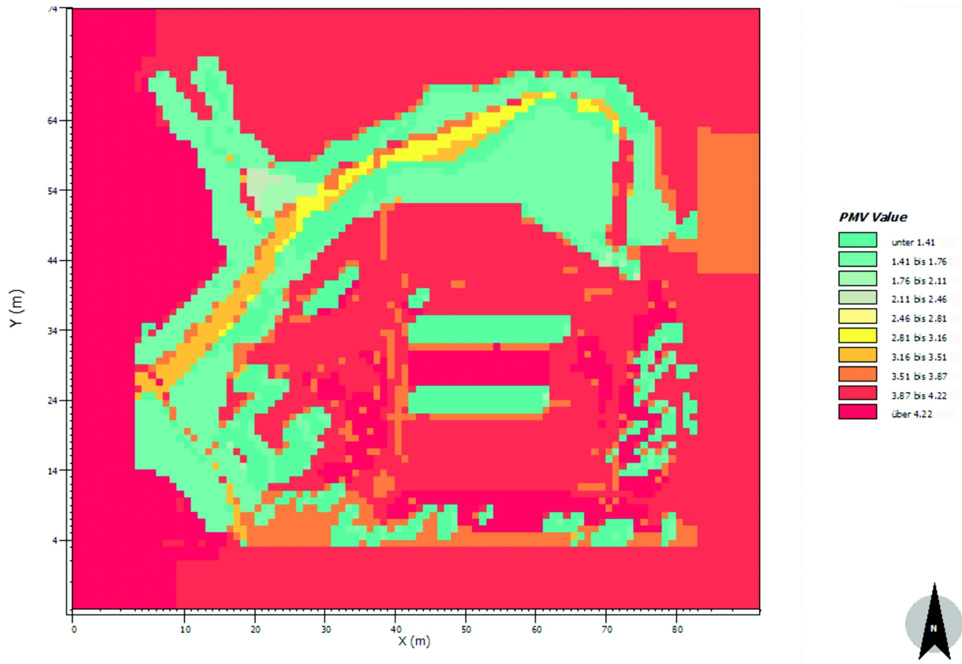

Figure 6 *Map of PMV index (ENVI-met simulation) for asphalt paving scenario.*

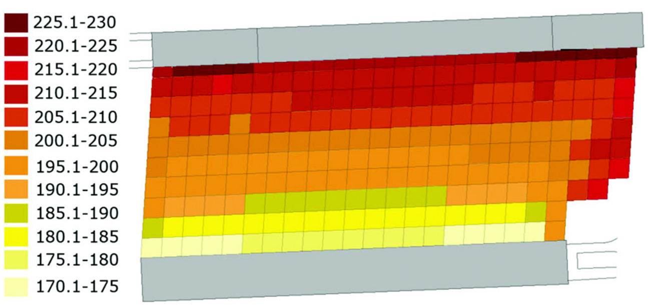

Figure 7 *Map of thermal balance (TB) index (COMFA method) for asphalt paving scenario.*

Table 2. Predicted Mean Vote (PMV) Index Calibrated and Thermal Budget (BT- COMFA) Index Calibrated

SENSATION	PMV calibration	TB COMFA calibration
Very hot	>3.6	>170
Hot	1.3/3.6	70/170
Warm	0.6/1.3	30/70
Neutral	–0.9/–0.6	–23/30
Cool	–1.5/–0.9	–55/–23
Cold	–3.5/–1.5	–125/–65
Very cold	<–3.5	<–125

and PMV indices in all points, resulting in a hot thermal sensation (not comfort conditions).

A quantitative comparison of two scenarios is represented by the difference plot (Figure 10).

Finally, after calibration procedures, an alternative scenario was proposed in order to improve microclimate and specifically thermal comfort conditions. The main devices used to improve microclimate in outdoor spaces were shading devices and pergolas with deciduous plants, to achieve solar control during the summer period.

The ENVI-COM+ tool was used to automatically investigate the effects of the proposed variations on the basis of the environmental parameters previously simulated.

Figure 11 shows the thermal comfort conditions values calculated for the 209 different points of the selected outdoor space considered and when the third scenario was applied using thermal budget (TB) and COMFA methods. From this map it can be seen that thermal comfort was significantly improved in the third scenario.

As shown, the thermal comfort conditions values calculated using ENVI-COM+ tool are remarkably lower than those of the first scenario. The thermal comfort conditions were improved in the last scenario. This is mainly caused by the existence of shading devices as well as by the use of materials with high emissivity and reflectivity values.

CONCLUSION

In this paper, the problem of bioclimatic design of a restoration intervention has been considered. In order to evaluate the effectiveness of different design choices, several prognostic techniques have been applied and compared. Specifically, the ENVI-met model and the COMFA+ method have been

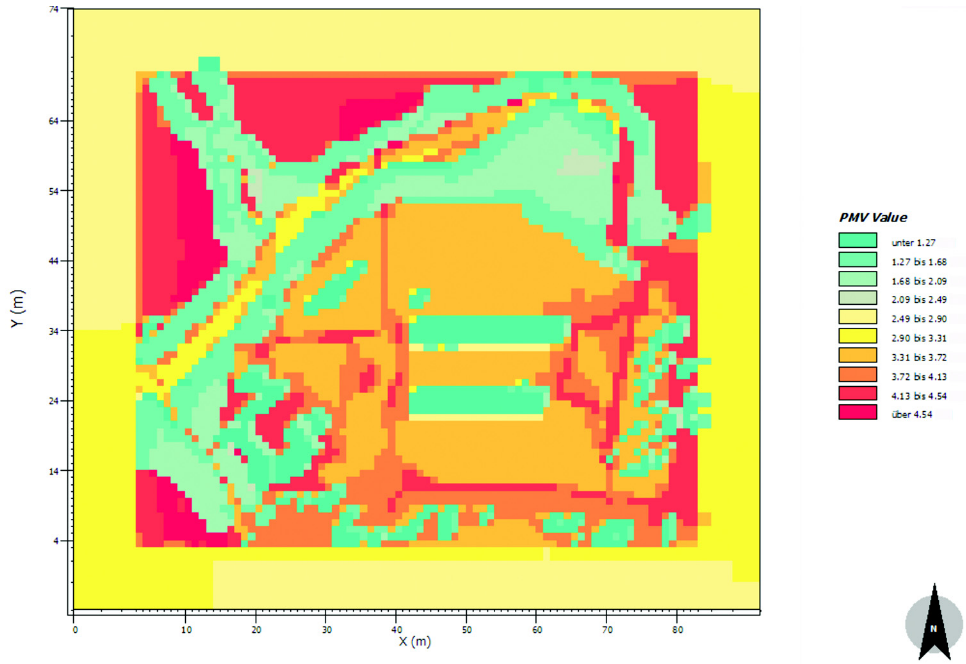

Figure 8 *Map of PMV index (ENVI-met simulation) for lawn grass scenario.*

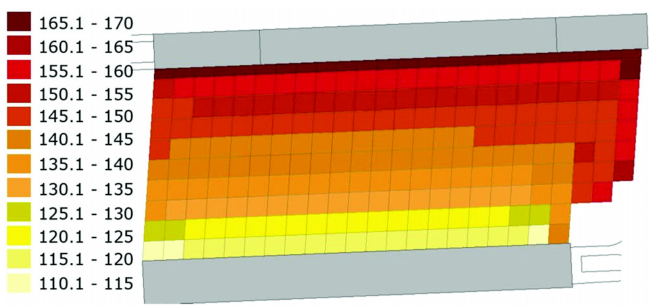

Figure 9 *Map of thermal balance (TB) index (COMFA method) for lawn grass scenario.*

examined and a new tool has been developed, named ENVI-COM+, aiming both to automate the calculation process in a steady approach such as the COMFA and to improve the simulation coherence. The last point has been achieved by introducing to the COMFA model an input parameter (namely wall temperatures), simulated by the ENVI-met, instead of estimating them by means of an external model.

A comparison has been possible since a calibration of the different indices (PMV and TB) used has been previously set up. From the comparison of the two approaches, a general consistency is evident, although the TB index seems to be more sensitive to the variation of environment radiation. This observation leads to consideration of the proposed model chain as a very interesting integration in simulating urban environment.

Simulations show how different paving materials affect local comfort, and greener solutions seem to perform even better than expected. Furthermore, designing of green surfaces seems to be insufficient to achieve an acceptable comfort sensation without further protection from solar radiation. The introduction of shading devices such as pergolas or trees determines a strong enhancement of local comfort.

NOMENCLATURE

M = net metabolic rate

K_{abs} = solar radiation absorbed

L_{abs} = thermal radiation absorbed

Conv = heat lost by convection

Evap = heat lost by evaporation

$TR_{emitted}$ = emitted thermal radiation

ε = emissivity

T = absolute temperature.

σ = Stefan-Boltzmann constant

SVF' = sky view factor

GVF = ground view factor

OVF = object view factor

BVF = buildings view factor

Subscripts

p = person

bi = i-building

sky = related to sky

g = ground

o = object

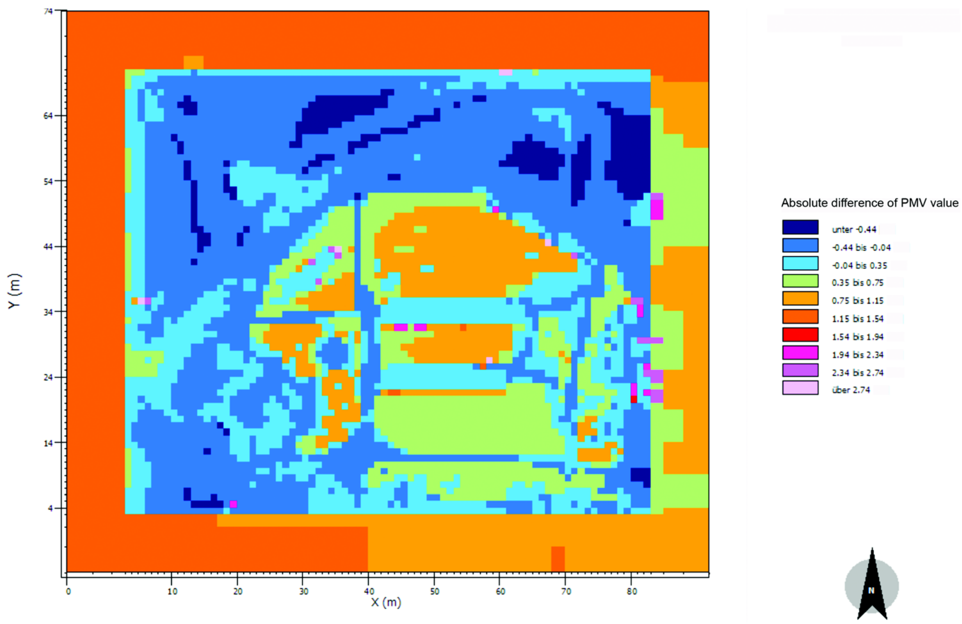

Figure 10 *Absolute difference of PMV values.*

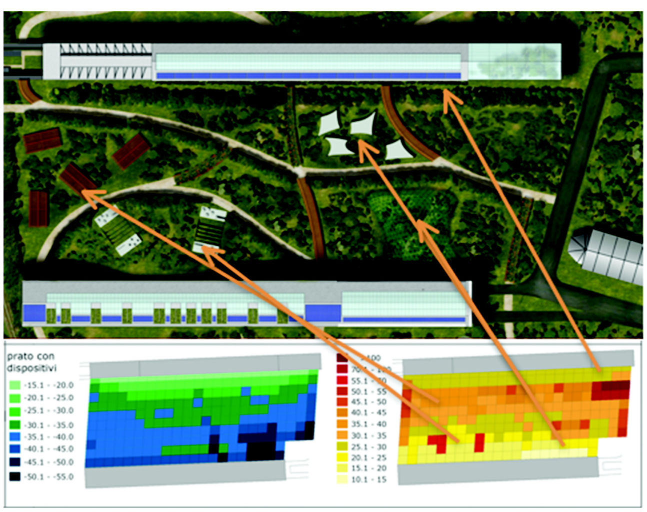

Figure 11 *Map of thermal balance (TB) index (COMFA method) for third scenario.*

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