A MODEL FOR PROGRAMMING DESIGN INTERVENTIONS AIMED AT REDUCING THERMAL DISCOMFORT IN URBAN OPEN SPACES:

A Case Study on the Politecnico di Milano Campus

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ABSTRACT

The environmental quality of urban spaces is strongly related to the thermal comfort perceived by people in open areas. At the micro-scale of neighbourhoods, the mitigation of the heat island effect can improve both the well-being of city-users in the public realm and the energy performance of buildings. A model intended for urban designers is presented, and it sets out to evaluate critical areas in the city context and define sustainable design solutions and concrete actions on the physical environment, in order to increase thermal comfort. In particular, variables used in the model are basically related to urban geometry, such as the accessibility of sunlight, sky view factors, aspect ratios of street canyons, and to the physical materials in the city, such as the albedo of horizontal and vertical surfaces and vegetation density. The technique is based on the use of algorithms defined in a Matlab environment and derived from image processing of Digital Elevation Models (DEMs) of the urban texture.

The application was tested on the case study of the Politecnico di Milano's main campus, located in the city of Milan. Especially in the case of limited resources, the results of the analysis suggest how public administrators and decision-makers could benefit from programming specific site interventions, based on the identification of critical weaknesses emerging at several points in the city. Moreover, the study focuses on the application of cool surfaces, the role of building layout (shape and size) and the effects of increasing the vegetation. Even in the absence of expensive thermal imagery from remote sensing, but simply referring to available cartography, this low-cost technique makes it possible to very quickly set up feasible environmental strategies over extensive urban areas. Furthermore, this tool proves to be useful for existing urban areas, as well as for simulating the impact of new design schemes.

KEYWORDS

thermal comfort, urban heat island, cool surfaces, Digital Elevation Models, environmental quality.

INTRODUCTION

Italian cities are currently becoming more and more crowded due to human activities and increased built-up spaces. This uncontrolled growth generates conditions that are difficult to manage without the help of techniques and behaviour aimed at preventing and reducing this phenomenon. Urban heat islands are formed under a combination of different conditions and therefore there is no unambiguous and absolute solution for reducing their effect. The study of the urban heat island makes it possible to link problems related to urban comfort and quality of environment architectural and urban design, by encouraging experimentation with new technologies and materials in order to reduce this negative phenomenon and improve living conditions in the cities. In fact, the generation of urban heat island generally coincides with densely built-up metropolitan areas where new technologies and materials coincide with the existing street network and buildings.

Even if the most effective solution in reducing the presence of 'urban heat islands' is that of increasing green areas, planted with trees if possible, it is also true that this is not always practicable, and it

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is therefore necessary to study alternative strategies acting on different variables. The research undertaken at the Politecnico di Milano deals with this subject starting from the identification of both the factors affecting the phenomenon occurring and its consequences on the environment (up to the urban and peri-urban scale) and goes as far as the formulation of proposals that could reduce the temperatures of the heat island.

1. RESEARCH CONTEXT

The Environmental Protection Agency (EPA, year 1992) uses the term 'heat island' to refer to temperatures of the air and urban areas that are higher than that of the surrounding rural areas. An 'Urban Heat Island' is a metropolitan area at significantly higher temperatures than the rural (or at least less built-up) areas that surround it (figure 1). The difference in temperature varies from 2 to 6 °C. This phenomenon generally occurs in urban environments, where the continuous increase in the population and human modification processes on the territory result in a contemporary variation of environmental conditions, especially temperature. Oke (1982) defines it as "[...] a transient feature of urban areas, usually nocturnal, where the urban surface and near surface air temperatures are warmer than at their surroundings."

It then uses the same term to indicate as contemporary a geographical area, a dome of heat and a phenomenon of increased temperatures related to urbanized areas. A heat island is formed by a layer of air that is located over the city, at a height of 3 to 5 times that of the buildings (Givoni, 1998) and the extent of which is defined by meteorological, geographical, urban and anthropogenic factors (Giriharam et al., 2004). This portion of atmosphere is denominated 'boundary level and corresponds to the layer of urban influence and it is subsequently divided into sub-layers that introduce different characteristics; the layer closest to the earth's surface is called the UCL (Urban Canopy Layer) and it extends from the earth's surface to the height of the tops of the buildings. The UCL belongs to the 'roughness layer that is the layer of atmosphere in which the movement of air is directly influenced by the morphology of the urban fabric, and thus its volumetric conformation (disposition, density, height, and proportion of the elements).

A key aspect of climatic studies on urban territory is the understanding of the relationships in place between morphological aspects and environmental conditions and the determination of the dimensional scale on which they act. An urban heat island has repercussions both on the external temperatures and on those inside buildings. If it is therefore seen as the general energy balance of an urban area there is also need to consider the degree to which this phenomenon affects energy consumption in relation to air-conditioning systems. The development of the urban heat island is substantially influenced by two types of variables: environmental variables of the urban surroundings and urban morphology, as shown in Figure 1.

Environmental variables:

- Climatic conditions and geographical location
- transit of atmospheric turbulences
- heat produced by anthropic activities
- greenhouse effect related to urban areas
- percentage of evaporation–transpiring surfaces

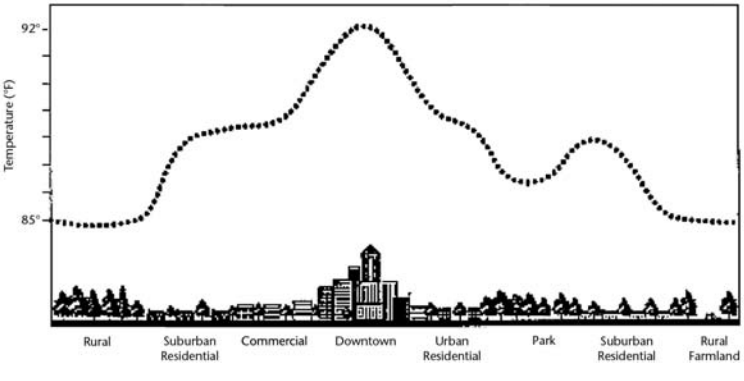


FIGURE 1. Profile of a heat urban island (source: EPA 1992).

Urban Design:

- urban morphology (roughness layer)
- dimension of the city, building and housing density, index of growth of the population (Mitchell 1953 and Oke 1973)
- proportion between building height and related distance (h_e/W_e)
- canyon effect (canyon irradiative geometry)
- part of visible sky (sky view factor or SVF, Oke 1981)
- material thermal properties (emissivity, power absorption, albedo, SRI)

The previous point is one of the key factors taken into account for the purposes of our case study, as particularly dense and dark materials have a strong impact on UHI, when vegetation is very sparse.

Cement and asphalt, which are widely used in metropolitan areas, have high thermal conductivity (therefore the ability to store and to release heat), high heat and high radiation capacity.

Since construction materials are generally impermeable, their thermal properties do not vary significantly. Nevertheless, it is possible to make some distinctions. Materials used for external surfaces are generally thick, solid and in contact with other solid materials. They present a superficial layer that separates them from the external environment and can be classified on the basis of their resistance.

Most of the thermal exchanges affect this layer that has limited volume and high heat capacity, it is necessary to factor this into account when evaluating the environmental conditions and comfort of an urban area. One way that this could be applied could be the use of pavements that are able to reflect short wave solar radiation and do not store heat. These are called 'Cool Pavements due to their ability to remain relatively cold, while at the same time guaranteeing the level of comfort, a substantial saving in the use of energy (electricity for conditioning plants) and an improvement in the quality of the air and water.

They have the following characteristics and composition:

- Permeability: they favour the drainage of water.
- In some cases (rubbery floors), they contribute to reducing noise.
- The ability to reflect (high albedo): they reflect short waves and they guarantee a relative increase in light levels, even at night.

The advantages produced by the use of cold floors substantially concern:

- The improvement of the quality of the air: Porous floors act as a filter for the substances contained in the air.
- The reduction of the noise produced by urban traffic: Porous floors absorb a good part of the sound waves.
- The increase of the safety level on the roads: Porous floors drain water and reflective floors provide a good level of passive illumination even at night due to the presence of light colours.

The albedo value of a material depends not only on the colour but also on the type of exposure to solar radiation and, not least, on the degree of wear. The same design strategy can be applied to cool roofs, checking the degree of insulation, shape and orientation of the building.

TABLE 1. Suggested causes of canopy layer Urban Heat Island [12].

Energy balance term	Urban features	Urban effect
Increased K*	Canyon geometry	Increased surface area and multiple reflection
Increased $L\downarrow_{sky}$	Air pollution	Greater absorption and re-emission
Decreased L*	Canyon geometry	Reduced sky view factor
Q_F	Buildings & traffic	Direct addition of heat
Increased ΔQ_S	Construction materials	Increased thermal admittance
Decreased Q_E	Construction materials	Increased water-proofing
Decreased (Q_H+Q_E)	Canyon geometry	Reduced wind speed

2. THE CASE STUDY OF THE CITY OF MILAN

The urban fabric of Milan is densely built-up and based on a nineteenth-century urban design scheme characterised by large, regular and compact urban blocks. From a climatic point of view, Milan is situated in the Padana lowland (closed to north by the Alps and to south by the Apennines) that predominantly experiences continental temperatures. The metropolitan region is characterized by poor ventilation rates (both seasonal and daily wind flows) and scarce influences from other regions due to sea basins and mountains. Both the limited variations of natural ventilation rates and the almost stable climatic conditions make the city of Milan an ideal case study for an analysis of urban heat island generation.

From an analysis of temperature trends over the year 2005 provided by ARPA (the Regional Agency for the Environment and protection in Lombardy), the phenomenon of the urban heat island over the Lombard capital city clearly emerges. Figures 2a and 2b show how clearly the heat island phenomenon is highlighted for the Capital city of Lombardy below show hourly values for air temperatures recorded on the warmest days of the year during the month of June. By comparing the temperatures in a suburban and low density built-up area (Park) with two central urban zones (Brera and Piazzale Zavattari) a typical pattern for an urban heat island is outlined:

- In the morning the urban and rural temperatures are nearly identical, in line with the indications to be found in scientific literature. This underlines a tendency to faster heating up of areas with a high density of vegetation, due to their thermal characteristics and direct exposure to the sun. In the urban context, however, the presence of large areas of shade instead results in a delay in the accumulation of heat.
- In the afternoon and after sunset, rural areas release the accumulated heat more quickly, while the city shows a tendency to delay this process. It is possible to obtain peaks with variations in temperatures of the order of 2 to 5 °C, after 9 pm. In some cases the urban fabric does not succeed in releasing a large part of this accumulated heat, which results in an accumulation of heat that surpasses the daily limits. This means that the heat is accumulated day by day.
- During the winter season temperature trends for the heat island do not appear as evidently as in summer. On the coldest day of the year (December 30, 2005) (Figure 2 c) a substantial difference in temperature was recorded with peaks of 6 degree differences between the city and countryside. In fact, the urban fabric was hotter during the night and during the early hours of the morning, even though this cycle could not immediately be detected on the days that followed.

It is important to underline the necessity of concentrating our efforts on the summer heat island, since by really mitigating the temperatures on the warmest days it is possible to get a meaningful energy saving. The winter heat island does not itself determine any additional energy expenses, on the contrary, it contributes to improving energy savings for buildings. In the cold season, nevertheless, overheating of the urban atmosphere has extensive implications regarding the quality of the air and the entrapment of polluting substances in the lowest layers of the air. The area considered for the analysis is a square 600 meters wide in the city of Milan, Italy (figure 3a). The site includes Campus Leonardo, i.e. the main campus of the Politecnico di Milano, and the Pytis characterized by the presence of a large number of isolated buildings and a high vegetation density (especially trees along streets and in the main park). Extensive horizontal surfaces are paved with asphalt (mainly roads and extensive parking lots).

3. CONSTRUCTION OF THE MODEL

3.1. Aims of the model

The principal objective of the model is to provide designers and urban planners with a quick. simplified tool for evaluating and establishing the parameters for works on the built-up environment with the aim to mitigate the urban heat island. It is important to state that the model cannot predict temperature trends, but it represents a qualitative tool intended for recognizing critical zones and obtaining maps of thermal discomfort on a neighbourhood scale at different daily intervals. In fact, this work stops

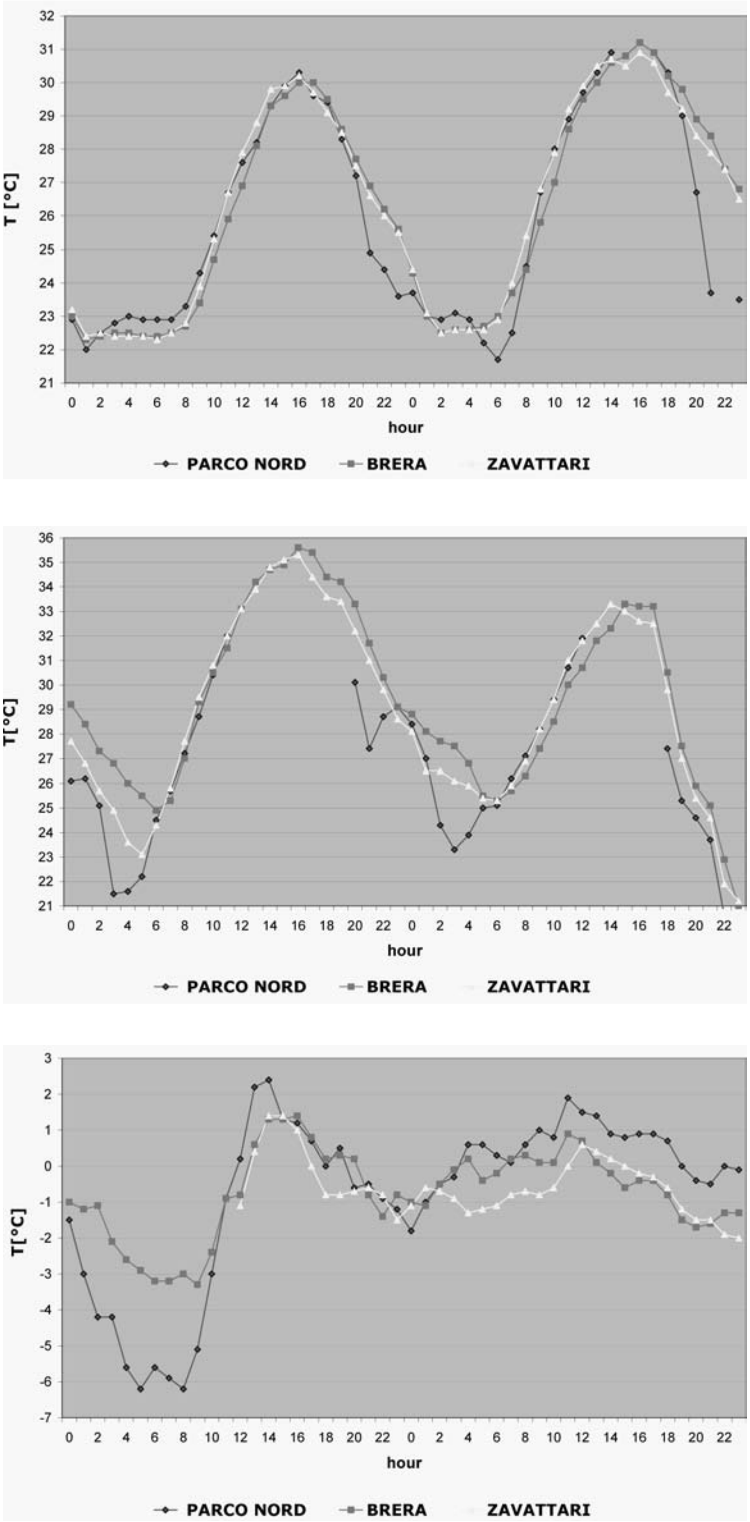


FIGURE 2. Hourly course of the recorded temperatures in three meteorological stations in Milan, in some days of interest in 2005; from the the top: (a) 20 and 21 June , (b) 28 and 29 June and (c) 30 and 31 December.

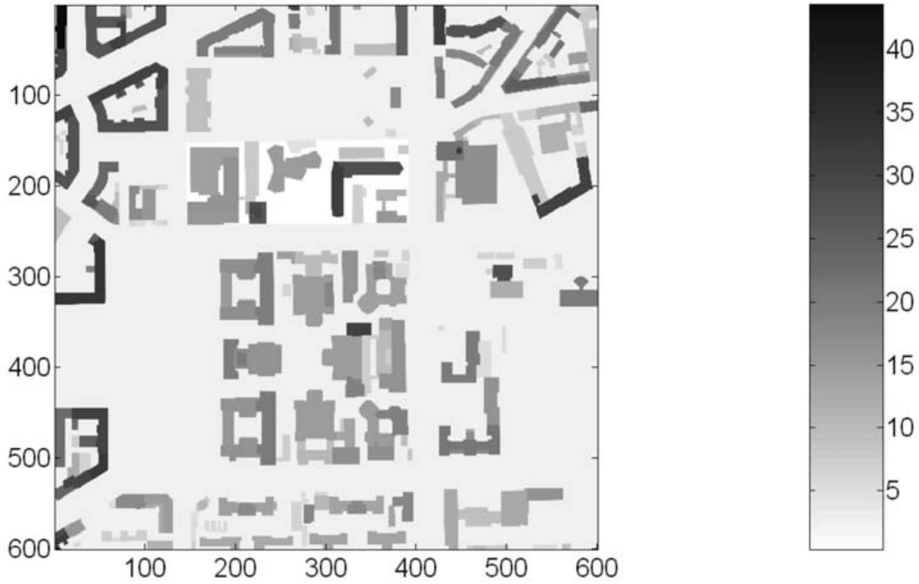


FIGURE 3. a) Above, the Orthophoto of the Politecnico di Milano main Campus in Milan, Italy (Source: CTR Comune di Milano); b) Below, the corresponding DEM.

short of taking into account the majority of complex parameters involved in thermal exchanges over the city, like heat gains and losses, anthropometric contributions, traffic, dispersal of pollutants, etc.. We concentrate only on those variables that are part of the design tool kit.

3.2. The technique

The technique employed for simulating the urban fabric is based on the use of digital images that reproduce the volumes of the city on a two-dimensional support. These raster images are known as Digital Elevation Models (DEMs), and are stored in bitmap format. The different intensity values of pixels represent the heights of the buildings. We can represent the highest building in black, the lowest levels, usually taken as street level in white (see figure 3b). This technique was and introduced in geographical and military studies and only was only first adopted for urbanistic and environmental studies a few years ago, thanks to the increasing availability of remote sensing imagery and 3-D information of cities on go-browser mash-ups, and technologies involving possible Pioneers in the use of image processing techniques used to analyse environmental indicators and the morphology of DEMs in a group of researchers at Cambridge University (Ratti, 2001; Ratti and Richens, 2004; Ratti, Baker, Steemers, 2005).

In particular, the DEM can be obtained from remote sensing imagery (often from LIDAR data) or from digital cartography (reconstruction using CAD software Computer Aided Design). In the absence of LIDAR data for the analysed area we used cartography to build the 3-D model. Even if this information is lacking in terms of minor details on the real physical world that often differs from the official, digital database, it still offers an adequate resolution for the purposes of this work and allows quick, low-cost implementation. In fact, by using cartography directly, we can easily separate buildings and vegetation in the model. For instance, the use of LIDAR data implies sophisticated techniques of interpolation and object recognition to obtain the DEM from the original dataset. In the future, with the increasing availability of remote sensing data and developments in the resolution of images and reconstruction techniques for urban models, this data will represent the first source for the technique presented.

Once the DEM has been processed, created, and stored in bit-map format (8 bit/canal, 256 colours), it is possible to apply specific algorithms developed for image processing in the *Matlab* environment; this can be done using the Matlab calculation. The image containing the area can be processed and 2-D array, using calculation for the purposes of the model itself. Basic algorithms used in the model include some shadow casting functions based on solar geometry (Ratti 2001, Ratti and Richens, 2004), and morphological calculations. The main advantage of the technique is the simplicity of the input data: by entering just one single image it is possible to process it from several points of view and obtain numerous results.

3.3. The variables considered in the model

As outlined above, the purpose of the model is to express critical zones of thermal discomfort during summer days and as a function of some characteristic and indicators related to urban planning. In this project macro groups are considered: Morphological variables: sky view factor, direct solar radiation, aspect ratios of street canyons and forms. Variables related to urban materials: albedo of the horizontal and vertical surfaces. Vegetation density, refer to Table 2.

TABLE 2. Variables considered in the model.

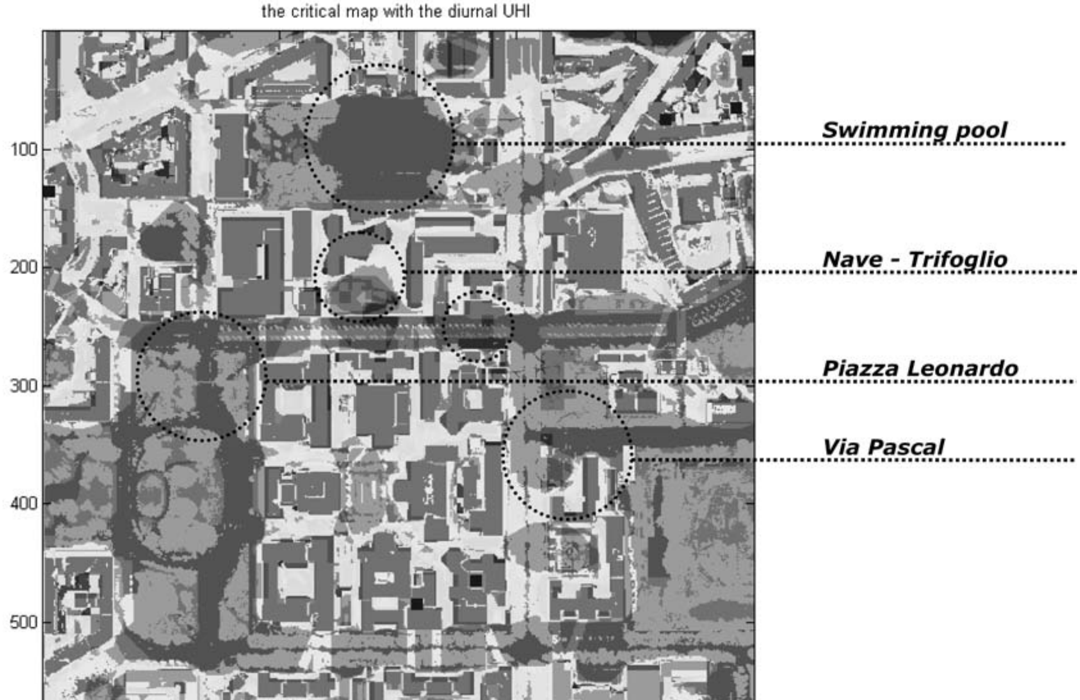
		Variables considered for the thermal discomfort during day time	**Variables considered for the thermal discomfort during night time**
Morphological variables	Direct sunlight—hours of sun and of shadow	X	
	Diffuse daylight—sky view factor	X	X
	Aspect ratio of street canyons—height to width ratio of street canyons	X	X
Variables related to urban materials	Horizontal surfaces albedos—albedos of roofs and pavements	X	
	Vertical surfaces albedos—albedos of façades	X	
	Vegetation density—presence of lawns and trees	X	

4. RESULTS AND APPLICATION OF THE MODEL TO THE POLITECNICO DI MILANO CAMPUS

In figure 4 areas of possible discomfort resulting from the synthetic diurnal map are highlighted. Places reveal different deficits for various reasons: some areas do not have enough vegetation, some have surfaces that are too dark, others are just exposed to sunlight during the day for too long or, on the contrary, are characterized by too narrow street canyons that are unable to release the irradiance collected overnight. From the emergence of critical areas on the campus, we want to define site specific strategies in order to achieve a general improvement in relation to the thermal conditions of the larger urban surroundings. Our belief is that even with limited resources it is important to act on those areas that can generate peaks in the urban heat island.

In order to finalize our study toward a concrete response in terms of urban design, we selected one of those areas and proposed a design solution according to the output indicators. In particular, the selected site is a parking lot inside the campus that works as a sunken plaza and is in fact a great heat accumulator during the hot season (figures 5 and 6). Furthermore, it has a low vegetation index and its urban surfaces are basically asphalt on the ground, while the main facades of nearby buildings are covered in dark ceramic tiles. This site does not offer the possibility of radical transformation, because the area still has to be designated as a parking lot and not much vegetation can be added. Moreover, building façades cannot be changed, since they are considered relevant examples of modern architecture. Hence, we can mainly work on increasing the albedo values of horizontal surfaces by replacing existing materials with cool surfaces. The proposal redesigns the parking lot in a more functional way, adding more vegetation without losing precious parking spaces (figure 5). For all horizontal surfaces we propose two alternative solutions.

FIGURE 4. Emerging critical subareas around and inside the Politecnico di Milano campus.



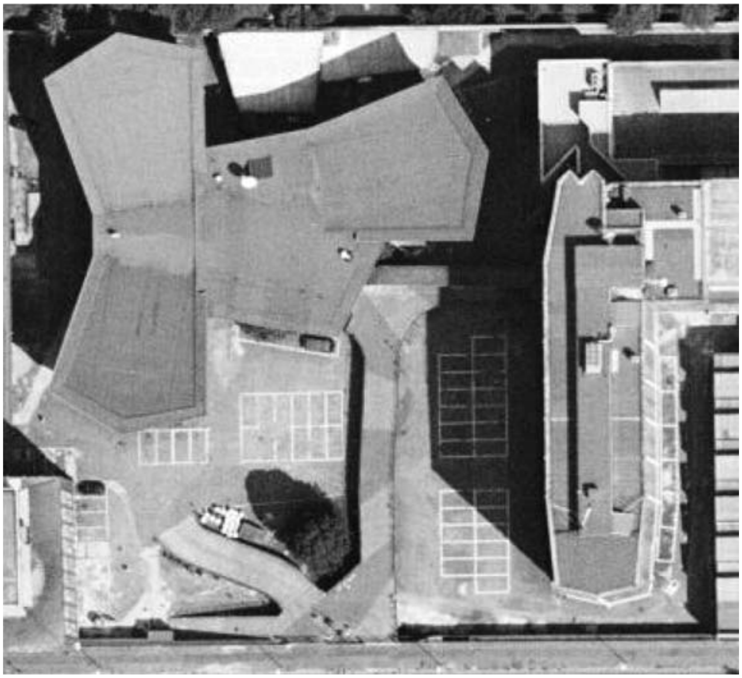


FIGURE 5. Areal view of the subarea with the parking lot on the Politecnico Campus. See the scarce presence of vegetation and the prevailing gray, asphalt surfaces and dark roofs.

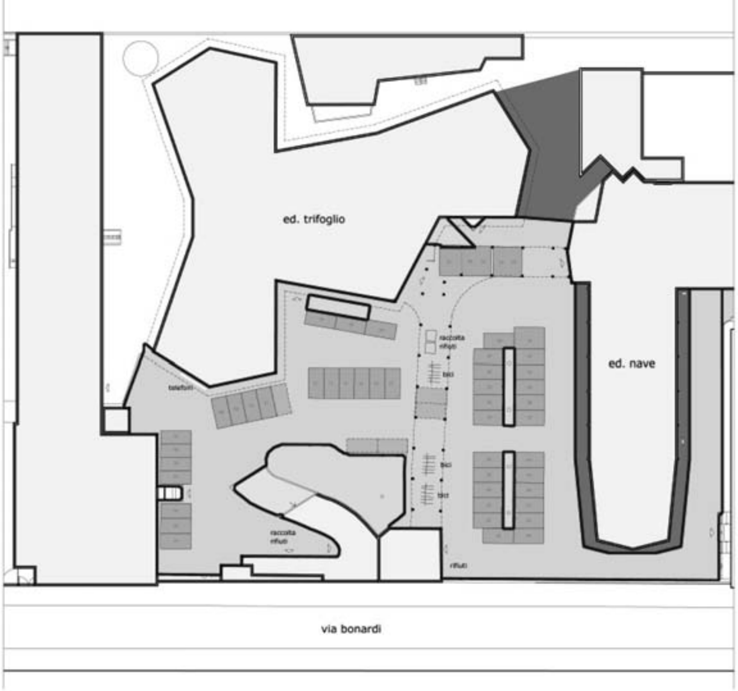


FIGURE 6. The present layout of the subarea with the parking lot on the Politecnico Campus.

FIGURE 7. The design scheme proposed on the parking lot inside the Politecnico Campus.

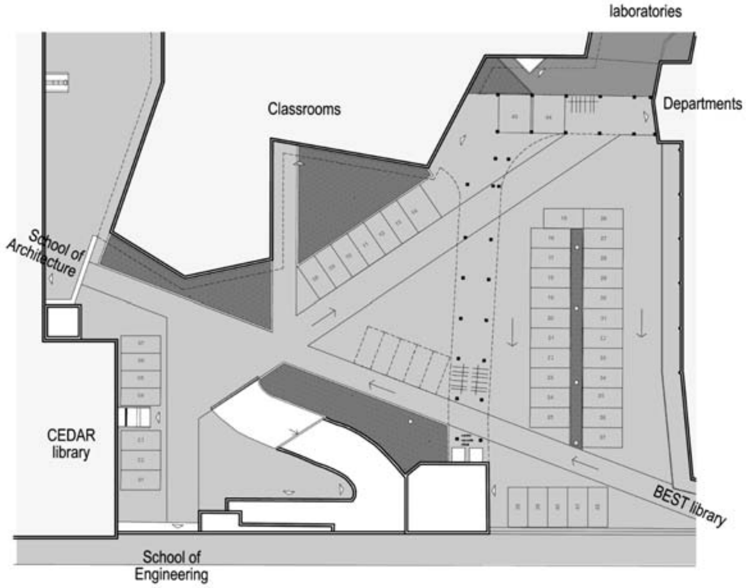
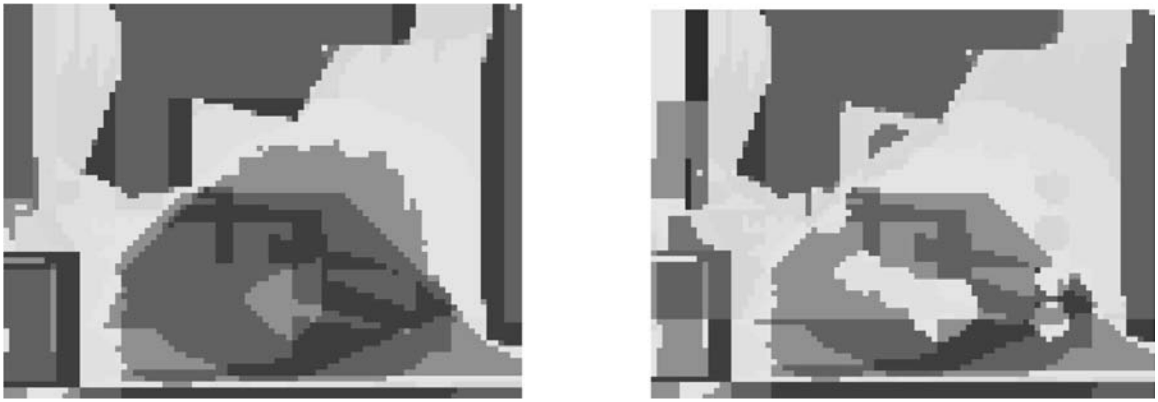


FIGURE 8. Left: present critical map of thermal discomfort; Right: the improvement with the proposed design scheme.



The first option is to completely remove the existing asphalt layer and substitute it with concrete tiles that have upper photo-catalytic cement finishing able to increase the albedo and capture pollutants. As an alternative solution, we propose simply covering the entire paved area with photo-catalytic paint, which acts as a cool surface as well. On roofs the same paint finish can be applied as an overlay to black bituminous membranes. As shown in figure 8, the renovation scheme decreases critical peaks on the sub-area of the parking lot and this should correspond to a parallel decrease in the temperatures during the summer season. A temperature monitoring campaign before and after the work is done should validate the results.

5. CONCLUSION

The model makes it possible to locate critical zones inside the case-study area and propose consequent design strategies for improving each zone in terms of thermal comfort. The tool proves to be a quick, low-cost, accurate vehicle for programming specific works for the city. For instance, starting from very simple cartography and some information on urban materials, it is possible to run this model.

The model still has to be improved with a richer database of intervention strategies and a more sophisticated agenda indicating all quantities and a rough estimate of expenses. Future work should validate the model, moving from qualitative maps to quantitative maps specifying temperature differentials between urban areas and rural sites. The validation of the model through thermal images or a temperature monitoring campaign will make it possible to correlate the variables implemented to the actual temperatures recorded. Finally, the use of the proposed tool is suitable not only for the analysis of the existing urban fabric, but also to assess the impact of design schemes on the thermal behaviour of its physical context.

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