The high-resolution computer models and the information system in the heat balance of the city

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Abstract. The definition of principles, criteria and basic models to be used in energy planning is a scientific and technological perspective promising, because it leads to a general reflection on the assessment of the quality of urban environments and their production and functioning processes. A city becomes more sustainable if it reduces the consumption of resources and the production of waste (its "ecological footprint"), but at the same time improves its vitality, quality and livability. In this context, it is fundamental to carry out a mapping of the territory that can emphasize the changes in the urban environment, especially in terms of energy consumption. Therefore it is necessary to develop new computer methods for analyzing and monitoring useful for the choice of strategies and actions to obtain a careful planning. From this point of view, a complete analysis in the urban environment can be accomplished through GIS technologies which allow performing a real screening on a territorial level and through the software ENVI-met, that is a three-dimensional computer model designed to analyze the small scale interactions between urban design and the microclimate. The objectives of the research were therefore the analysis of the urban fabric and the simulation of a number of scenarios in order to develop strategic actions for the prevention of urban environmental damage and environmentally friendly technologies for process and product of the city components (buildings and open spaces) in relation to diseases of thermal pollution and diseases of the large urban settlements.

Keywords. Urban Heat Island, Energy evaluation, Urban Spaces, Building Heritage

1. Introduction

Several urban environmental problems are directly related to the cities climate and to the global warming. One of these is the emission of the artificial heat generated by the combustion of hydrocarbons for transports and for the industrial and domestic use (heating and air conditioning systems, refrigerators, etc.). During the summer season in the big cities located in the middle latitudes, the contribution of anthropogenic heat is of the order of 10-20 watts per square meter, equal to the 5-10% of the incident solar energy. This surplus, apparently modest, is actually able to raise up of one degree the temperature of a medium size metropolis. This is evident just looking at the trend of the summer average temperatures in the city of Bari. The results are also dangerous by the health point of view.

The temperatures increase is a result not only of the global atmospheric warming (IPCC 2007), but also of the way in which our cities are built. Several morphological elements, including the streets width, the buildings height, the impermeable surfaces, the aspect ratio, the sky view factor, the green areas are really important for the city energy balance. Since this reason, the need of urban expansion models based on technical and scientific criteria and objective and measurable thermal considerations, focusing on buildings, blocks, districts and cities, becomes significant.
2. Methods

The building heritage of a city is too difficult to study in its details because of its extent. So, the applied methodology uses Gis (Geographic Information System) to give a better understanding of parameters necessary for the analysis of the urban area in terms of energy and environment. Heating of the city causes the “urban heat island”, a phenomenon that needs extensive and accurate analysis tools. Gis allows a territorial mapping of building characteristics that are necessary to obtain useful input data for other software like ENVI-met.

2.1. The use of ArcGis: a territorial mapping of buildings geometric characteristics [1]

ArcGis is a platform for designing and managing solutions through the application of geographic knowledge. It allows to make spatial analysis and obtain many results. [2]

Gis represents real objects with digital data that can be divided into raster images and vectors.

A raster data type is any type of digital image represented by reducible and enlargeable grids. Raster data type consists of rows and columns of cells, with each cell storing a single value. The smallest individual grid unit is the pixel; its size is closely related to the precision of the data. The resolution of the raster data set is its cell width in ground units.

The raster data type will reflect a digitized abstraction of reality. In raster datasets, the informations are associated with each unique value of a raster cell through the attributes. Additional values recorded for each cell may be a discrete value, a continuous value or a null value if no data is available.

Aerial photos are one commonly used form of raster data. Additional raster datasets used by a Gis will contain information regarding elevation, a digital elevation model, etc.

Moreover in a GIS, geographical features are often expressed as vectors (points, lines, polygons), by considering those features as geometrical shapes. Each of these geometries are linked to a row in a database that describes their attributes. Through this information, it is possible to create a map to describe a particular attribute of the dataset.

Both types of data are referenced in the Universal Transverse Mercator (UTM) WGS84 geographic coordinate system. It uses a 2-dimensional Cartesian coordinate system to give locations on the surface of the Earth. [3]

Figure 1. UTM Grid System and the location of Italy.
UTM is a projected coordinate system that divides the world into sixty north and south zones, six-degrees wide and uses a secant transverse Mercator projection in each zone. It can map a region of large north-south extent with low distortion. Each zone is segmented into twenty latitude bands. Each latitude band is eight-degrees high, and is named with alphabetic letters. The combination of a zone and a latitude band defines a grid zone: Italy is located in zone 32 – 33 – 34 and latitude bands are T and S.

The creation of ArcGis database is a way to analyze the urban fabric. At first, historical data attributes can be associated to each buildings to obtain a map that classifies buildings according to their period of construction [4]. Through this information, it is possible to assign particular transmittance value to each building envelope component. This values increase according to the age of buildings.

Secondly, the attributes of buildings geometric characteristics, like area, perimeter and number of the floors, allow obtaining the surface area to volume ratio (S/V) by Gis. It is an important factor determining heat losses and gains. S/V ratio means ratio between heat loss area and volume and it is a characteristic element because expresses building geometric type immediately. In fact, a low rise building has higher S/V ratio value than a tower building.

So, small S/V ratios imply minimum heat gain and minimum heat loss. A compact shape is desirable to minimize the losses and gains through the fabric of a building.

Climatic effect of this parameter is very important. In hot dry climates S/V ratio should be as low as possible as this would minimize heat gain. In cold-dry climates also S/V ratios should be as low as possible to minimize heat losses. In warm-humid climates the prime concern is creating airy spaces. This might not necessarily minimize the S/V ratio. Further, the materials of construction should be such that they do not store heat.

The factors of the external environment that influence heat transfer through the building envelope are: temperature of ground; air with which the building envelope is in contact, the direction and speed of winds blowing at the building; solar radiation incident on the building [5].

So, the building shape should be as compact as possible, to minimize heat transfer through the building envelope. [6]

Another important parameter to characterize urban heat island is the aspect ratio or height/width ratio: it is the ratio of the average height of the buildings to the width of the street. A great aspect ratio means that heat remains into the narrow urban canyons and the phenomenon of urban heat island increases. Gis allows obtaining this parameter, too. [7]

**Figure 2.** Representation of S/V Ratio: minimal surface area reduces heat transfer; increased area causes greater heat transfer.
2.2. A software for the energy evaluation in the urban spaces: Envi-met [8]

ENVI-met is a three-dimensional computer model designed to analyze the small scale interactions between urban design and the microclimate. The model combines the calculation of fluid dynamics parameters such as wind flow or turbulence with the thermodynamic processes taking place at the ground surface, at walls and roofs or at plants. ENVI-met was developed by Prof. Bruse (University of Mainz, Germany) and is based on different scientific research projects and is therefore under constant development [9] [10] [11] [12]. It is a freeware software and a prognostic model based on the fundamental equations of fluid dynamics and thermo-dynamics (Navier-Stokes) that for an incompressible fluid are used in the non-hydrostatic form, approximated according to Boussinesq, which includes the terms that take into account the resistance forces in contact with the vegetation:

\[
\begin{align*}
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} &= -\frac{\partial p}{\partial x} + K_m \left( \frac{\partial^2 u}{\partial x^2} \right) + f(v-v_g) - S_u \\
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} &= -\frac{\partial p}{\partial y} + K_m \left( \frac{\partial^2 v}{\partial x^2} \right) + f(u-u_g) - S_v \\
\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} &= -\frac{\partial p}{\partial z} + K_m \left( \frac{\partial^2 w}{\partial x^2} \right) + g \frac{\theta(z)}{\theta_{ref}(z)} - S_w \\
\frac{\partial u}{\partial t} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} &= 0
\end{align*}
\]

Where \( f \) is the Coriolis parameter, \( p \) the pressure, \( \theta \) the temperature, \( \theta_{ref} \) the reference temperature (average of all cells excluding those of buildings); \( u, v \) and \( w \) are the components of the speed. The additional terms of the sources/wells \( S_u, S_v \) e \( S_w \) describe the loss of wind speed for the forces of resistance in contact with the plants. These are calculated using the following formula:

\[
S_{u(i)} = \overline{\frac{\partial p}{\partial x_i}} = c_{d,f} LAD(z) \cdot W \cdot u_i
\]

With \( W \) average speed, \( LAD \) surface density of the leaves [m²/m³], \( c_{d,f} \) coefficient of mechanical resistance. The flow is updated at intervals of fixed time. ENVI-Met also supports a flow calculation in real time, which means that the flow field is treated as a normal prognostic variable and calculated at each step. The three-dimensional model equations are solved using the finite difference technique ADI This is an implicit method of calculating with alternating direction that allows you to solve simultaneously at every moment all the equations of the ENVI-met model.

Concerning the comfort is calculated the PMV (expected average vote) defined by Fanger (1972). It relates to the energy balance of the human body for thermal comfort of the person. Normally the value of PMV is defined between -4 (very cold) and 4 (very hot), but, as it is connected to the energy balance, you can also achieve higher or lower values. The model used for PMV in ENVI-Met is a special adaptation to external conditions performed by Jendritzky [13].

The program includes the simulation of:

* flow and shadow around and between buildings;
* exchange processes of heat and vapor at the ground surface and at walls;
* turbulence;
• temperature of surfaces and walls in every point of the grid;
• exchange at vegetation and vegetation parameters, as transpiration, evaporation and the sensible heat flux between vegetation and air including simulation of all physical parameters of the plants (eg rate of photosynthesis);
• exchanges of water and heat in the soil system, including water bodies (sea, rivers, lakes);
• calculation of the bioclimatic parameters of comfort as the mean radiant temperature and the Fanger PMV (predicted mean vote);
• particle and inert gases dispersion including sedimentation of particles on surfaces and on leaves.

In the Envi-met software is necessary to create two files (Fig. 3), the Configuration File and the Input file, that contains all the data required for the simulation:

![Figure 3. Screenshot of the ENVI-met homepage](image)

In the INPUT file there are all the geometric description and the location of the model. It is necessary to introduce some nesting grids, in this case equal to 3, for the correct resolution of the equations at the system boundaries. The albedo data for the asphalt and the pavement are equal to 0.6, corresponding to a light color.

In the CONFIGURATION file there are several sections:
  • in the MAIN DATA section the meteorological data are the experimental ones of 17/06/2010: an initial calculation temperature equal to 23 °C at 6 a.m., a minimal wind speed (0.5 m/s) and a random direction of it (North);
  • in the BUILDING section appears the average internal temperature of the buildings equal to 26 °C, the thermal transmittance of the walls and the ceiling that have high values, but corresponding to those of the 70's-80's buildings of the district, and, in the end, the albedo of the surfaces. In the PMV section to the comfort calculation it is assumed a resistance of the clothing equal to 0.5 m²K/(W), a typical summer value, and a walking activity with a normal speed;
  • in the SOILDATA section there are the values of temperature and humidity for the three layers hypothesized that are respectively decreasing and increasing with the depth.
3. Results

3.1. Gis analysis of Japigia district area[14]

The case study regards an urban area of Bari, in the South of Italy. It is located in zone 33, according to UTM Wgs84 coordinates.

Raster data consist of mosaic of Regional Technical Map of Bari; vectors regard Administrative and Municipal Districts boundaries and buildings of Bari.

At first, the historical map was obtained through a query, dividing buildings into six ages of construction in order to understand the architectural features (Fig. 4). Japigia district was built mainly after 1950, when the phenomenon of urban heat islands and the need of energy savings and buildings insulation were still neglected. Therefore, components of the buildings envelope are characterized by high transmittance values.

![Figure 4. Map of historical evolution of Bari and of Japigia district.](image1)

Secondly, the corresponding number of floor is important to calculate the height of building and derives from aero-photogrammetric survey and direct investigation of the urban fabric.

This parameter was assigned to each building of the analyzed area, according to a relation of “one to one” or “many to one”. This operation was carried out between a theme of points (number of floors) and a theme of polygons (buildings), by means of a query.

The query is generally formulated by a map and a table, representing entities and attributes in the information system. The result is normally displayed as a map on the screen where the selected items are suitably highlighted. According to the map (Fig. 5), the most of the buildings is composed by four or five floor.

![Figure 5. Thematic map of buildings of studied area, classified according to the number of floors.](image2)
To estimate S/V ratio, it was necessary to calculate the volume of each building, defined by the area and considering the height of 3 meters for each floor (Table 1). The histogram shows how S/V ratio decreases with increasing of the floors (Fig. 6). The average height of buildings is 14.5 m, while the width of streets is around 19 m: so the aspect ratio results 0.75. This street canyon geometry’s parameter is one of the most relevant urban parameters responsible for the microclimatic changes in a street canyon. These parameters directly affect the potential of airflow at street level, solar access and therefore urban microclimate. [15]

Table 1. Extract from the Gis table for calculation of the S/V ratio and geometric characteristics.

<table>
<thead>
<tr>
<th>FID</th>
<th>Shape *</th>
<th>Description</th>
<th>Number of floor</th>
<th>Area [m²]</th>
<th>Perimeter [m]</th>
<th>Volume [m³]</th>
<th>Heat Loss Area [m²]</th>
<th>S/V [m⁻¹]</th>
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</table>

Figure 6. Distribution of buildings average S/V ratios according to number of floors.
3.2. The simulation of the urban microclimate in a Japiglia district area [16]

The simulations were conducted in the weather conditions described above. A consideration should be made with respect to the wind conditions. They are not critical to the calculation, but only to make the result stable from the numerical point of view. These conditions of neutral wind allow to assess in a more understandable way the influence on the formation of the Urban Heat Island and on the comfort for the individuals located in the urban spaces (height from the ground equal to 1.2 meters) of parameters such as the percentage of the built areas, of the vegetation and of impermeable surfaces, the aspect ratio of the urban canyons, the type of the urban texture and the radiative properties (albedo, emissivity) of the surfaces.

A first set of simulations was carried out considering the current conditions of the district Japiglia. For buildings that tend to a light-colored gradation the albedo of the facades and of the roofs (certainly less influential on the comfort of pedestrians) was set equal to 0.6, while the albedo of pavements (tiles) and of the roads (asphalt) is equal to 0.4 and 0.6.

The high temperature recorded in Japiglia in the central hours of the day is due to the increased insolation and the large percentage of impermeable materials that have a predominantly dark-colored gradation that allows low rates of reflexivity. During the hours when minimal or no insolation does not affect the results, you have lower temperature, thanks to a greater air circulation due to the presence of big spaces and to the evapotranspiration of vegetation that allows the air cooling [17].

A second sequence of calculations shows how the use of clearer surfaces with greater albedo equal to 0.6 for pavements and roads causes a reduction of temperature and PMV (Figs. 7, 8).

**Figure 7.** Temperature at 13 a.m and at 22 p.m.

**Figure 8.** PMV at 13 a.m and at 22 p.m.
A third set of simulations was developed by splitting the studied area of Japigia, in the same conditions of the cases examined above, in an area without green spaces and in an area with green spaces to evaluate the effect of the vegetation on the same types of urban texture.

The area of Japigia with green, despite being subject to a greater insulation than because of lower concentration of buildings and because of the lower average height of them, has temperature and PMV values more limited thanks to the presence of the plants, which give a fundamental contribution to the environmental quality of the area: through the evapotranspiration, the process of the vegetal metabolism, the air temperature becomes lower. This benefit is smaller or less significant with small trees, increases the larger the green surface designed.

The green used as turf or planted area contributes significantly to raising the level of comfort because it reduces the surface temperature and contributes to the evaporative exchanges, in addition to the benefits that are concerned with the perceptive aspects. So the combined use of lighter surfaces and green ones determines a decisive improvement of the conditions of the comfort and the temperature (Figs.9,10).

**Figure 9.** Comparison between the temperatures of the areas without green and the areas with green in the current conditions and with an albedo equal to 0.6.

**Figure 10.** Comparison between the PMV of the areas without green and the areas with green in the current conditions and with an albedo equal to 0.6.
4. Conclusions

The territorial screening of the energy performance of the urban texture can be achieved with the help of GIS technologies and energy calculation programs as ENVI-met.

The intention is not to add a further specialist phase to the design path, but rather to integrate in the process of energy requalification, from the planning of the interventions to final design, a number of aspects related to environmental comfort and urban microclimate control. This assessment is in fact preliminary to the design of envelope elements and systems for heating and cooling in buildings and to the definition of mitigation technologies, materials and essences in the open spaces.

The beneficial effect of the vegetation should be further exploited in the urban energy planning in order to the adaptation to the climate change impacts. During hot summer nights, the coolness produced by parks and green areas can be a much more effective, sustainable and healthy solution if compared to the excessive use of air conditioning, whose excessive employment can be harmful to your health and contributes to increase the energy consumption and emissions.

In addition to the discomfort during the day, the fact that the temperatures remain high even in the night hours means that the human body is not able to “recover” from the stress conditions that has suffered during the hot day.

For the first time in the world everyone has to evaluate the environmental impacts of choices that until now had only one criterion: the economic availability. It a complex game, where there are many forces and actors involved. Among them, with distinct powers and responsibilities, there are the science, institutions and citizens.

References

[1] The text was edited by Silvia Di Turi.
[8] The text was edited by Tiziana Cardinale.
[14] The text was edited by Silvia Di Turi.
[16] The text was edited by Tiziana Cardinale.