Greening Actions and the Related Potential Impacts on Outdoor Comfort in a Dense Built Environment

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Abstract. The increasing attention paid to the effects of climate change on the dense urban fabric of contemporary cities had led Public Authorities to develop local adaptation plans in order to suggest some effective measures to mitigate and reduce the impacts of urban heat island [UHI] and heat waves as well as to improve water management capacity. Among the suggested actions, the greening of in-between spaces of the built environment and the introduction of new green surfaces (roof and/or facades) in the framework of wider regeneration plans offers interesting perspectives and impacts. The paper reports the outcomes of a research activity run by the Department of Architecture and the Municipality of Bologna to investigate how to define/optimize the most effective arrangement of greening solutions with the aim to improve outdoor comfort conditions. The study takes into account several aspects including paved/green surfaces extension, the use of material, the geometry of the site, etc. and simulate the potential effects of changes using simulation software ENVIMET. Once the main features of each site are modelled the different deriving scenarios can be compared evaluating the different architectural, economical and practical constraints. The results are then compared with other factors, related to the social aspects, the use of the spaces, the perception of the sites, etc. A district of the city of Bologna is used as test bed in order to test the proposed methodology and the related potential impacts.

1. Introduction
The strict connection experienced by many cities, especially those characterized by a high-density fabric in historical areas, between the effects of climate change and some remarkable environmental and socio-economic impacts [1–5] led many Public Administrations to develop specific guidelines or protocols to address initiatives and measures aimed at mitigating or adapting the urban fabric and the related communities to more resilient solutions. New design paradigms [6-8] are expected to respond to the impacts that extreme phenomena should have on energy demand and energy balance [9] as well as on health and wellbeing for urban population. The introduction of policy instruments to drive the transition became a priority especially with relation to UHI (Urban Heat Island) and Flash floods [10–11] that may lead to critical consequences for different reasons. The city of Bologna was on the first to adopt between 2015 and 2016 the so called Bologna Adaptation Plan, as the result of a process started in 2008 when the contents of PAES (Sustainable Energy Action Plan) were shared with more than one-hundred stakeholders (among them the University, the Fair, the Airport, trade associations, etc.) to define public-private partnership projects and the creation of a website to promote the relate activities in 2011. The Plan itself is the outcome of the BLUE AP project (Bologna Local Urban
Environment Adaptation Plan for a Resilient City), funded by the LIFE+ program (LIFE11 ENV/IT/119), which the Municipality of Bologna coordinated between 2012 and 2015 [12].

From a methodological point of view, the definition of the Plan was based on the assessment of the local climate situation and of the future climate scenarios (elaborated by ARPAE – regional environmental protection agency), to extract three macro-factors of vulnerability: drought and water scarcity; heat waves in urban areas; unconventional events and hydro-geological risk. As table 1 reports, the Plan accordingly identifies some strategies and a set of objectives.

Table 1. Bologna Adaptation Plan main objective according to the identified vulnerability.

| Vulnerability: DRAUGHT AND WATER SCARCITY | Main objectives: |
|------------------------------------------|-----------------|
| Strategies:                              |                 |
| - reduce the use of natural water resources | withdrawals from groundwater <45 M m³/year |
| - eliminating parasiting and mixed water | minimum water flow in Reno river 1,87 m³/s |
| - regulate the Reno river flow           | network losses < 18% |
| - protect agricultural production        | domestic water consumption < 130 l/i/day |
| - domestic water consumption < 130 l/i/day | drinkable water for other use <5 M m³/year |

| Vulnerability: HEAT WAVES IN URBAN AREAS | Main objectives: |
|-----------------------------------------|-----------------|
| Strategies:                             |                 |
| - increase urban greening, protect green areas | + 5.000 trees |
| - increasing insulation and greening in public and private buildings | + 5 hectares of urban vegetable gardens |
| - reduce health risk for population exposed to temperature increase | greening interventions on 10 public buildings |
| - greening of 4 public spaces in historic center | prevention of health waves effects |

| Vulnerability: EXTREME RAIN EVENT AND HYDROGEOLOGICAL RISK | Main objectives: |
|-----------------------------------------------------------|-----------------|
| Strategies:                                               |                 |
| - improve city hydrogeological response                    | limit the increase of waterproofed areas |
| - make the territory more resilient to intense rain         | new drainage systems > 11,5 ha |
| - reduce water pollution                                   | pollution load < 50% |
| - increase resilience of population                         | increase resilient infrastructures |
| - adequate maintenance of cultural heritage                 | adequate maintenance of cultural heritage |

In order to put the purpose into practice, the related key topics were included in a study, developed by the Technology Research Unit of the Department of Architecture at University of Bologna, concerning the regeneration of Bolognina district with the aim to define effective pathways for integrating energy efficiency measures [13] while greening the spaces in between the buildings according to Adaptation Plan perspective.

2. Goals
The original request expressed by the housing association and the inhabitants of the neighbourhood was to provide cost-effective solution to reduce energy demand at building scale while increasing quality and comfort condition [14–16]. However during the study, the role of the intermediate scale of open spaces connecting the urban fabric clearly emerged as a key element both to optimize the systemic vision for energy management and to exploit the mitigation potential. This is strictly related to the very regular grid in which the district is organized according to plots where the building blocks surround one or more inner courtyards or green areas. The analysis of the microclimate condition of these in-between spaces assumed a relevant importance in the understanding of outdoor comfort implication. UHI recurrence is directly related to the outdoor temperature increase [17, 18] and the direct or indirect reaction of inhabitants is to boost Heating, Ventilation and Air Conditioning [HVAC] use in cooling mode with consequent energy demand increase. The scientific literature is mostly
focused on analysing UHI and related effects at large scale [19–21] as well as the building elements connected to the overheating working on specific parameters like albedo and reflectance [22–24], while less attention is given to the district meso-scale where outdoor space quality shall influence the micro-climate and the perceived comfort.

The general objective of the study is to test the modelling approach on the courtyard and the related outdoor thermal comfort implications within the framework of a larger renovation strategy. Accordingly, the following specific goals were assumed during the study:

• to investigate the impact of the design solution/layout on the thermal comfort improvement and/or air temperature decrease to mitigate outdoor comfort conditions in summer time;
• to adequately translate the outcomes into useful information for decision makers to support the general regeneration process of the area through a more resilient design

3. Methodology and case study description

The study required to define a model adequately set to describe the case study before and after the envisaged renovation, taking into account the main variables and material characteristics with the scope to tailor the design solutions. The regeneration project involves a wide area, named Bolognina, located on the north side of the Central Railway Station in the city of Bologna. Most of the buildings, dating back to the 50s and 60s are part of a social housing initiative. Some renovation actions already took place but a comprehensive vision is still under development. A pilot block (figure 1a), well representing the typical situation, was selected for the purpose of this study.

Due to its poor energy performance and obsolescence level, the North-West corner building is supposed to be heavily renovated as well as the related courtyard used as car park. The model focuses on the courtyard surface that is currently paved with asphalt and where very few green portions and trees were left while does not include the new façades facing the court (because it can’t be adequately compared with surroundings). A greening action is foreseen to completely redesign the court with new trees and large grass portion to be used as playground for children. Vegetation will replace the 90% of the paved surface of the former carpark).

The main goal of the simulation is to match the most effective solution for shaping the outdoor area. Outdoor comfort conditions depends on several inter-related factors (materials, energy use, etc.) impacting on local micro-climate parameters such as: Temperature, Solar Radiation, Wind distribution, Wind Speed, Absolute and Relative Humidity. For the purpose of this study, the Predicted Mean Vote index (PMV) [25] was calculated adopting ISO 7730 [26] with limits to outdoor situations following German VDI 3787 Part 2, 2008 [27]. The software ENVI-met was used to investigate the main variables (air-temperature, wind-speed, relative humidity, etc.) and comfort index PMV for creating isolines strictly connected to the specific site features. ENVI-met [28], is a three-dimensional microclimate model designed to simulate the surface-plant-air interactions in a urban environment with a typical resolution of 0.5 to 10 meters spatial grid and 10 sec frame time [29]. The obtained images of isolines distributions were used to facilitate the understanding of comfort zones and micro-climatic variations in the test-bed site to both the decision makers and the end users, with the purpose to increase the community awareness level.

Envimet input data and the assumed boundary conditions can be listed as follows:

• Envimet model area (Space) is 107x70x30 Grid with 2x2x2 meters Cells. Consequently the Model area can be represented by a squared surface of 214 x 140 meters (figure 1b);
• After considering the historical trends and significant variations, the selected day for simulations is assumed 15th July 2015. Table 2 reports Air Temperature (in °C hourly average at 2 m above ground) and Relative Humidity (in % hourly avery at 2 m above ground) provided by Regional meteoclimate Agency (ARPAE);
• Wind speed was assumed as 3.6 m/s (10 m above the ground) and wind direction 260 (deg)
### Table 2. Meteorological data in Bologna (Italy) 15th July 2015, used as input data for the ENVI-met model.

| Hour   | Temperature (°C) | Relative Humidity (%) | Hour   | Temperature (°C) | Relative Humidity (%) |
|--------|------------------|-----------------------|--------|------------------|-----------------------|
| 00:00:00 | 26.2             | 59                    | 12:00:00 | 32.3             | 42                    |
| 01:00:00 | 25.7             | 63                    | 13:00:00 | 32.7             | 42                    |
| 02:00:00 | 25.3             | 64                    | 14:00:00 | 32.9             | 40                    |
| 03:00:00 | 24.9             | 64                    | 15:00:00 | 32.9             | 38                    |
| 04:00:00 | 24.5             | 64                    | 16:00:00 | 32.5             | 38                    |
| 05:00:00 | 24.7             | 63                    | 17:00:00 | 32                | 39                    |
| 06:00:00 | 25.9             | 59                    | 18:00:00 | 31.1             | 43                    |
| 07:00:00 | 27.2             | 56                    | 19:00:00 | 30.1             | 51                    |
| 08:00:00 | 28.5             | 52                    | 20:00:00 | 29.2             | 55                    |
| 09:00:00 | 29.5             | 48                    | 21:00:00 | 28.3             | 61                    |
| 10:00:00 | 30.4             | 46                    | 22:00:00 | 28.1             | 62                    |
| 11:00:00 | 31.7             | 43                    | 23:00:00 | 27.5             | 62                    |

**Figure 1.** a) the test-bed site is highlighted in the district regular grid; b) the model area reproduces the plot main features and is used to simulate the design options (paved vs green surface)

The main involved variables can be listed as follows:

- **Air temperature**, measured in °C (evaluate the temperature distribution with relation to the influence of the building arrangement/shading effects, the properties of the materials used for paving the interested area, the eventual influence of wind in specific parts of the site);
- **Wind speed** (or **Air Velocity** or **Air Speed**), measured in m/s (evaluate air movement distribution, especially situations of Still Air – wind speed = 0 m/s);
- **Relative humidity** (RH), measured in % (evaluate the effect of vegetation, combined with the main ventilation directions. The relative humidity value influences human sweating: at the demo-case latitude and conditions in summer time, RH > 65 % is perceived as muggy sensation of great discomfort);
- **Specific Humidity** (SH) measured in g/kg (a useful indicator to evaluate the effect of plants and vegetation).
Furthermore, Predicted Mean Value (PMV) allows to evaluate thermal sensation following ISO 7730 [26] range from $-3 = \text{very cold}$ to $+3 = \text{very hot}$, with 0 as neutral thermal sensation (comfortable). PMV index values may therefore exceed $+4$ in the range defined by ISO 7730. In the present study PMV evaluation, performed using bio-met application of envi-MET software, assumes a standard subject of $1.75 \text{ m height}$, $75 \text{ kg weight}$ and $35 \text{ years old}$, with a metabolic activity corresponding to a conventional walk and normal clothing corresponding to $0.90 \text{ clo}$.

Energy simulation and microclimate analyses are used during the design process to better understand the outdoor conditions and consequently adapt or correct the design solutions to optimise the potential deriving benefits. The process consists in comparing the outdoor maps before and after the intervention scenario, assuming a specific time and day that adequately represent a typical standard situation during the summer season. For this study the 16th July at 1 pm was chosen adopting the meteorological data set provided by the local agency. The choice of this date is coherent with the period of widest use for the residents and maximum risk of heat waves. During this period inhabitants perceive a strong thermal discomfort, increasing the energy demand trend for cooling.

4. Results of the performed study

The results of the specific research activity dealing with outdoor comfort conditions are Outdoor-Microclimate-Maps that reflect the effects of the designed greening solution compared to the starting situation of the case study. Each map includes the isolines distribution and homogeneous zones for each variable. It must be said that the main scope of the study is not to assess the design quality of the proposed solution (which in fact is not described in detail) in terms of materials choice and architectural layout, but rather to demonstrate how the proposed modelling activity can be used to predict and evaluate the deriving impacts. The proposed design offers of course some benefits that can be higher or lower according to different possible scenarios. The outcome of the simulation shows that there are no relevant variations of minimum (nearly $19 \degree \text{C}$) and maximum (nearly $35 \degree \text{C}$) values of Air-Temperature, however the homogeneous $32–34 \degree \text{C}$ temperature red zone is smaller in the renovated scenario (right side, line A of figure 2). This can be considered a positive improvement at plot scale.

The maximum Wind Speed value varies from 7.66 m/s to 9.70 m/s that means the adopted solution produced a better ventilation (right side, line B of figure 2) and a significant reduction of still air zones (0.00 m/s, in blue) which are limited to the spaces very narrow to the buildings. The increased presence of light breeze (ranging between 0.80 m/s and 1.40 m/s) can also facilitate convective thermal exchange of human body providing a sense of freshness on the skin. Air Speed values exceeding 1.80 m/s at the border of the map have to assumed as “boundary errors” of the model.

RH minimum (nearly 29 %) and RH maximum (nearly 75 %) values seem to reflect quite limited effects of the vegetation in the plot as a whole, however it can be noticed a variation of RH between 40%-45% distribution that moves from the north-east side to the south-west one, probably due to a more balanced vegetation distribution encouraging to scale the greening action to the residual parts of the plots enlarging the simulation area for further studies. The RH 30 % (dry environment), typically representing the summer situation in a metropolitan area, shifts to 33 %–36 % (cyan zones) in the renovation scenario evidencing the positive impact of green areas increase. At the current stage trees and green areas are too limited to influence all the site as reflected by minimum (nearly $9.83 \text{ g/kg}$) and maximum (nearly $11.65 \text{ g/kg}$) Specific Humidity values (line D of figure 2). Never the less, it shows that Specific Humidity shifts from 9.60 g/kg (green) to 10.20–10.40 g/kg (orange) with a significant increase around 1 g/kg reflecting the achieved effects on the north west corner.

Maps concerning PMV index (line E of figure 2) must be carefully analysed: PMV seems to generally shift from 0.17 (neutral, before) to 1.03 (hot, after), but without considering the “boundary effects” and focusing only on renovated area (highlighted in the circle) PMV shifts from “very hot” (+3.50, +4.00 red zone) and “very very hot” (above +4.50 violet zone) to “Warm” (+1.50, +2.00) reflecting the benefit deriving by the proposed solution.
| A | Air temperature distribution, in °C: (before - after) |
|---|-------------------------------------------------------|
| B | Wind speed distribution, in m/s: (before - after)    |
| C | Relative Humidity distribution, in percentage: (before - after) |
| D | Specific Humidity in g/kg: (before - after)          |
| E | Predicted Mean Vote (PMV) index: (before - after)    |

**Figure 2.** (A, B, C, D, E) Outdoor-Microclimate-Maps obtained by the simulation.
5. Discussion of the outcomes and conclusions

The reported study explores the use of maps, representing the key investigated parameters, as tool to guide the design process in order to adapt or tailor the possible solution towards a quite balanced configuration especially with reference to greening actions on outdoor spaces to be completely renovated in dense urban fabric. The use of the maps allows an immediate and easy to understand visualization of a multi-variable situation, providing a clear and synthetic display of achievements, and to compare the effectiveness of possible design scenarios on outdoor thermal comfort. The proposed methodology can support decision makers in planning a coherent regeneration vision for large portion of the cities bringing the gap between single actions and the possible effects at the meso-scale.

Without focusing on the architectural layout of the greening action, the case study allowed to demonstrate how a certain percentage of vegetation can influence local conditions improving outdoor Thermal Comfort and contributing to potentially mitigate UHI.

Despite the simulation has been tested on a quite small portion of the urban fabric and the results may sound limited in the value range, the process is relevant with reference to the specific context and the study purpose. It can be easily replicated extending the testing area and analysing how different scenarios in the same combined portion may impact on the plot as a whole. The presence of the “boundary errors” typical of this kind of simulations suggests to enlarge the investigated area checking the reliability of results for the part really interested by the evaluation process before scaling the process and applying the methodology to the district intended as a unique, coherent system.

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