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# Outdoor Comfort: the ENVI-BUG tool to evaluate PMV values Output Comfort point by point

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**Abstract**

Studies on Outdoor Comfort in urban open spaces adopt several tools and software to simulate microclimate models, energy performances and the fluid-dynamics of winds. Air temperature, wind speed, relative humidity are the typical input data used by the software to evaluate comfort indexes such as the Predicted Mean Vote [PMV], the Physiological Effective Temperature [PET] or the Universal Thermal Climate Index [UTCI]. Among the available software, Envi-met provides accurate outputs as well as the PMV index space distribution starting from a three-dimensional microclimate model. However it is affected by some limitations for what concerns a user centered approach including the changes in human metabolic activity (met) or clothes (clo). This paper offers a synthesis of a study performed on ENVI-BUG, an Envi-met algorithmic app, to obtain a fast calculation and distribution of local PMV point-by-point displayed with mannequin representation.

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*Keywords:* Outdoor comfort; PMV values; ENVI_BUG; mitigation; environmental design.

## 1. Introduction

Used during the design process, Building Performance Simulation (BPS) software concerning thermal comfort evaluation gives to architects and engineers the opportunity to better refine solutions and support decision making process. BPSs applied at building level use dynamics simulation to evaluate: a) energy performance (e.g. heating/cooling energy need, primary energy consumption, HVAC performance and/or efficiency, etc.), b) human behavior influence on interior design management (e.g. windows opening, user habits, etc.), c) thermal comfort, indoor air quality and indoor environmental quality (including lighting and acoustic issues). Several researches and a

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consistent scientific literature are addressed to explain how to apply Building Simulation to understand future Building Virtual Environment. A reduced number of studies is instead addressed to investigate outdoor spaces, such as square, street, parking, city park, garden, courtyard, etc., that are mostly included in researches and papers concerning the Urban Heat Island effects, or outdoor microclimate. There is a general lack of attention to support designers in understanding the impacts of their design choices with relation to comfort conditions and environmental impacts in outdoor spaces (i.e. green surfaces, pavements, etc.). Outdoor comfort can be influenced by several factors at local and global scale, but in most cases it depends on Temperature, Solar Radiation, Wind distribution, Wind Speed, Absolute, Relative Humidity and the way the materials characterizing the surfaces bordering the open spaces react to climatic solicitations.

Building Simulation is typically associated with indoor environments and less attention is usually paid to the space in-between the buildings where outdoor comfort simulation [1, 2, 3] could provide very interesting outcomes. Outdoor Comfort is a specific field of study that is strictly connected with the effects of Urban Heat Island (UHI) phenomenon and its impacts on energy demand in the building sector. Due to the increase of the temperature in the dense urban fabric, people tend to avoid to go out during the daytime and to increase HVAC use in cooling mode with significant impacts on energy demand trends during summer time. A better understanding of outdoor conditions might provide useful information to address mitigation strategies and design solutions both at building and urban scale. The relationship between energy use and climate conditions in the urban built environment as well as the factors influencing the Urban Heat Island are described in several studies such as the ones of M. Santamouris [4, 5], G.M. Stavrakakis et al. [6] and in RUROS by CRES [7].

When analyzing Indoor Thermal Comfort the Predicted Mean Vote [PMV], introduced by Fanger P.O [8] and standardized in the ISO 7730 [9], is normally used, however the complexity of outdoor situations led to the adoption of many other indexes, available from a literature review, to adequately consider the greater relevance of air speed as well as the mean radiant temperature variations due to the sky, the sun and ground reflection. The PMV is also adopted in case of outdoor thermal comfort, but in ENVI-MET software, is adapted following German VDI 3787 Standard [10]. These could be interesting case study to improve research.

The study by Matzarikis A. et al. [11] reports the Comfort Sensation Index called Physiological Equivalent Temperature [PET] also in Urban Climate studies [12]. PET is a universal index for characterizing the thermal bioclimate. Hoppe P [13] and Nagato K. and Horikoshi T. [14] adopt modified Effective Temperature (ET*) derived by Gagge AP et al. [15], and P. Brode et al. [16] use the Universal Thermal Climate Index [UTCI]. With the aim to use PMV index to evaluate Outdoor Comfort, the study assumed air temperature, by a meteorological station integrated with software simulation, wind speed, relative humidity (from globe thermometer testing [17, 18]) as main data input and performed Outdoor PMV calculation considering solar incidence irradiation and ground, material and building surface reflections.

## 2. Main Goals

The main objective of the paper is to test and describe the use of a new tool, called ENVI-BUG, that combines Envi-met and LadyBug input data to include several human activities and clothing in Outdoor Thermal Comfort evaluation adopting PMV index that is displayed by 3-D simulations. The first part of the paper describes the standard approach in a case study with the purpose to report the Thermal Comfort Outdoor Map and Section (or Urban Canon) outcomes, the second part describes an innovative approach with a 3-D output, by ENVI-BUG, which includes mannequins PMV graphics.

## 3. Case study: standard approach

The case study is referred to a specific area located in Bologna (44.511°N, 11.397°E) and describes the canyon condition created by some building blocks in ‘Pilastro’ Social Housing District (figure 1).

The simulated scenarios are based on the following assumptions: a) the Urban Canyon Height/Width ratio is 1; the track road and car parks are paved in asphalt; the building vertical surface has several textures and colors (red, grey and white); b) the performed analysis are focused on the horizontal surface of the Urban Canyon, and particularly with reference to the new one way road replacing the car-park; the replacement of the existing road with a green area; the introduction of vegetation and tall trees.


Fig. 1. (a) General layout of 'Pilastro District'; (b) demo-case portion.

### *3.1. Results of PMV indexes in Horizontal Distribution*

The results of simulations before interventions report an homogeneous zone of maximum discomfort in the central area. The data of simulations are referred to 25th July 2006 at 11:00. Figures from 2 to 5 offers a visualization of results by physics variable and PMV values.

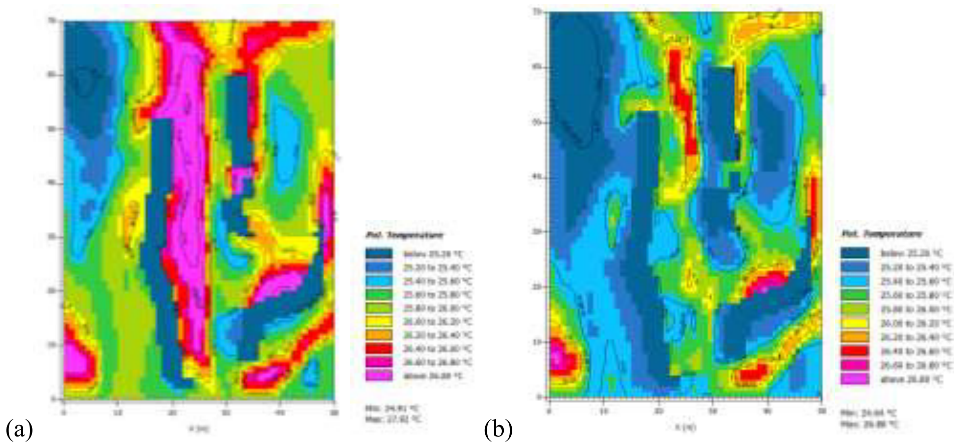



Fig. 2. Comparison between (a) state of art (before) and (b): Temperature distribution

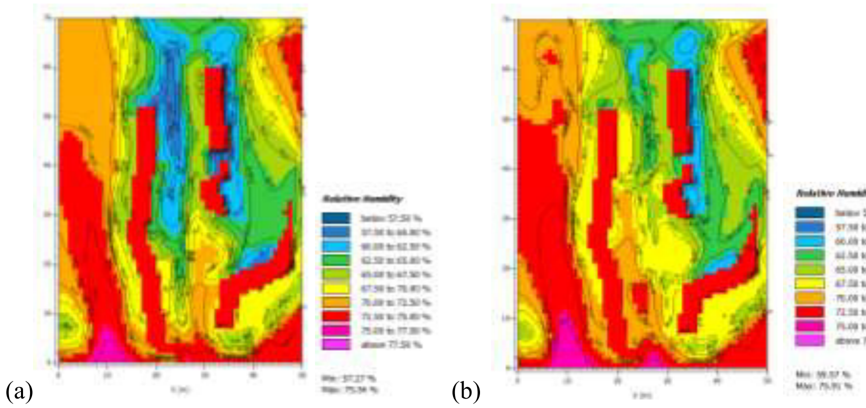



Fig. 3. Comparison between (a) state of art (before) and (b): Relative Humidity distribution

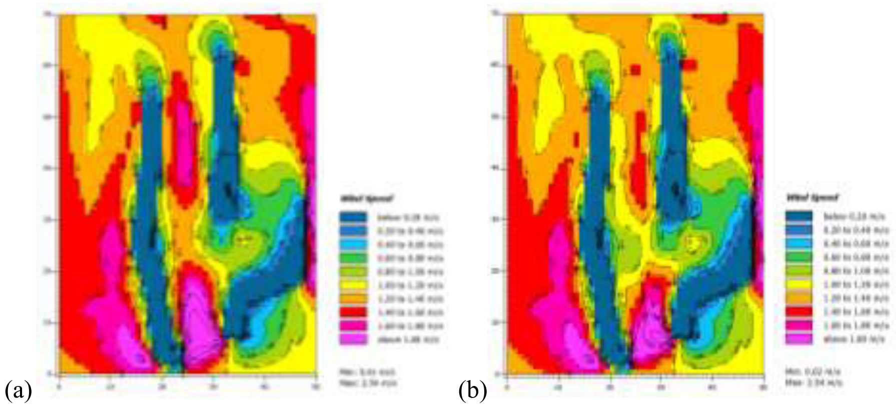



Fig. 4. Comparison between (a) state of art (before) and (b): Wind Speed distribution

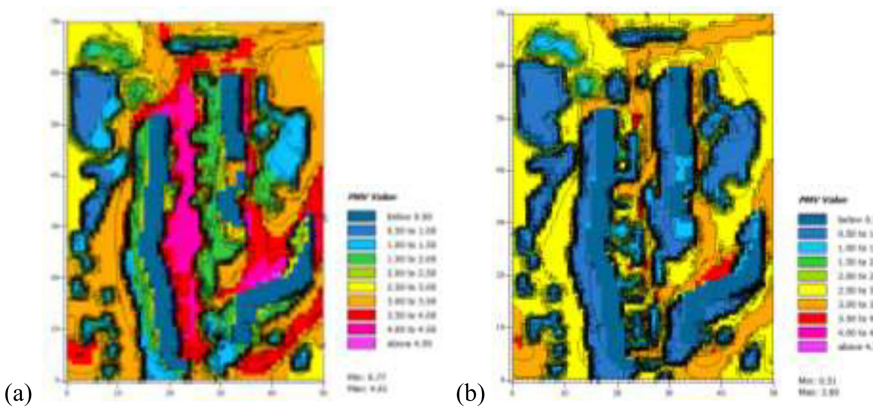



Fig. 5. Comparison between (a) state of art (before) and (b): PMV value distribution. How it can be observed PMV values on street between building shift, from 4.00 (magenta) to 2.5-3.0 (yellow-orange) showing the effectiveness of pavement albedo improvement.

### *3.2. Results of PMV distribution in Vertical Section of Urban canyon*

The second part of simulation concerns Urban Canyon vertical section. The simulation ranges from the ground level up to 3 meters, that is considered enough to visualize PMV vertical distribution. The situation before interventions shows a main discomfort area near the north-facing building. The PMV values are between +1.8 and + 3.4, that depends on: south exposure; a large area with asphalt; lack of trees and vegetation. The situation after interventions shows a decrease of discomfort area, derived by the reduction of the road surface (shifted to the south side); the increase of green areas; the presence of new trees. A numerical analysis of Urban Canyon Section, related to the central zone of the demo-site, is provided in Table 1 where microclimate data and PMV indexes are compared.

Table 1: Central Values of Urban Canyon Section: Scenarios comparison

| status | Temperature (°C) (min-max) | Wind Speed (m/s) (min-max) | Relative Humidity (%)(min-max) | Mean Radiant Temperature (°C) (average value) | PMV (average value) |
|---|---|---|---|---|---|
| Before intervention | 23.98 – 27.75 | 0.09 – 2.76 | 57.59 – 76.20 | 65.56 | 0.34 |
| After intervention | 23.84 – 26.71 | 0.09 – 2.76 | 57.50 – 75.73 | 46.43 | -0.63 |

The main benefit of the envisaged design solutions can be listed as follows: Bulleted lists may be included and should look like this:

- air-temperature reduction, tree shading and evapo-transpiration;
- wind speed reduction, thanks to presence of trees;
- an increase of Relative Humidity, thanks to green grass;
- reduction of mean radiant temperature, thanks to asphalt surface reduction.

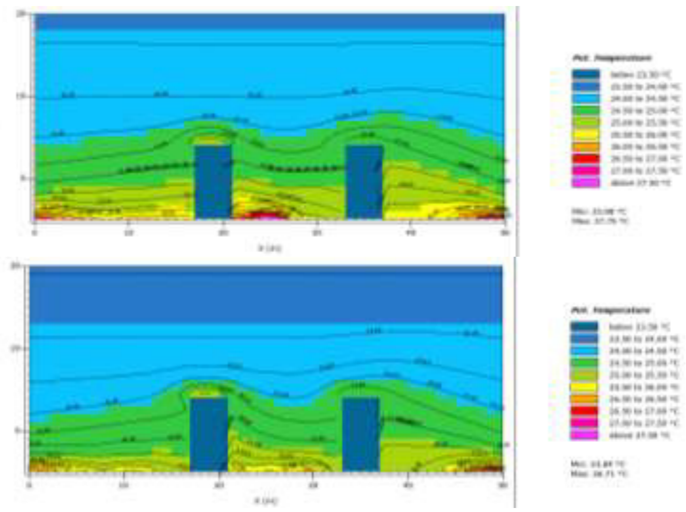


Fig. 6. Urban Canyon section: Temperature distribution (a) before interventions.; (b) after interventions.

As described by Ketterer C. and Matzarakis A. [19], human bio-meteorological evaluation can provide useful information to address design choices especially to those key players such as architects and designers who are involved in renovation and regeneration processes to include environmental friendly solutions based on a better understanding of the microclimate conditions of outdoor spaces. Despite simulation modeling and calculation require expert users (and this is the reason why in most cases this tools are not included in conventional projects) the use of 2D and 3D visualization can be of great help in providing an accessible tool to show the effects of design choices and how they can influence comfort conditions with relation to human activities and wellbeing. The adoption of this kind of tools will certainly improve the understanding of phenomena [20, 21] and will support the studies on the outdoor comfort standardization as remarked by Johansson et. al. [22, 23].

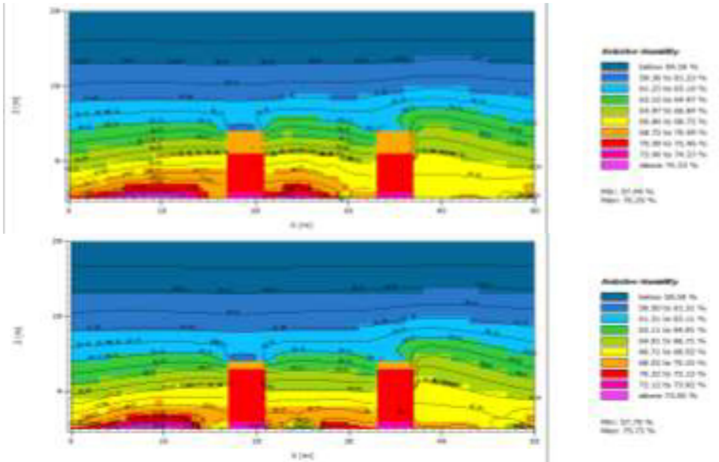


Fig. 7. Urban Canyon section: Relative Humidity distribution (a) before interventions.; (b) after interventions.

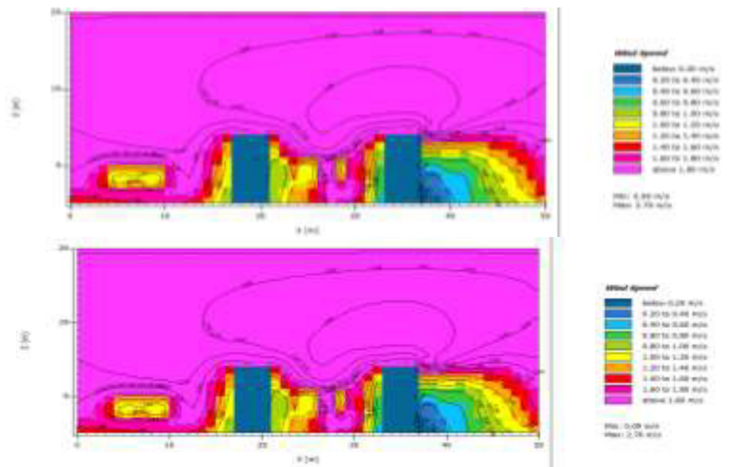


Fig. 8. Urban Canyon section: Wind Speed distribution: (a) before interventions.; (b) after interventions.

## 4. Methodology for results display optimization

The isolines images display in a very immediate and clear way the impacts of the envisaged design solutions becoming a useful graphic output to drive the implementation process and the technological choices. The further step is to describe isoline physics variables (air temperature, relative humidity, etc.) with a Thermal Comfort index PMV and to display the results in a clear output. The adopted methodology requires the simultaneous application of three kind of software: first, ENVI-MET is used to obtain microclimate data distribution in outdoor space, including point- by-point, air temperature, wind speed, relative humidity and mean radiant temperature; second LadyBug (PMV-Index) is used to define human subject and distribute data in 3-D with Rhinoceros and Grasshopper; third ENVI-BUG is used to display 3-D results. The application of ENVI-BUG was described in a previous paper by Fabbri K. et al [24] and this text reports the natural development of the study that has been improved in the while especially for what concerns 3-D output to provide a simplified visualization for architect, engineer, stakeholders and non-expert users to better understand the impacts of technical choices.

### *4.1. The Envi-met Model*

ENVI-MET is a free software to simulate outdoor microclimate values in open spaces; energy and mass exchanges (heating and water vapour); wind turbulence; vegetation effect on the microclimate; bioclimatology data; pollution scattering. ENVI-MET is used to create a simulation model according to an inventory of parameters such as basic settings, building, clouds, sources, soil-data, etc. The typical basic settings define ah hourly and a daily time range (when simulation starts and ends), the total duration of the simulation, wind direction, wind speed at 10 meters height from the soil, initial outdoor temperature and relative humidity. Using Leonardo application is possible to visualize the ENVI-MET outputs in 2D colored maps (or sections depending on the settings) representing the main variables (outdoor air-temperature, wind velocity, relative humidity, mean radiant temperature and PMV) variations according to isolines distribution. The software allow 4 different tools for modeling:

- SPACES – to define the general site layout and the characteristics of materials defining the related surfaces;
- ConfigWizard – to set the specific climate condition of the site (for the present study, climatic data are provided by the Regional Environmental Protection Agency [ARPA] by the tool DEXTER);
- Biomet – to define some set-point parameters to assess comfort condition thresholds and particularly metabolic activity (met), clothing (clo) and the day when the simulation is performed (in the demo-case the 11 am of 23$^{rd}$ July);
- Leonardo – to display the results of calculations into outdoor microclimate maps used to visualize the situation before and after interventions.

The model reproduces the building position and main features, the characteristics of the soil, pavements and vegetation. Climatic data are: Air Pressure (hPa), Wind Speed (m/s), Wind Direction (Sexagesimal), Relative Humidity (%), Air Temperature (°C), Solar Radiation (W/m$^2$). In order to evaluate the potential impacts on outdoor comfort with relation to the overheating phenomena of the summer time (and particularly those connected with UHI), the average monthly temperature was calculated and July was chosen as the hottest period. Then the same process was used to define the hottest day and the 23$^{rd}$ was conventionally adopted. Then the typical hourly variation of the day was re-created. These settings were used in the simulation model to calculate the variations of PMV and of the other parameters before and after the envisaged interventions.

### *4.2. LadyBug and Grasshopper models*

However, the main scope of the study is to obtain 3D simulations, thus the following step has been to process the ENVI-MET outputs using LadyBug, an open source environmental plugin for Grasshopper3D created to help architects and engineers in developing environmentally-conscious architectural design solutions. LadyBug imports standard EnergyPlus Weather files (*.EPW) into Grasshopper and provides a variety of 3D interactive graphics to support the decision-making process during the initial design stages. Developed by Mostapha Sadeghipour Roudsari [25, 26] LadyBug enables Grasshopper software to include microclimate and human body data according to the following categories: Climate data analysis: day degree, wind velocity calculation, PMV calculation, etc.; Climate data visualization: Psychrometric Chart, Sun-path Diagram, Rose of the Winds, etc. Environmental data: solar radiation, sky-view factor, solar exposition, etc.

### *4.3. The ENVI-BUG model*

The ENVI-BUG Software is a generative algorithm (or plugin) that combines ENVI-MET, Rhinoceros, Grasshopper and LadyBug. The aim of ENVI-BUG is to obtain 3-D output results from ENVI-MET and to simulate a punctual distribution of PMV, in 3D space, including several human body and clothing data. The implementation of the process requires to create a “file folder” (called OUT_ENVIMET_CSV) where all input data file are saved, so to allow the plug-in to make a complete file directory. File must be a test (*.csv) file; then a Rhinoceros file (*.3dm) of the case study is created to let Grasshopper process data. Then ENVI-BUG files in *.3dm are created to save any 3-D geometry, tree or graphics changed and to insert a "model-man" to represent punctual PMV; to be created in Grasshopper file (*.gh) environment with ENVI-BUG plug-in. To start ENVI-BUG, "ENVI-BUG.gh" must be drug into Grasshopper Canvas. The ENVI-BUG input files are the ENVI-MET output files on outdoor microclimate data useful to evaluate PMV: mean air-temperature, relative humidity, wind speed, mean radiant temperature. To achieve a realistic evaluation of PMV, data concerning human body metabolism (met) and clothing thermal resistance (clo) have to be included in the process. ENVI-BUG allow to simulate several Human Body settings of data input to obtain the correlated PMV from the ENVI-MET outdoor microclimate data. The ENVI-MET data input for ENVI-BUG is a text file (*.csv) with several 3D (x, y, and z) coordinates where (z) is assumed as output variable.

## 5. Modeling results and 3-D distribution with thermal comfort mannequins

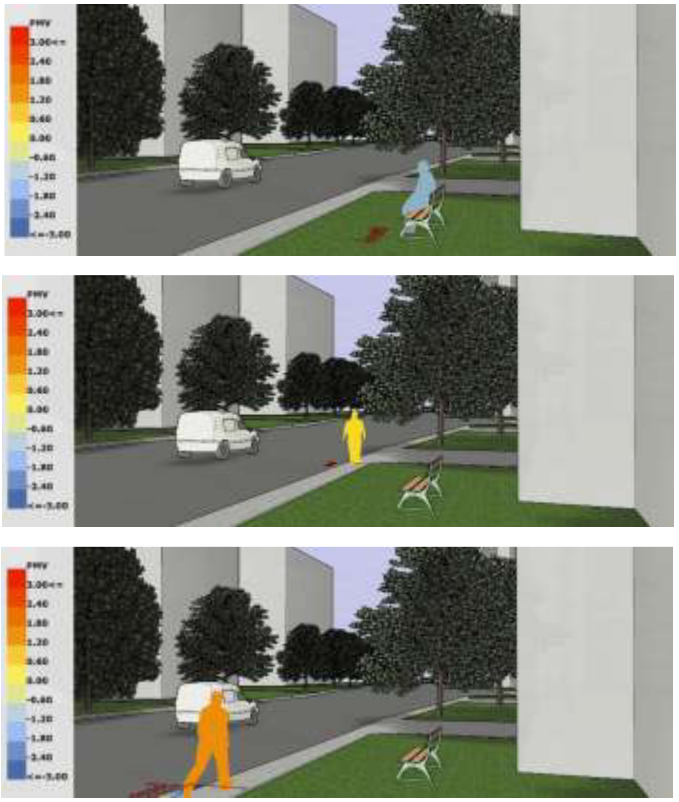
ENVI-MET includes four output modules: Configuration Editor, ENVIEddi, LEONARDO 3.75 and "Xtract tool". This last one is used to export output data. ENVI-BUG enables two kind of simulations with reference to PMV index plan-space distribution - in this it is necessary to set ENVI-MET "Xtract tool" with the human body height at 1.6 m, exporting file data into the *.csv file. The outdoor layout (building, place, train, people etc.) is 3D simulated using Rhinoceros. The Grasshopper file allows ENVI-BUG to read the input file in the file-folder, then ENVI-BUG transforms the input text file (by ENVI-MET output in *.csv) into a point grid. The Envi-met outputs in *.csv are a list of coordinates with (z) as PMV value. When ENVI-BUG is started, it instantly reads the *.csv data in the OUT_ENVIMET_CSV folder and subsequently converts data into point grid values. Grasshopper might be of great help in the case the study would include Urban Canyon evaluation. The components allow: to import data input; to visualize point grid (in section); to select a portion of the grid; to visualize matrix values; to calculate mean values of matrix. Thus, it is possible to visualize each variable result - air temperature, relative humidity, wind speed, mean radiant temperature, and PMV – point by point - in the matrix in horizontal or vertical section.

Fig. 9. The 3-Dimension visualization of PMV vectors (z)

The grid is displayed in Rhino Viewport and each grid node is associated with a PMV number (Fig.9). The software allows to zoom on specific areas if needed. Each single variable is connected with the PMV input data of LadyBug. In addition, the metabolic activity and clothing level (Fig.10) can be displayed. Figure 10 shows a simplified output to understand the effects of design solution in a specific outdoor boundary, with reference to: 1) the kind of human activity, sitting, stand-up or walking, 2) a color is associated to a PMV simulation at the same outdoor microclimate data, so if a orange-mannequin-walking is included any end user can easy understand that the subject feels warm, rather the azure-mannequin-sitting appears neutral or little cool. This can be used to drive decisions concerning the green area or the benches arrangement.

## 6. Discussion

The research of Santamourios, Matzarakis and CRES defines a specific field of research, and in recent years several software for simulation purpose were created accordigly (i.e. Envi-met, Rayman). These studies concern software simulations, physics variables, UHI effect, and, sometimes, users' comfort perception (e.g in case of children, Fabbri K [26]).



(a) (b) (c)

Fig. 10. ENVI-BUG: Example of 3D visualization - the color of the stick figure reports a correlated PMV value using "PMV valued color scale" (a) PMV = -1.2 ; (b) PMV = 0; (c) PMV = + 1.2

The greatest barrier in integrating these analysis in conventional design activities lies in the software complexity both in terms of settings and of users' interface that certainly require an expert user or at least a dedicated resource. The present paper reports how a new tool to improve ENVI-MET can be used to simulate several input data and to show the spatial distribution of PMV. A well defined graphic visualization of PMV index for each point of the urban grid is a powerful tool to address design choices and to select the best option in terms of volumes and vegetation configuration. 3D visualization of microclimate condition is not only a way to provide a better understanding of phenomena, but also to define coherent and comprehensive strategies at district and building scale both for designer and for decision makers as well. The originality of the research reported in this paper deals with the use of simulation to address effective solution at design stage. According to this goal a new software, ENVI-BUG, was developed to display 3-D results with mannequins.

## 7. Conclusions

The paper links the simulations performed on an case-study related to outdoor-comfort-map and canyon section with the outcomes of literature review about outdoor thermal comfort. As maps are usually quite complex to be understood, a new software ENVI-BUG to improve 3-D output was developed to achieve a simplified method for displaying results and make them easier o read for non-expert users. The analysis of microclimate conditions might be of great help in the early stage of the design phase adopting a step by step simulation process that – *with acceptable simulation times* – shall provide a predictive feedback about the envisaged solutions with reference to outdoor thermal comfort.

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