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A study on the use of outdoor microclimate map to address design solutions for urban regeneration

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Abstract

Climate change and the deriving impacts on the built environment certainly represent one of the most challenging issue for several key players involved in shaping the cities of tomorrow. This is not simply a matter of adapting buildings to new requirements, but rather to rethink the way the urban fabric reacts to new and sometimes unpredictable phenomena. The process is related to increasingly evident extreme conditions in the summer time, that strongly improve the energy demand for cooling with negative impacts on the energy balance as well as on thermal comfort conditions of the end users and of urban population with severe implication on health and wellbeing. Outdoor comfort depends on a number of inter-related factors: the characteristics of the built environment, the relationship between materials and energy use, global climate change and local micro-climate: Temperature, Solar Radiation, Wind distribution, Wind Speed, Absolute and Relative Humidity. The objective of this specific study is to test the microclimate modeling of a city portion in a demo-case – a plot of building blocks with inner courtyards – as a tool for supporting the regeneration phase addressing technological choices and design solutions to improve outdoor comfort conditions. The outcomes of the performed envi-MET simulations, comparing the situation before and after intervention, are consequently discussed. In the specific case, the developed project involving the courtyard has led the Thermal Comfort perception, evaluated in terms of PMV, to shift from "very hot" (+3.50, +4.00 red zone) and "very very hot" (above + 4.50 violet zone) to "Warm" (+1.50, +2.00) at urban plot scale.

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Keywords: Outdoor thermal comfort; envi-MET; district regeneration; outdoor microclimate map [OMM]; climate responsive solutions; mitigation

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1. Introduction and context

One of the most challenging issue in addressing the future form of the cities in the next future is certainly connected with the answers to climate change and the deriving impacts on the built environment [1]. New design paradigms are expected not simply to respond to new requirements for adapting buildings to emerging needs, but rather to enable a reaction to new and sometimes unpredictable phenomena [2]. On the one side, this is related to increasingly evident extreme conditions in the summer time (and altered winter/summer cycles especially for what concerns the temperature trends and the rainfalls) that strongly improve the energy demand for cooling with negative impacts on the energy balance [3]. On the other one, this affects the thermal comfort conditions of the end users and of urban population with severe implication on health and wellbeing. The most evident phenomena at city level are the so called heat-waves and the Urban Heat Island [UHI] effect that may lead to critical consequences such as heat strokes and generally to a sense of outdoor discomfort [4, 5]. According to the Adaptation Plan adopted by the City of Bologna, this topic was 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, climate condition monitoring and renewable energy exploitation into a smart city perspective [6].

The importance of considering the climate and micro-climate condition of the space in-between the buildings, defined as a very specific environment shaped into courtyards, passages and outdoor spaces enclosed by aggregated volumes, emerged from the beginning as a strategic element in the general framework of the research.

The main driver of the study was to provide cost-effective solution to reduce energy demand at building scale while increasing quality and comfort condition [7, 8, 9] as well as to deliver a comprehensive strategy to support the integration of the district in smart-city related infrastructures. During the work, the role of the intermediate scale at district level clearly emerged both with reference to the achievement of a systemic effect for energy management and to the impacts in terms of mitigation potential. The district is indeed organized in a very regular grid of rectangular plots where building blocks are arranged around one or more inner courtyards or green areas. The analysis of the microclimate condition of these spaces assumed a relevant importance in the approach to the regeneration process as a whole and particularly in the understanding of outdoor comfort implication. Despite this represents just a part of the overall context of the research, outdoor comfort captured the team attention and a dedicated study was developed on a portion of the district in order to evaluate the impacts and the potentialities before applying the process at a larger scale.

Outdoor Comfort is a specific field of study and its linkage with UHI phenomenon is quite clear: UHI recurrence is directly related to the outdoor temperature increase [10, 11]. As a reaction, people tend to stay inside the buildings with a consequent increase of energy demand due to HVAC use in cooling mode.

However, the performed review of the scientific literature evidenced that outdoor comfort and related phenomena are mostly studied at two different level:

- the climatic one, well represented by some works of Matsarakis and Santamouris [4, 5, 12], that analyses UHI at large scale focusing on the relation between climate conditions and the deriving effects on the city and particularly on the dense city centers and historic/touristic sites;
- the material one, that focuses on the characteristics of the elements at building scale to reduce the risk of overheating, working on specific parameters such as albedo and reflectance which were widely investigated in studies of Doya, Hernández-Pérez and Zinzi [13, 14, 15] among the others.

A minor attention is usually given to this issue at district meso-scale where, working on surfaces bordering a limited outdoor space, is possible to influence its micro-climate and the perceived comfort.

The paper reports the specific study developed on a portion of the main research project case-study describing the main goals, the assumed constraints, the key parameters investigated, the adopted methodology, the main outcomes and the potential impacts within the general scope of the main project.

2. Goals

The study is focused on investigating the thermal outdoor comfort of urban blocks organized around one or more inner courtyard according to the layout of a specific case study located in Bologna. The general objective is to test the modeling approach on the courtyard and the related outdoor thermal comfort implications to consider a possible development and inclusion of this issue in the mitigation strategy to be applied at district scale. According to this framework the following specific goals were assumed during the study:

- to investigate the relation between the design solution/layout and the *thermal comfort improvement* and/or *air temperature decrease* to improve outdoor comfort conditions in summer time;
- to adequately translate the outcomes into useful information to guide the key stakeholders and players towards a resilient design that effectively support the general regeneration process of the area.

3. Methodology

The study required to define a model adequately set to describe the meso-scale of the demo-site, then the output variables, before and after renovation, were compared so to understand which materials and characteristics were able to influence the micro-climate (improvement of comfort conditions and air temperature decrease) and to address design solution accordingly. abstract text etc.

3.1. Case study selection and description

The regeneration project involves a wide area on the north side of the Central Railway Station in the city of Bologna, named Bolognina district. The buildings, dating back to the 50s and the 60s, were erected during the reconstruction phase after the bombing of WWII following a regular rectangular grid according to a layout based on inner courtyards and green spaces. Most of the buildings belongs to a social housing initiative and the district is indeed a mix of different cultures and people from different countries. However, the residents' low income and the lack of resources for ensuring adequate maintenance activities during the time contributed in significantly reducing the quality of the built environment. Therefore a comprehensive regeneration project has been promoted focusing both on cost-effective design solution for retrofitting the buildings and on suitable options to re-arrange the outdoor spaces that are currently used as car park.

Figure 1 points out the selected case-study in the Bolognina area. The block was selected because it very well represents the typical situation adding some peculiar elements, such as the location narrowing a daily local market and the multiple courtyard layout, that makes it more interesting both in terms of simulation outcomes and of social engagement. The block is clearly divided in two main areas by a building crossing the plot from North to South creating two main spaces and one passage connecting the street on the South side with the market in the North side.

Fig. 1. (a) location of the demo-site in the Bolognina District; (b) the North-West portion of the plot where the study is focused.

A more detailed model was created to study the North West corner and the West side courtyard. The corner building is subject to a heavy renovation action involving also the two façades facing the court, where a new volumetric addition based on timber based construction, provides new balconies, buffer zones for overheating mitigation during summer time and a new layout to the elevation. Therefore the refurbished vertical surfaces were not included in the model at this stage due to the incomparable condition with the surroundings. The model focused on the courtyard surface that is currently paved with asphalt and where very few green portions and trees were left. The main goal of the simulation is to couple the most effective solution for shaping the outdoor area according to the retrofit action performed at building level.

3.2. Simulation model

Comfort conditions of outdoor spaces depends on a huge number of inter-related factors dealing with the main geometrical and material features of the built environment as well as with the relationship between materials and energy use, with global glimate change impacts and local micro-climate parameters such as: Temperature, Solar Radiation, Wind distribution, Wind Speed, Absolute and Relative Humidity. One of the most used index to evaluate Indoor Thermal Comfort is the Predicted Mean Vote index [PMV], introduced by Fanger P.O [16] and standardized by ISO 7730 [17]. Many other indexes have been introduced in the studies about Outdoor Comfort due to the greater importance of air speed and of the mean radiant temperature that depends on the sky conditions, the sun and ground reflection. In the specific case Outdoor PMV calculation was adopted ISO 7730 with limits to outdoor situations following German VDI 3787 Part 2, 2008 [18]. The most frequently software used to model outdoor comfort, also described in Dessì V. [19] and UHI-CE Project [20], are: Bulleted lists may be included and should look like this:

- ENVI-met [21], 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. Typical areas of application are Urban Climatology, Architecture, Building Design, Environmental Planning, etc. ENVI-met is a prognostic model based on the fundamental laws of fluid-dynamics and thermo-dynamics [22];
- rayMan, is a freely available radiation and human bio-climate model. The model simulates the short and long-wave radiation flux densities from the three-dimensional surroundings in simple and complex environments, as described in Matzarakis et.al. [23];
- SkyHelios [24, 25] is a tool for applied climatology, calculating the continuous sky view factor and sunshine duration in high spatial and temporal resolution for each point in a complex area.

All these software require expert users and this is the reason why the outdoor comfort issue is not conventionally included in the design process. Thus, the aim of the present study is also to provide a simplified guide for architects, engineers, planners, but also stakeholders and citizens about the potential outcomes in order to address political choices and design solutions at community level as suggested by results of Republic-med [26] and REBUS projects [27]. The software choice – and the deriving model – depends on the output typology it is expected to be obtained by the study. SkyHelios creates models based on a Polar Coordinate System focusing the study on human centered approach where human body is assumed as the core element of the outdoor environment. A similar approach drives rayMan that includes the Energy exchange with the sky dome (Extra heat transfer by thermal radiation to the sky) in the model to provide the Physiological Equivalent Temperature [PET] index which is frequently used as a Heat Stroke index (Heat Stroke is an acute syndrome caused by an excessive rise in body temperature as the result of overloading or failure of the thermoregulatory system during exposure to heat stress. [28]) and not as an index of Thermal Sensation. ENVI-met enables to manage the main variables (air-temperature, wind-speed, relative humidity, etc.) and comfort index PMV for creating isolines strictly connected to the specific site features. Thus creating Outdoor-Maps it is possible to provide a very effective image of isolines distributions in order to support the understanding of comfort zones and micro-climatic variations in a specific site such as the courtyards included between the building blocks adopted as demo-case in this study.

ENVI-met was therefore chosen for creating geo-referenced maps that could be representative of the specific site conditions.

3.3. Variables

The main variables used to analyze the outdoor microclimate of the site, at the current conditions and after renovation, can be listed as follows:

- *Air temperature, measured in °C*, to 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. The minimum and maximum temperature decrease during summer time as well as the temperature isolines distribution allow to evaluate the benefit provided by the envisaged design solution with reference to the Sensible Heat exchanged by the human body with the outdoor environment;
- *Wind speed (or Air Velocity or Air Speed)*, measured in m/s, to evaluate air movement distribution, especially situations of Still Air (wind speed = 0 m/s) where, during summer time, there is a lack of the positive effects deriving by air/body exchange, or those situations where Turbulence (wind speed > 1 m/s) or "Venturi effect" may create discomfort condition and particularly in winter time facilitate the increasing of fine dust, particulate matter and pollutants;
- *Relative humidity (RH)*, measured in %, to evaluate the effect of vegetation, particularly in case of wide surfaces (fields, grass, etc.), combined with the main ventilation directions (as ventilation influences vapor dilution). The relative humidity value influences the Latent Load and consequently human sweating: at the demo-case latitude and conditions, the relative humidity (RH > 65%) in summer time is perceived as muggy sensation of great discomfort;
- *Specific Humidity (SH)* measured in g/kg, that is a useful indicator to evaluate the effect of plants and vegetation.

In addition, the PMV isolines are included to evaluate the different zones in which the site can be divided according to the thermal sensation a subject express in a range between 3 = Very cold, 0 = neutral, + 3 = Very hot. With reference to the outdoor comfort and Thermal Sensation evaluation using PMV index, it has to be said that:

- PMV is usually adopted as indoor comfort indicator where thermal exchange, and particularly the radiant ones, involves the six faces of the space, while in the case of outdoor comfort the exchange is towards the sky dome;
- Variables change in the site during the time as well as the presence of people may change while they move in the site (and this leads to metabolic changes in the involved subjects);
- There are no available statistical surveys concerning the relation between the subject thermal perception in the outdoor environment and the microclimatic variables defining it. *This is mostly an unexplored field in the literature.*

Most of cases, PMV is evaluated considering only the outcomes of the calculation model and this is the reason why PMV values may exceed +4 in the range defined by ISO 7730, thus a *critic analysis of the outcomes* and of the isolines shape is needed. In the present study PMV evaluation, performed using bio-met application of envi-MET software, assumes a standard subject of 1.75 m height, 75 kg weight and 35 years old, with a metabolic activity corresponding to a conventional walk and normal clothing corresponding to 0.90 clo.

3.4. Outcomes

The objective of this specific study is to test the microclimate modeling of a portion of the city – in the case-study a plot of building blocks with inner courtyards – as a tool for supporting the regeneration phase addressing technological choices and design solutions (including architecture, green and paved areas) to improve outdoor comfort conditions. More in detail, envi-MET was used to create a model of the case-study before and after rurban intervention and landscaping comparing the impacts on the outdoor microclimate maps. The proposed solution completely re-design the courtyard area with new green areas and vegetable gardens as figure 2 shows. No heavy demolition are envisaged on the corner building but a new wooden based volumetric addition provides new balconies and an extensive shading system on the south/east façades to mitigate overheating.

The study is based on the assumption that energy simulation and microclimate analyses have to be carefully considered and included during the design process to achieve a better understanding of the outdoor conditions and to drive solutions towards more comfortable levels. This position is supported by other studies such as the ones of Naboni E. [29] and Xuan Y. [30] and in Fabbri K. [31] where a point-by-point evaluation of the outdoor comfort is used to choose the most suitable location of seats and other elements. The evaluation process operates comparing the outdoor maps before and after intervention, assuming a specific time and day that adequately represent a typical standard situation during the summer season. For the demo-case 16th July at 1 pm was chosen, using real data from a local meteorological station to feed the model. The period choice depends on the purpose of the study and clearly the main objective was to analyze comfort conditions during summer when outdoor activities are more frequently performed by the residents and when the risk of heat waves may affect a conventional situation. This is indeed the most problematic period for the case-study when residents perceive thermal discomfort conditions and avoid to go out, increasing the energy demand trend for cooling.

Fig. 2. The site layout before (a) and after (b) intervention (c, d) (credits: L. Ferrari, D. Galassi)

The comparison between the maps is based on isolines distribution, minimum and maximum values as well as on considering those areas with homogeneous variables distribution.

During a day of the summer season, the evaluation of Thermal Comfort must take into account that: PMV index may be overestimated (e.g PMV > 4); it is not possible to have neutral thermal situations (PMV =0) or fresh areas (PMV = -1); thus PMV decrease is mostly evaluated and, as a consequence, the shift from a “very, very hot” condition (PMV = 4) to a “Hot” one (PMV =2) can be assumed as a positive improvement.

4. Results

The deriving results are specific *Outdoor-Microclimate-Maps* of the case study with isolines distribution and homogeneous zones for each variable. It has to be clearly remarked that the main objective of this study is not to critically evaluate the specific design and material choices adopted to renovate the courtyard layout, but to demonstrate how the modeling activity allow to evaluate the impacts of the project. In the specific case, the developed project involving the courtyard has led some benefit at urban plot scale. The outcomes of the performed envi-MET simulations, comparing the situation before and after intervention, are commented below.

Figure 3 shows there are no significant variations of minimum (nearly 19 °C) and maximum (nearly 35 °C) values of Air-Temperature in the demo site, thus it seems the new courtyard layout does not influence this parameter. However, the homogeneous 32-34°C temperature zone (red) is smaller after renovation (right side figure b) as well as the 36°C one (violet) especially if the boundary effects are not included. *These can be interpreted as positive effects at the plot scale, even if the renovation doesn't produce evident effect on the demo-site itself.*

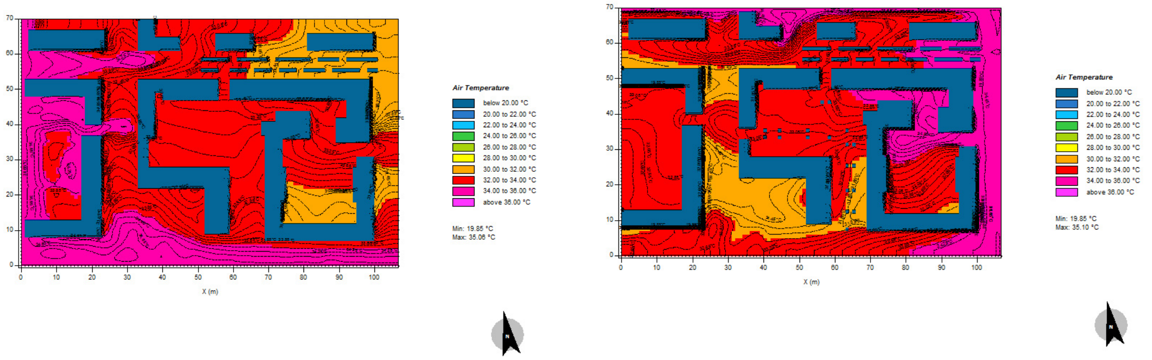

Fig. 3. Air temperature distribution, in °C: (a) before; (b) after.

Figure 4 shows maximum Wind Speed value in the plot varies from 7.66 m/s to 9.70 m/s that means the adopted solution produced a better ventilation and a significant reduction of still air zones (0.00 m/s, in blue) which are limited to those areas narrowing the buildings. The right side map (b) shows a reduction of the Venturi effect (turbulences) where the building elevations are separated by the urban passages. Wind Speed shows an increased presence of light breeze (ranging between 0.80 m/s and 1.40 m/s) that can facilitate convective thermal exchange of human body providing a sense of freshness on the skin. Air Speed values exceeding 1.80 m/s in the map external areas can be considered "boundary errors" of the model.

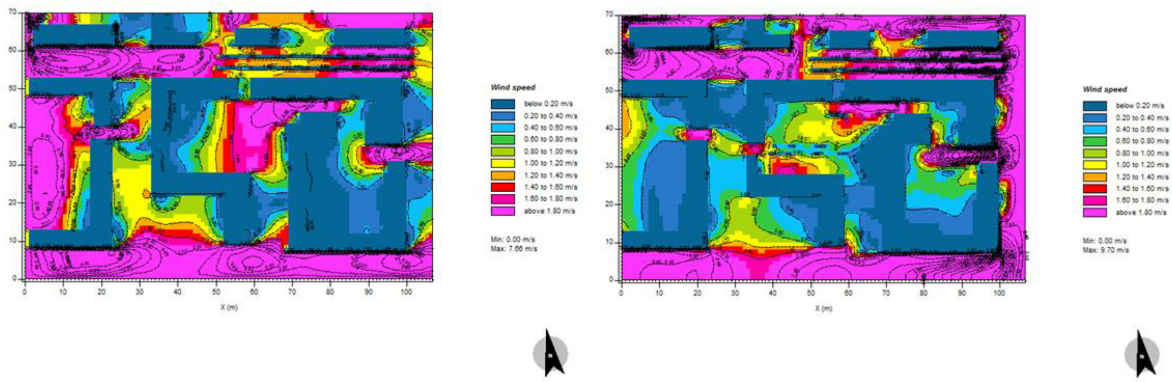

Fig. 4. Wind speed distribution, in m/s: (a) before; (b) after.

Figure 5 shows RH minimum (nearly 29%) and RH maximum (nearly 75%, on the boundaries while it can be assumed 45% considering the rest of the involved area) values seem not to significantly vary at plot level, meaning that the intervention on the north-west corner courtyard is too limited in terms of green area for impacting on the site 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 (that might require specific additional simulation in different days of the year).

The RH 30% (dry environment), corresponding to the typical situation of a summer day in a metropolitan area, shifts to 33%-36% (cyan zones) after renovation evidencing the positive impact of green areas increase.

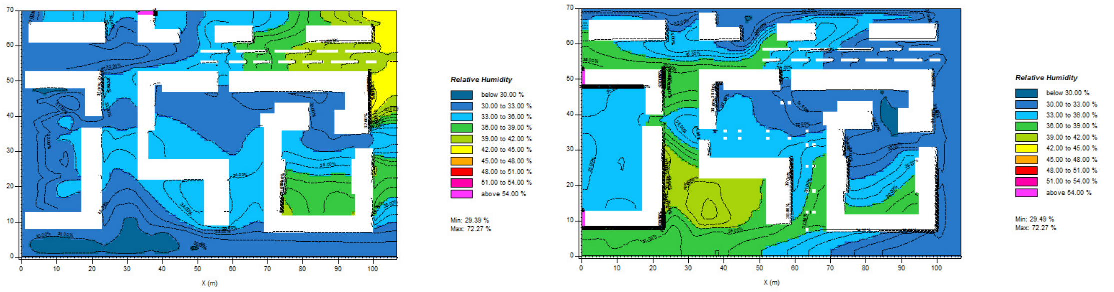

Fig. 5. Air temperature distribution, in °C: (a) before; (b) after.

As evidenced in figure 5, minimum (nearly 9.83 g/kg) and maximum (nearly 11.65 g/kg) Specific Humidity values have no relevant change at plot level. Trees and green areas are too limited to influence the other parts of the demo-site. However, figure 6 shows a variable distribution in the space with the exception of north-east corner where the vegetable gardens are placed. If we compare - *only to courtyard designed area* - the situation before and after the project, 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.

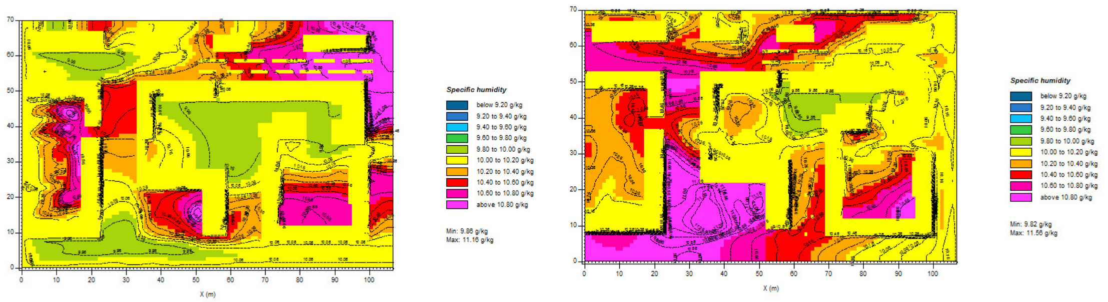

Fig. 6. Specific Humidity in g/kg (a) before; (b) after.

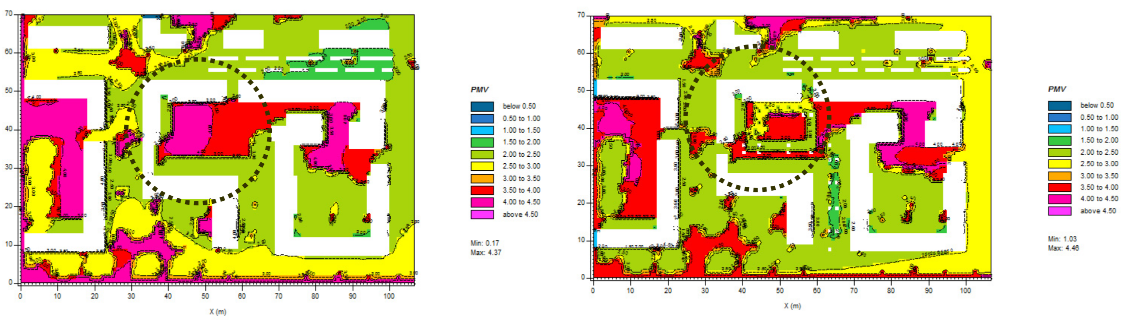

Fig. 7. Predicted Mean Vote (PMV) index (a) before; (b) after.

The last simulation concerning the Thermal Comfort (figure 7) evaluation using PMV index has to be carefully analyzed with specific reference to the demo-site north-west corner otherwise the results may appear contradictory as PMV seems generally to shift from 0.17 (neutral, before) to 1.03 (hot, after). Excluding the “boundary effects”, in the renovated area (included in the circle), where the vegetable gardens are located, 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) with an effective decrease produced by the adopted solution.

5. Discussion

The study, reported in this paper, addresses the attention to a meso-scale - that has already been investigated by Fabbri et al. [32] for what concerns energy demand - focusing on the urban plot and particularly including building blocks arranged around inner courtyards, open spaces, squares, green areas and clearly delimited by the street grid. In spite of above scientific literature mostly focused on the deep analysis of single variables, the reported results show the utility of maps to guide urban design improvement according to an immediate multi-variable perspective. It indeed provides a clear and synthetic display of achievements to compare the effectiveness of design solution on outdoor thermal comfort. Most of the studies from the performed literature review deals with city, physics model, software, comfort perception, while in this case a gap-improvement of variable physics between before/after design solution is adopted. Cities play a key role in the future challenge to climate change: the increasing population and density of the urban environment will influence the perceived impacts as well as the effects of UHI. Thus, most of mitigation or adaptation measures are driven at city or regional scale rather than at building scale even though each single part of the urban fabric can significantly contribute to system behavior as a whole.

The described case-study demonstrates that a limited number of actions on the courtyards surfaces and the introduction of a certain percentage of vegetation can influence local conditions improving outdoor Thermal Comfort and contributing to a reduction of UHI decreasing air temperature. The spatial representation of the microclimate conditions is an useful tool to understand and address design choices and technological solutions to be adopted. The OMM can be used to define design strategies and to demonstrate (comparing the situation before and after interventions) the potential benefit of each option. Despite the process has been implemented just on a small portion of the urban fabric, the results – that apparently sounds limited in the value range, but are relevant with reference to their specific context and the study purpose – encourage to apply this methodology in a systematic approach to the regeneration process at district level replicating the adopted model on the involved building plots. The emerging results suggested to consider some further improvements to assess the reliability of simulations. Thus two new actions are under development during the next moths: 1) on site observation (from data collection by sensors and instruments) to compare the software accuracy and the model assumptions; 2) direct interviews with residents by the use of a questionnaire to assess the real comfort/discomfort perception in the case-study site in order to map values on a real status base. These actions will let the model to be refined before a wider mapping process starts with the aim to monitor the combined effects and the design option can be driven accordingly increasing the potential benefit in terms of mitigation and comfort conditions at district scale.

6. Discussion

This paper provides a description the methodology developed to evaluate outdoor comfort and applied in the specific case study at Bolognina District (Italy). ENVI-met was then used to evaluate the OMM for each physics variable. Outdoor comfort was simulated before and after the courtyard redesign with garden, grass e new trees. Outdoor-Microclimate-Map was used to compare results. This procedure shall be used to support decision making process and to compare alternative options. It has also to be remarked that the use of OMM will certainly translate in a easier and more accessible way the output data that are typically produced for expert users. The adoption of this tool facilitate the understanding of the related phenomena to both professionals (that have to be able to consider the boundary effects and other specificities) and non-expert users such as decision makers, stakeholders, citizens for whom the isolines of the maps can provide an easy access to information and therefore to the general understanding of the analyzed phenomena. This is certainly relevant to consider the potential effects of the design choices on the microclimate when a regeneration action is under discussion or is going to be developed in a specific site.

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