Design choices and comfort outdoors in sustainable neighbourhoods

MONICA ROSSI[1], VALERIA MARTA ROCCO[2], ROBERTO GRASCELLI[1], ALESSANDRO ANTOINE ANDREA MAGNY[3], ANGELA GIOVANNA LEUZZI[1]

[1]Università degli Studi di Camerino - SAD, Ascoli Piceno, Italy
[2] Valeria M. Rocco Architect, Torino, Italy
[2]Politecnico di Torino, Torino, Italy

ABSTRACT: The research intends to verify - in some well-known European residential districts characterized by high levels of sustainability - the relationship between urban and building design choices and the outdoor comfort level. Generally the level of comfort outdoors is neglected since the design focuses on the buildings and not on the "empty spaces between the buildings". In this research four well-known European sustainable neighbourhoods have been selected, have been analyzed based on their design characteristics and have been simulated with ENVI-met (a CFD software) in order to verify the level of comfort outdoors - in particular the values of Predicted Mean Vote, relative humidity, air temperature, wind velocity and direction – in winter and summer climate conditions. The results of the research are: 1) verification of the level of comfort outdoors in the selected sustainable European neighbourhoods; 2) understanding the relationship between design choices and level of comfort outdoors; 3) suggestion and development of design modifications to improve the comfort outdoors in one of the selected neighbourhoods; 4) assessment of the proposed design modifications for the improved neighbourhood with further ENVI-met simulations.
Keywords: sustainable urban design, outdoor comfort, microclimate condition, PMV outdoor simulations.

INTRODUCTION

The design of outdoor spaces close to residential buildings is a key issue not only in the outdoor comfort, but also in the indoor comfort and in the inhabitants' quality of life. In neighbourhoods or in parts of the city, in fact, environmental sustainability and high quality of life do not only depend on the buildings energy performance, but also on a good quality of outdoor spaces. In particular a well-temperate outdoor microclimate reduces the energy demand for heating and for cooling of the adjacent buildings and encourages outdoor social life and relationships between people.

Often, unfortunately, the level of comfort outdoors is neglected since the design focuses on the buildings and not on the *"empty spaces between the buildings"*. Indeed, until a few years ago, in the design of outdoor spaces the level of comfort was not considered as an important goal to achieve. Instead in the last years several studies have focused on outdoor comfort, particularly on the development of calculation models of the urban environment [1,2,3] or on understanding the effects that specific design choices - like urban geometry [4], orientation of urban streets [5] and presence of trees [6] - have on outdoor hydrothermal comfort. Generally the researches carried out so far have usually analyzed every element of the urban project (like urban geometry, streets orientation, green superficies, etc.) separately and have not taken into account interactions between them and the consequent complexity of designing well-temperate outdoor spaces. In urban districts the level of comfort outdoors is affected by multiple factors: *site characteristics* (climate and micro-climate conditions, height above sea level, etc.), *urban design choices* (presence and quality of green spaces and water, outdoor flooring materials, etc.) and *buildings' design choices* (external surface area to volume ratio: S/V , position in relation to winds and cardinal points, materials, etc.).

Accordingly, this research aims to address the issues of outdoor comfort in their complexity (through the analysis of many design choices on the urban scale and on the buildings scale) and to try to understand the interrelationships between the various design choices and the impact that these have on the level of outdoor inhabitants' comfort. This analysis aims to develop guidelines for designers to ensure that new projects of energy efficient neighbourhoods will be finalized not only to save energy, but also to obtain a high level of outdoor comfort and a consequent improvement in the inhabitants' quality of life.

SELECTION OF CASE STUDIES

To achieve this goal, four well-known European residential districts, designed and built as sustainable and high energy efficiency model districts, have been selected as case studies.

The first selected case study is the BedZED (Beddington Zero Energy Development), an environmentally friendly housing development in Hackbridge, London, England. BedZED was built in

2000-2002, has a surface of 1,88 hectares, includes 83 homes and 1405 m^2 of work spaces. This neighbourhood was selected because it has a very low ecological footprint, excellent buildings' energy performance and extremely positive feedbacks. In addition, the small size of this district favoured its use as a "test-district" to develop the evaluation systems and the thermodynamic simulation method. After the "test-district", three bigger and more complex high energy performance districts have been selected: Bo01 in Malmö, Sweden; Solar City in Linz, Austria and Vauban in Freiburg, Germany.

As the selected neighbourhoods are quite famous, it was very easy to find their buildings' characteristics, dimensions, energy performance and used materials in literature. Nevertheless it was complicated to have detailed information about the design choices that aimed at improving the comfort level of their outdoor spaces. Therefore it is not clear if in the selected well-known sustainable residential districts the level of outdoor hydrothermal comfort is well designed on purpose or if it is only an "unexpected consequence" of the design choices that were made based on other priorities.

1st STEP: ANALYSIS OF THE DESIGN CHOICES AT URBAN AND BUILDING SCALES

In the first step of this research, the design choices are analyzed with the intent to understand how these affect the quality of the outdoor space (Tab. 1).

Table 1: Characteristics of the four selected neighbourhoods.

	BedZED	Bo01	Solar city	Vauban
General and climatic characteristics				
Location	London	Malmö	Linz	Freiburg
Dimension [ha]	1,88	20,44	14,75	41
Latitude [°]	51°30′ N	55°36′N	48°18′N	47°59′N
Altitude a.s.l. [m]	15	10	266	278
Inhabitants [-]	250	1.400	5.000	5.000
Energy demand [kWh /m²a]	34	132	22 - 44	0 – 50
Design choices at urban scale				
Urban density [persons /m²]	0,013	0,007	0,034	0,012
Building surface [m² GFA]	12.000	130.000	37.330	76.384
Green surface [m²green /m²]	0,56	0,63	0,76	0,60
Water surface [m²water/m²]	no	0,93 + sea	no	no
Street width [m]	12/6	19/10/5	10/5/2,5	15/10/5
Street surface [m²street /m²]	0,16	0,11	0,10	0,20
Design choices at building scale				
Building orientation	E - W	E - W	various	NE / SW
Building height [m]	6 - 21	3 – 9	7 - 10	10 – 20
S/V [m^2/m^3]	0,93	0,64	0,2 - 0,27	0,18-0,31
Envelope materials	bricks	plaster glass	plaster wood	plaster wood

Furthermore soil characteristics have been evaluated not only qualitatively but also quantitatively. Indeed, several studies [6,7,8] have demonstrated that soil characteristics (materials and permeability) and typology (not only the dimension) of the green surfaces have an important influence on the level of the outdoor hydrothermal comfort. To numerically evaluate the quality of the soil, an efficient index, called R.I.E. has been introduced by the municipality of Bolzano, Italy.

R.I.E. expresses the ratio between the elements modifying the land use and the management of storm water and is usually applied to districts or building complexes to evaluate the environmental quality of the outdoor spaces considering soil permeability and extend and typology of the green surfaces [9]. The municipality of Bolzano provides a free software for calculating the R.I.E.-value and some reference R.I.E.-values depending on the function of the buildings. In residential districts the R.I.E.-value must be greater than 4. In all the selected districts the R.I.E.-values are higher than the minimum value (Tab. 2).

Table 2: R.I.E.-values in the four selected neighbourhoods.

	BedZED	Bo 01	Solar city	Vauban
R.I.E.-value	5,06	4,88	4,76	4,37

2nd STEP: 3D FLUID-DYNAMIC SIMULATIONS

In order to understand if a high energy efficiency of buildings and a good R.I.E.-value are sufficient to obtain an outdoor environmental comfort, the four case studies have been simulated with ENVI-met: a three-dimensional non-hydrostatic computational fluid dynamics software for analyzing small-scale interactions between buildings, surfaces, plants and air inside the urban environments.. "*The model calculation includes: shortwave and long wave radiation fluxes with respect to shading, reflection and re-radiation from building systems and vegetation; transpiration, evaporation and sensible heat flux from vegetation into air including all plant physical parameters (e.g. photosynthesis); surface and wall temperature for each grid point and wall; water- and heat exchange inside the soil system and bio-meteorological parameters*." [10]

The selected districts have been simulated to verify their external environmental comfort level, in particular the values of PMV [-], relative humidity [%], air temperature [K], wind velocity [m/s] and wind direction [deg]. PMV index (Predicted Mean Vote Index), developed by Fanger in 1970 and subsequently improved by Fanger and Toftum [11], is based on thermoregulation and heat balance theories: the human body tries to maintain a balance between the heat produced by its metabolism and the heat lost from the body. This index predicts the mean response of a larger group of people according to the ASHRAE thermal sensation scale where +3 means hot, 0 neutral (comfort condition) and -3 means cold. The outdoor comfort conditions in the districts have been simulated in two days: one in summertime (21st of June - summer solstice) and one in wintertime (21st of Dec. - winter solstice) as these are the days with the lowest and the highest level of sun radiation. The climate data have been taken from Metonorm, software that, from measured, interpolated or imported values calculates hourly of all climatic parameters using a stochastic model. The resulting time series correspond to "typical year" [12]. The correctness of climate data in the simulations have been verified by comparing the climate data calculated (in the course of the day) by ENVI-met with those of the hourly values of the "typical year".

The simulations have been started at 6:00 a.m. and were run during daytime hours up to 4:00 p.m., because daylight hours represent the time of the day with a regular frequentation use of outdoor spaces. The districts' surfaces are divided in square homogeneous modules of 6 x 6 m in the horizontal plan and 2 m in the vertical dimension. The districts have been simulated including the surrounding environment, with the intent to understand how the context (like soil material, green surfaces, water, buildings, roads) affects the microclimate of the neighbourhood itself. The following PMV visualisations are only an example of the simulation results and for clarity they only show the selected areas without surrounding context. The visualisations have been taken at 1,20 m (the height of the bust of a normal height person) in two particularly disadvantaged conditions: on 21st of June at 2 p.m. (the "longest day" at the hottest hour) and on 21st of Dec. at 10 a.m. (the "shortest day" in one of the colder hours).

EVALUATION OF SIMULATION RESULTS

Simulations have shown that in the selected neighbourhoods (famous for their environmental sustainability and low energy demand and with a good R.I.E.-value) not all the outdoor spaces are characterized by a high level of comfort both in summer and winter. Actually the median PMV values are close to the comfort condition in all the selected neighbourhoods, although there are some situations of local discomfort. The numerical simulation results have been evaluated in relation to climate characteristics of the site and to the design choices in order to understand:

- which part of outdoor comfort level is mostly depending on the climatic conditions and which part on the design choices;
- how more appropriate design choices at urban and buildings scales can improve the outdoor comfort level and reduce the "negative effects" of climate conditions.

Analyzing each district individually it is possible to make many considerations about the numerical results and about the influence of the design choices on the comfort outdoors. Short summary follows.

BedZED (Fig. 1) is characterized by a good level of outdoor comfort in summer and an acceptable level in winter. Simulations have demonstrated that a district so small is not significant enough to analyze the relationships between the various parameters that affect the outdoor comfort. Fig.2 and Tab. 3 show the outdoor comfort level in summer - Fig. 3 and Tab.4 in winter.

Figure 1: Aerial view of BedZED, London, England.

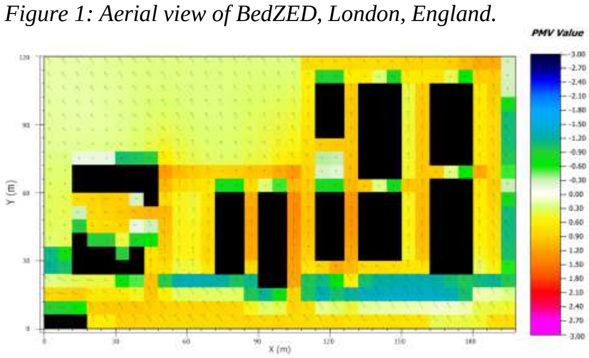

Figure 2: PMV and wind on June 21 st at 2 p.m. - BedZED.

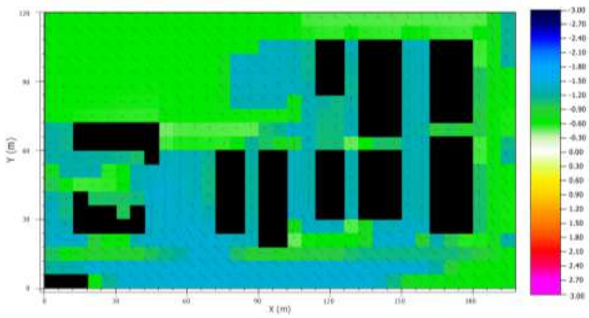

Figure 3: PMV and wind on Dec. 21 st at 10 a.m. – BedZED.

Table 3: Micro-climate conditions in BedZED in summer.

PMV-value	Slightly warm: -0,60 to +1,50. Median: +0,41
Humidity	Rather high relative humidity: 80-90%
Air temperature	Temperatures close to comfort: about 291 K
Wind	Low wind: 0,25 - 2,29 m/s
Influences of design choices - BedZED in summer	
The PMV depends mainly on soil materials and permeability. Presence of asphalt roads between buildings worsens considerably local PMV. Under the particular site climatic conditions and the proximity to a small lake, the presence of high stalk green plants determines areas with too much humidity and therefore discomfort. The best comfort condition is in the area with lawn but without plants. Characteristics of buildings do not affect much the PMV.	

Table 4: Micro-climate conditions in BedZED in winter.

PMV-value	Cool: from -0,60 to -1,50. Median: - 0,97
Humidity	Close to the condensation
Air temperature	Low temperatures: about 277,70 K
Wind	Low wind: 0,55 - 2,50 m/s. Mainly in the streets.
Influences of design choices - BedZED in winter	
The PMV-values depend mainly on high humidity and on soil materials. Asphalt streets and paved surfaces determine a discomfort area and the presence of trees increases too much the relative humidity. The small green surfaces close to the buildings are not sufficient to reduce the negative effect of the asphalt. Characteristics of buildings do not affect much the PMV.	

Bo01in Malmö (Fig. 4), definitely larger than the "test-district", is characterized by a good level of outdoor comfort in summer and a quite discomfort in winter. Figure 5 and Table 5 show the outdoor climate condition in summer - Figure 6 and Table 6 in winter.

Figure 4: Aerial view of Bo01, Malmö, Sweden.

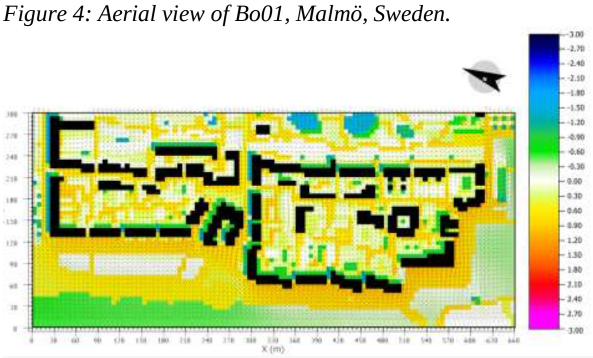

Figure 5: PMV and wind on June 21st at 2 p.m. - Bo01.

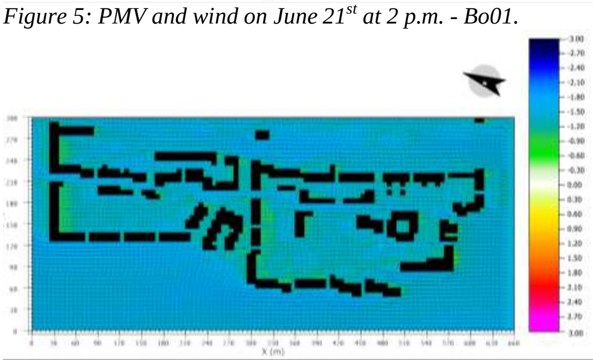

Figure 6: PMV and wind on Dec. 21 st at 10 a.m. - Bo01.

Table 5: Micro-climate conditions in Bo01 in summer.

PMV-value	Comfort condition: -0,30 to +0,90. Median: +0,19
Humidity	Acceptable relative humidity: 64-66%
Air temperature	Temperatures close to comfort: about 290,50 K
Wind	Quite strong sea wind blows towards the district: 4,22 m/s. Low wind in the district: 0,50 m/s
Influences of design choices - Bo01 in summer	
The PMV-values depend mainly on soil characteristics and on buildings' orientation. Indeed in the district there is a good micro-climate condition, thanks to the high presence of green surfaces and because buildings protect the outdoor social spaces from the cold wind from the sea.	

Table 6: Micro-climate conditions in Bo01 in winter.

PMV-value	Cool/cold: from -0,90 to +1,80. Median: -1,20
Humidity	Out of the district towards the sea: close to the condensation. In the district 80%
Air temperature	Low temperatures: about 277 K
Wind	Wind out of the district: 2 m/s. No wind in the district.
Influences of design choices - Bo01 in winter	
The PMV-values depend mainly on soil materials and on buildings' orientation. Buildings are arranged towards courtyard and protect the outdoor district spaces from to high humidity and cold wind. Temperature is low and the design choices don't influence it.	

The biggest part of outdoor spaces of Solar City in Linz (Fig. 7) is characterized by a very low level of comfort in summer and a slight discomfort in winter. Figure 8 and Table 7 show the outdoor micro-climate condition in summer - Figure 9 and Table 8 in winter.

Figure 7: Aerial view of Solar City, Linz, Austria.

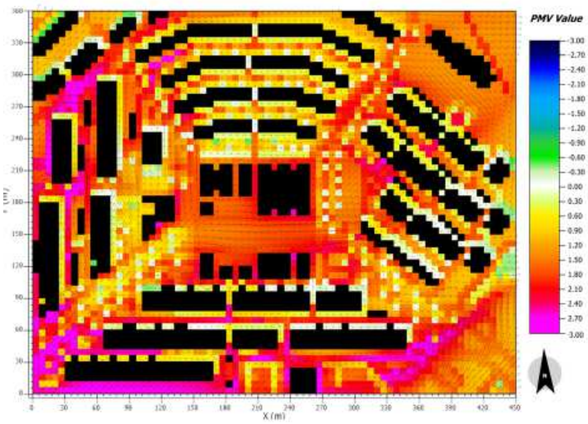

Figure 8: PMV and wind on June 21 st at 2 p.m. - Solar City.

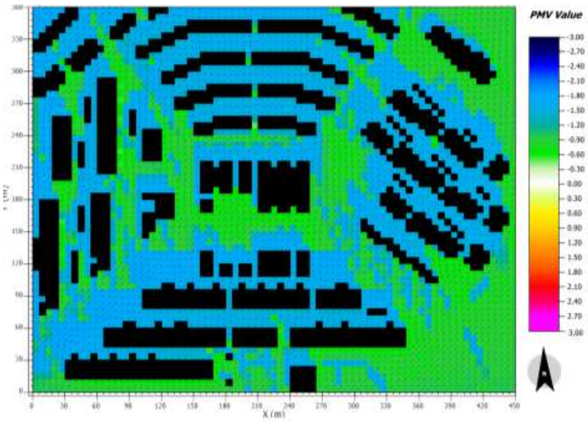

Figure 9: PMV and wind on Dec. 21 st at 10 a.m. - Solar City.

Table 7: Micro-climate conditions in Solar City in summer.

PMV-value	Inhomogeneous: +0,30 to +1,50 Median: +1,45
Humidity	Acceptable relative humidity: 52-68%
Air temperature	Warm/hot temperatures: 292 -298K
Wind	Low wind: 0,25 - 1,50 m/s
Influences of design choices - Solar City in summer	
PMV-values depend on soil characteristics and street orientation through prevalent winds. The presence of paved surfaces and asphalt streets determines a discomfort condition also in the nearby areas. The presence of big and long streets (one of which is in the direction of the prevailing wind) contributes to worsen the discomfort condition in the main square, where sunscreens are not always sufficient to constrain the sun radiation. Trees minimize the negative effects of the asphalt, but are unable to cancel them. The green outdoor spaces between high density low buildings reach the highest level of comfort.	

Table 8: Micro-climate conditions in Solar City in winter.

PMV-value	Inhomogeneous -0,70 to +2,50 Median: -1,55
Humidity	Acceptable relative humidity: 75-80%
Air temperature	Low temperatures: about 273 K
Wind	Very low wind: 0,10 - 0,89 m/s
Influences of design choices - Solar City in winter	
PMV-values are inhomogeneous and depend on soil characteristics. The paved surface of the main square increases the level of comfort outdoors. Generally the temperature is very low.	

Vauban (Fig. 10) is characterized by a good level of comfort in summer and a slight discomfort in winter. Figure 11 and Table 9 show the outdoor micro-climate condition in summer – Table 12 and Figure 12 in winter.

Figure 10: Aerial view of Vauban, Freiburg, Germany.

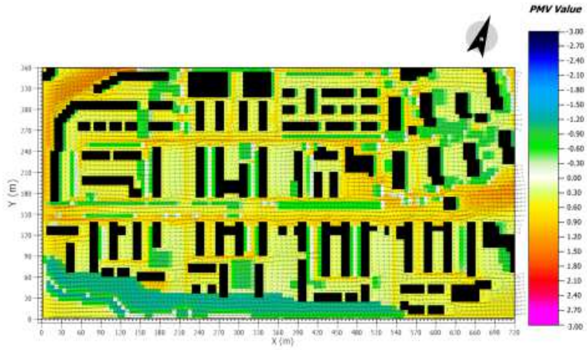

Figure 11: PMV and wind on June 21st at 2 p.m. - Vauban.

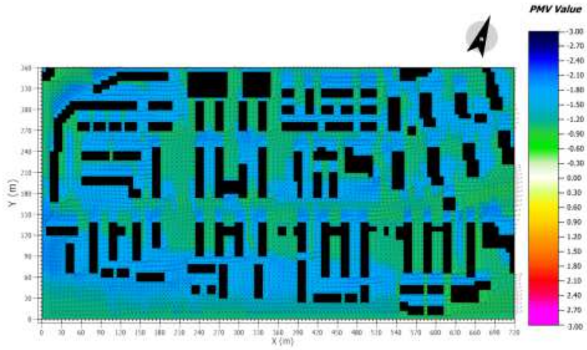

Figure 12: PMV and wind on Dec. 21 st at 10 a.m. - Vauban.

Table 9: Micro-climate conditions in Vauban in summer.

PMV-value	Comfort condition: -0,80 to +0,80 Median: +0,37
Humidity	Acceptable relative humidity: about 70 - 80%
Air temperature	Temperatures close to comfort: about 290,50 K
Wind	No wind: 0,13 - 0,70 m/s
Influences of design choices – Vauban in summer	
The PMV-values depend mainly on soil materials and permeability. Presence of diffused green and the low local temperature help to get a good level of outdoor comfort. The tall trees and the river on the south part of the site determine an almost excessive increase of relative humidity.	

Table 10: Micro-climate conditions in Vauban in winter.

PMV-value	Cool/cold: -1,20 to -1,80 to Median: -1,36
Humidity	Close to the condensation
Air temperature	Cold temperatures: about 273 K
Wind	Low wind: 1,25-3,00 m/s
Influences of design choices – Vauban in winter	
The PMV-values depend mainly on the very low temperatures and the high relative humidity. The design choices are not always able to reduce the negative effects of temperature on the level of outdoor comfort. The presence of many tall trees contributes to greatly increase the relative humidity.	

DESIGN MODIFICATIONS TO IMPROVE THE COMFORT OUTDOORS

Based on the results of the fluid-dynamic simulations and on the considerations on the site characteristics and design choices, design modifications at urban and buildings scales have been developed to improve the comfort outdoors in the selected neighbourhoods.

In particular, the attention has been focused on the summertime, when the inhabitants spend more time outdoors. Simulations have been shown also that design choices influenced more the summer than the winter outdoor comfort condition and that the design choices at the urban scale are more efficient than those at the building scale. The neighbourhood with the worst level of outdoor comfort in summer is Solar City so it has been used as "example district" to test the developed design guidelines.

The proposals for improvements at the urban scale are:

- changing the angle of the main roads so that they aren't parallel to the prevalent winds (in the specific case of the simulations: provide windbreak elements);
- increasing the amount of green (tall trees and grass) in the area of the main square and of the main streets;
- inserting a selective solar-shading system more efficient than the current at the main square.

The proposals for improving at the building scale are:

- bringing together the tallest buildings (located in the East, West and South part of the site) and reduce their height;
- increasing the overhang of the roofs facing south.

VERIFICATIONS OF THE IMPROVED DISTRICT

The "improved Solar City" has been simulated with ENVI-met on June 21st from 6 a.m. to 4 p.m. Simulations results (Fig. 12 and Tab. 11) show that the design modification are very efficient and that the PMV-values have been improved, particularly in the main square and in the main street.

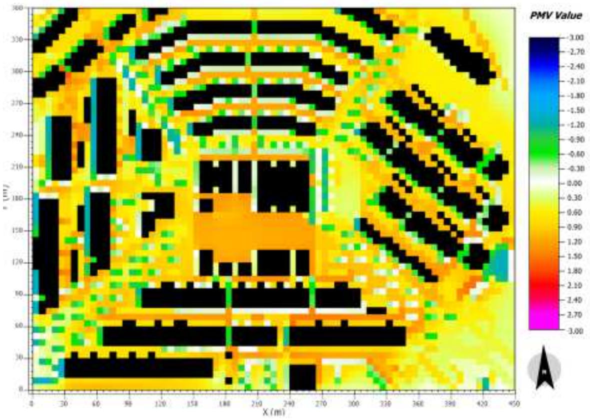

Figure 12: PMV and wind on June 21st at 2 p.m. - "improved Solar City".

Table 10: "Improved "climate conditions – Solar City in summer.

PMV-value	Close to comfort -0,90 to 1,20. Median: +0,30
Humidity	Acceptable relative humidity: 55-70%
Air temperature	Warm temperatures: 293K
Wind	Low wind: 0,20 - 1,50 m/s

CONCLUSION

In conclusion this research has demonstrated that:

- Also in the design of some well-known residential districts characterized by a high energy efficiency and good R.I.E.-value, the level of the outdoor comfort is not always very high. The median PMVs are often close to the comfort condition, but there are many "local discomfort hotspots" depending on design choices.
- Appropriate design choices at urban and at building scale can be sufficient to obtain an outdoor environmental comfort, particularly in summer.
- Design choices at urban scale influence more the level of outdoor comfort than those at building scale.
- It is possible to develop proposals for improving the outdoor comfort of existing districts based on a careful analysis of the climatic conditions, of the effects that the design choices have on the micro-climate and of the interaction between the many involved parameters.
- Easy design guidelines (like those developed for Solar City in this paper) can improve essentially the outdoor comfort of the relational spaces and can determine as consequence an improvement of the inhabitants' quality of life and of the relationships between people.

REFERENCES

1. Bruse M. and H. Fleer, (1998). Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. *Environmental Modelling & Software*, 13: p. 373-384.
2. Orosa J.A., (2009). Research on general thermal comfort models. *European Journal of Scientific Research*, 27: p. 217-227.
3. Yang X., Zhao L., Bruse M., Meng Q., (2012). An integrated simulation method for building energy performance assessment in urban environments. *Energy and Building*, 54: p. 243-251.
4. Krüger E.L., Minella F.O., Rasia F., (2011). Impact of urban geometry on outdoor thermal comfort and air quality from field measurements in Curitiba, Brazil. *Building and Environment*, 46: p. 621-634.
5. Ali-Toudert F. and H. Mayer, (2006). Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. *Building and Environment*, 41: p. 94-108.
6. Vos E.J., Maiheu B., Vankerkom J., Janssen S., (2012). Improving local air quality in cities: To tree or not to tree?. *Environmental Pollution*, in press, available online: http://dx.doi.org/10.1016/j.envpol.2012.10.021
7. Gaitani N., Santamouris M. and Mihalakakou G., (2005). Thermal comfort conditions in outdoor spaces. In *International Conference Passive and Low Energy Cooling for the Built Environment*. Santorini, Greece, May 19-21.
8. Cocci Grifoni R., D'Onofrio R., Sargolini M., (2012). In search of new paradigms to interpret and design the contemporary city. In *Sustainable City VII* Ancona, Italy, May 7-9.
9. Procedura R.I.E. (Riduzione dell'Impatto Edilizio), [Online], Available: http://www.comune.bolzano.it
10. ENVI-met, [Online], Available: www.envi-met.com
11. Fanger P., Toftum J., (2002). Extension of the PMV model to non-airconditioned buildings in warm climates. *Energy and Buildings*, 34: p. 533-536.
12. Metonorm [Online], Available: www.meteonorm.com