Introducing a Hybrid Energy-Use Model at the Urban Scale: The Case Study of Turin (Italy)

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Abstract

As in the past, urban morphology plays an important role for the livability of the city and for both outdoor and indoor human comfort. Nowadays, the relationship between the urban form and energy consumption has been estimated by many researchers, showing how the morphological aspects influence the energy consumption of the buildings, the thermal comfort of the urban spaces and the district air quality. Conversely, in recent urban planning processes, these morphological aspects are undervalued or not considered, any more. To reinforce their importance, this paper presents an optimization of a previous statistical model made by the complementary use of bottom-up and top-down models to evaluate the energy-use of residential buildings. The average intensity of energy-use data for residential buildings with a different age, shape, and heated volume has been corrected using the urban energy-modelling tool CitySim Pro. This hybrid approach describes how the urban form, the solar exposure of the buildings, the outdoor spaces and the material characteristics of the urban surfaces impact the energy performance of the buildings. This research analyzed a case study in the city of Turin (Italy) to quantify the space heating energy-use of residential buildings. To estimate the buildings heating energy-use, the urban energy simulation tool CitySim Pro was used, and the building information model of Turin was validated with the real consumptions data based on two years of monitoring data. The results of this research show a direct correlation between the buildings energy-use and the following five urban variables: Building Coverage Ratio, Aspect ratio, Main Orientation of the Streets, Solar factor, and albedo coefficients of outdoor surfaces. The building density and the urban canyon phenomenon play an important role, as they reduce the heating energy-demand in medium density urban contexts. Furthermore, the solar exposure strongly influences energy demands, especially for high buildings density contexts, as well as the presence of green surfaces. The proposed methodology, based on a multivariate compensative approach, can support urban planning to improve the energy sustainability of the cities.

1. Introduction

According to the European Commission (European Commission, 2016), buildings are responsible for 40 % of energy consumption and 36 % of CO_2 emissions in the EU. Within this frame, the buildings energy efficiency is an increasingly important instance for environmental sustainability. Recent studies demonstrate that the building energy consumption depends not only on the climate, the envelope characteristics, and system efficiencies, but also on the surroundings urban texture (Delmastro, 2015). This means that, in order to decrease the buildings' consumption, the urban context design plays an important role, as well as the design at the building scale. Several studies show the impact of the urban form on buildings' energy consumption. The first studies date back to the '70s, when Martin and March (1972) analyzed the urban form for what concerns soil occupancy. Although this study does not take into account the effects of urban density on energy consumption for the heating or cooling demand of buildings, it laid the foundations for future research. Baker and Steemers' study (1996) focuses on the importance of using tools, in the early stages of architectural design, that can provide the annual primary energy consumption for lighting, cooling, heating, and ventilation as output results. For this purpose, Steemers

developed the LT method (Lighting and Thermal) for non-residential buildings, which takes into account the orientation of the facades and solar gains, by defining passive and not passive zones inside the buildings. Thanks to the development of new software, capable of taking into account the complexity of the urban texture, the impact of the urban form on building energy consumption is becoming an increasingly important research topic. In his study, Kaempf et al. (2010) propose a methodology to minimize the buildings' energy consumption in urban areas by using a new evolutionary algorithm, so called hybrid CMA-ES/HDE. Through this methodology, three urban typologies have been parameterized (terraces flat roofs, terrace courts, and sloped roofs) in order to find an optimal urban form for the exploitation of solar gains. The study by Ratti et al. (2005) analyze the impact of the urban form on building energy consumption, by taking into account some urban parameters such as the Aspect Ratio and the orientation of the facades, and tries to overcome the concept that the Surface to Volume ratio (S/V) is the main influential factor in urban energy consumption. In 2014, Rode et al. (2014) try to determine the theoretical energy efficiency as a function of the city's spatial conformation. For this purpose, the authors take as case studies standard urban areas of 500X500m in the cities of Amsterdam, Berlin, Paris, and Istanbul, and some urban parameters such as Building Density, Building Coverage Ratio, Building Height, and Sky View Factor. As a conclusion, this study shows that the highest and compact buildings have greater energy efficiency than the low and isolated buildings. Moreover, Delmastro's study (Delmastro et al., 2015) takes into account some urban parameters (such as the Building Coverage Ratio, Building Density, Building Height, Aspect Ratio, and Solar Factor) to show how the urban form influences the heating demand of residential buildings in Turin (Italy). The vastness and variety of the studies carried out in the field of energy sustainability at an urban scale show how a good design of the urban texture is crucial for buildings' energy consumption reduction. Conversely, there are still few researches that demonstrate the impact of the urban form on buildings' energy demand in a quantitative manner.

This study aims to propose a methodology to analyse how some urban parameters affect the buildings' heating energy-use.

2. Methodology

This study starts from the energy consumption models for residential buildings at an urban scale, developed from the research project "Cities On Power" (Mutani, 2015; Mutani et al., 2016). With these simplified models, the energy-use for space heating and hot water production was represented for about 50 municipalities of the Metropolitan City of Turin. The energy-use models were based on energy consumptions data at buildings and municipal scales with a statistical approach and applied with a GIS-based tool. The results of this paper will improve the previous models, taking into account the differences in buildings' heating energy needs, due to their surrounding context. The assumption is that the buildings' measured heating consumption is partly influenced by its characteristics and climate but also by the surrounding context and its microclimate variations:

$$\left.\frac{kWh}{m^2 \cdot year}\right|_{measured} = \left.\frac{\mathrm{kWh}}{\mathrm{m}^2 \cdot \mathrm{year}}\right|_{building} \pm \left.\frac{kWh}{m^2 \cdot year}\right|_{context} \quad (1)$$

For this analysis, a territorial unit called "census parcel", corresponding to a block of buildings, was considered and the buildings' heating demand variations were correlated to the urban form, the solar exposure, and the outdoor materials. In particular, six urban parameters, calculated with ArcGIS 10.1.2 (ESRI), were taken into account:

- the Building Coverage Ratio (m^2/m^2) is the ratio between the built area and the total census parcel area;
- the Aspect Ratio, or H/W ratio, (m/m) is the ratio between the building height (H) and the distance between buildings (W);
- the Main Orientation of the Streets (-) defines the quality of the streets' orientation. A MOS=1.3 defines the best orientation (East-West), while a MOS=0.8 corresponds to the worst one (North-South) (Delmastro, 2015).
- the Albedo of external surfaces (-) indicates the reflecting power of a surface;

- the Solar Exposure, or H/H_{av}, (m/m) is the ratio between the building height (H) and the surrounding buildings average height (Hav);
- the Solar Factor, a statistical parameter equal to $MOS*H/H_{av}$ (Delmastro, 2015).

In order to analyse different urban layouts, the software CitySim Pro was used, proposing consistent variations on the urban form and outdoor materials, compared to the real case study. CitySim is an urban energy modelling tool (Robinson et al., 2009), able to quantify the energy demand from the building to the urban scale. The thermal model of buildings is based on an analogy with the electrical circuit, more precisely on a resistor-capacitor network (Robinson et al., 2009; Kämpf and Robinson, 2007). The radiation model is based on the Simplified Radiosity Algorithm (SRA), where the radiant external environment is represented by two hemispheres, discretized into several solid angles (Robinson and Stone, 2005). CitySim was also certified by the IEA BESTEST (Walter and Kämpf, 2015). In order to understand the impact of greening the outdoor environment, further models are under development, able to quantify the evapotranspiration as well as the impact of trees on the urban microclimate (Upadhyay et al., 2015; Coccolo et al., 2015). CitySim provides the energy needs of buildings on hourly values, by including the interactions within the built environment. As an example, the interrelations between buildings, as well as the mutual shading, are calculated. In order to perform the calculations, hourly weather data are required, as the one created by the software Meteonorm (Remund et al., 2015), or by on-site monitoring. The geometry of urban layouts is created by CAD modelling tools, and it is directly imported in the software. The physical properties of buildings (i.e. envelope, glazing ratio, occupancy profile, and energy systems) as well as the ground covering are defined within CitySim Pro. The proposed case study is a traditional settlement in the central district of the city of Turin (IT) called "Crocetta" characterized by old and high-rated row buildings.

3. Results

Turin is an important city in the northwestern part of Italy with about 900,000 inhabitants, 10 Districts, 3,839 census parcels, and about 40,000 residential buildings. 86 % of residential buildings in Turin were built before the '70s, and 43 % are characterized by a Surface to Volume ratio S/V <0.4 and a compact form. The Crocetta district (Fig. 1) is a portion of District 1, in the historic centre of Turin, with 16 census parcels and a total area of about 160 km^2. The data on the buildings' period of construction were obtained thanks to a Geographical Information System model. This information allowed us to assign to each building its construction system, in terms of materials, type of envelope and level of thermal insulation (Table 1).

Table 1 – Physical characteristics of Crocetta buildings (in brackets the number of buildings used for the energy-use models validation)

Construction period	U_{wall} W/m^2/K	U_{window} W/m^2/K	g_{value} (-)	Glazing ratio(%)	N° of Buildings
Before 1945	1.5	4.7	0.85	18	150 (24)
1946-1970	1.15	4.2	0.75	19	69 (16)
1971-1980	0.81	4.9	0.75	34	18 (2)

The roads and the courtyards in the Crocetta district are made of asphalt with an average albedo coefficient of 0.17. The average building height is about 20 meters and the urban form can be considered homogenous, as the urban parameters of the census parcels are similar (Table 2).

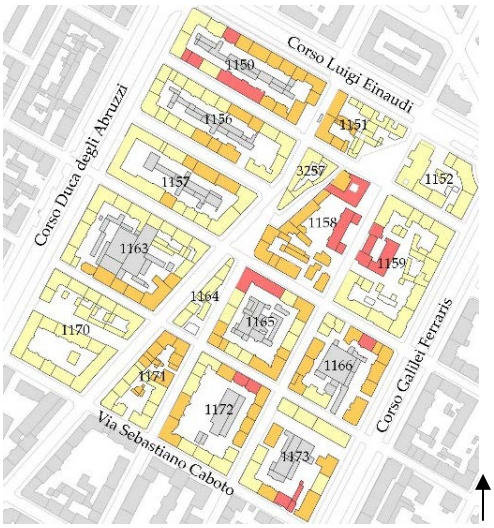

Fig. 1 – The Crocetta district with census parcel numbers and the buildings' period of construction: before 1945 (yellow), from 1946 to 1970 (orange), and from 1971 to 1980 (red)

Table 2 – Crocetta urban parameters: Building Coverage Ratio (BCR), Aspect Ratio (H/W), Main Orientation of the Streets (MOS), and Albedo (A)

Crocetta	BCR m^2/m^2	H/W m/m	MOS (-)	A (-)	H/H_{av} (m/m)
Average	0.41	0.89	1.3	0.17	1.02
Dev.st	0.07	0.17	0.25	0.01	0.34

The building heating energy-use was calculated with CitySim Pro by considering the following input data: an internal temperature of 20 °C, a number of air changes per hour of 0.5 as infiltration rate, an occupancy profile based on ASHRAE Standard for residential buildings (ANSI/ASHRAE/IESNA Standard 90.1-2007 - Energy Standard for Buildings Except Low-Rise Residential Buildings), and a traditional heating system connected with the district heating network. As regards the outside temperature, two hourly climate files were generated by Meteonorm, and further calibration of the air temperatures according to the data measured by the weather station "Via della Consolata" in Turin. Meteonorm is a worldwide well-known meteorological database; the hourly data provided by the software are based on the average irradiance data for the period 1991-2010 and the average temperature data for the period 2000-2009. For the dynamic simulations two heating seasons were considered (in Table 3 the average monthly air temperatures): the season from October 15, 2013 to April 15, 2014 and the season from October 15, 2014 to April 15, 2015.

Table 3 – Average monthly air temperatures in Turin for the heating seasons 2013-14 and 2014-15

Air temp. [°C]	Oct	Nov	Dec	Jan	Feb	Mar	Apr
2013-14	14.6	9.2	5.5	5.7	7.1	12.0	15.6
2014-15	16.2	10.6	6.6	5.6	5.4	10.8	15.1

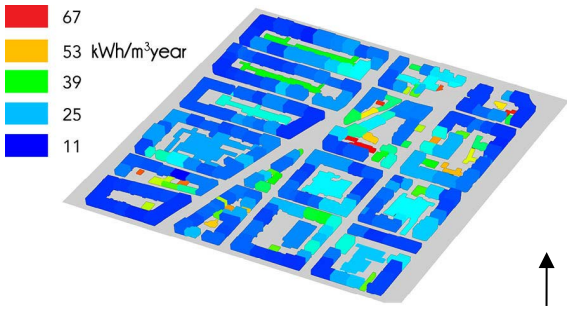

Fig. 2 – Yearly heating demand of Crocetta District calculated by CitySim Pro

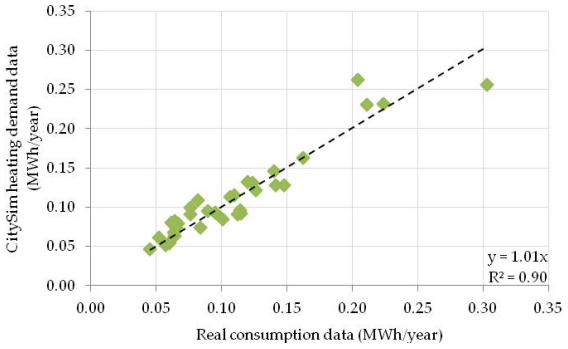

Fig. 3 - Linear relationship between the buildings heating demand calculated by CitySim Pro and the real consumption data

The building space heating consumption data calculated by the software (Fig. 2), were compared to the real building consumption data, provided by the district heating company "IREN". The validation of the model took into account 42 buildings, with different periods of construction. As shown in Fig. 3, there is a strong correlation between the calculated data and the real data (R^2=0.9). As mentioned before, the aim of this research was to define how urban variables can influence space heating consumptions. Since the urban texture in the Crocetta district

is very homogeneous, new urban layouts were created in order to achieve greater changes in the urban form, useful for determining major differences in buildings' heating energy-use. For this purpose, the census parcel numbers 1,154 and 1,163 (Fig. 4), that have the highest number of validated buildings belonging to the same construction period (before 1945), were taken into account.).

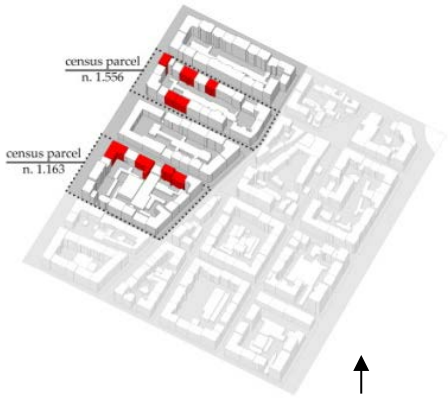

Fig. 4 – Census parcel n. 1,156 (top) and 1,163 (bottom) taken into account in order to analyse the influence of urban form on buildings' heating demand

In this research, every single urban variable was changed one at the time to evaluate their influence on energy consumptions, while the buildings' characteristics, such as the surface to volume ratio, the physical characteristics of the envelope, and system performances, remain unchanged. First of all, new urban layouts were created by varying BCR from 0.25 to 0.55 (Fig. 5). Next, the width of the roads was changed to evaluate the H/W parameter effect. In this case new models were created with values of aspect ratio H/W from 0.4 to 1.9. New layouts were also created by rotating the blocks of 30°, 60° and 90° in order to have configurations with MOS of 0.9, 1 and 1.1 (Fig. 6). Finally, new configurations were created with different values of Albedo coefficient: 0.07 (new dark asphalt), 0.5 (light asphalt), 0.25 (dark green), and 0.35 (light green).

After creating the new configurations, the dynamic simulations were performed with CitySim Pro, in order to obtain the new buildings heating consumption data.

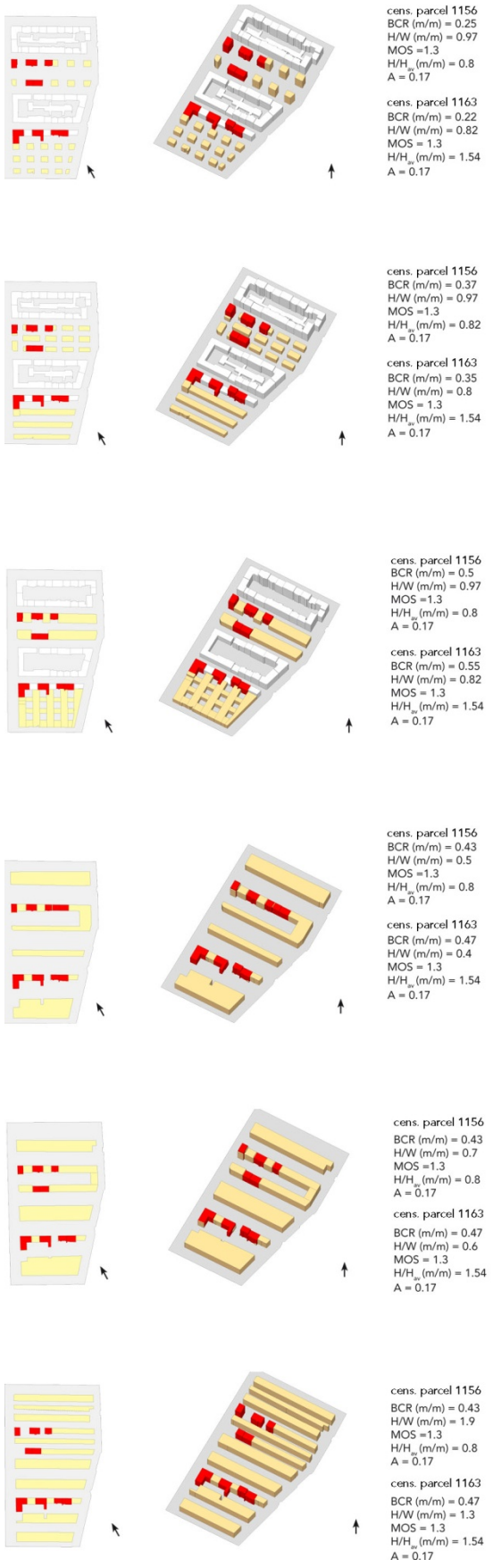

Fig. 5 – New layouts of BCR and H/W

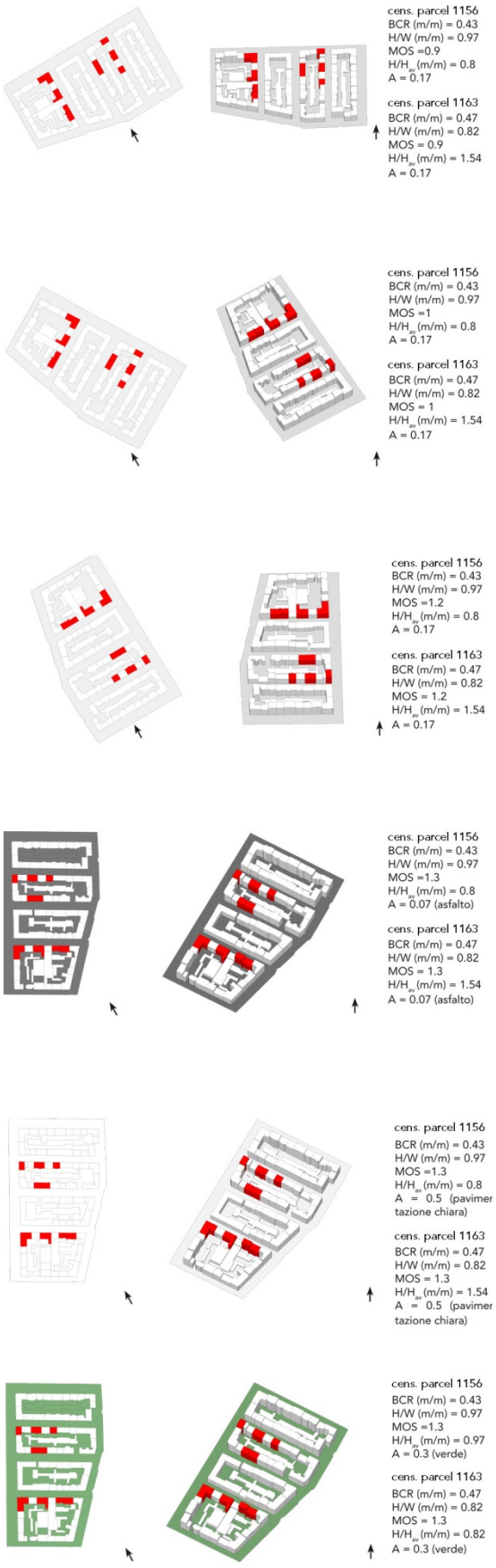

Fig. 6 – New layouts of Albedo and MOS

The results show how energy consumption varies in the different urban layout as a function of the urban variables. The trend of the heating energy-use as a function of the BCR and H/W parameters is parabolic as shown in Fig. 7. In particular, for high and very low values of BCR and H/W the heating demand is higher, while for medium values of the parameters, energy consumptions are lower.

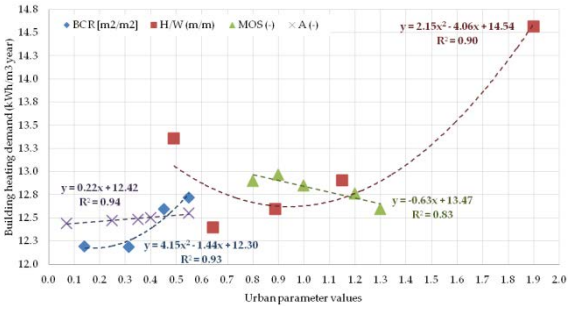

Fig. 7 – Buildings heating demand trend as a function of urban parameters: BCR (rhombus), H/W (squares), MOS (triangles) and Albedo (crosses)

The results show an inversely proportional correspondence between the buildings' heating energy-use and MOS: the best orientation, in order to reach reductions in heating consumption, is West-East (MOS=1.3). Heating consumptions increase linearly by varying the albedo coefficient A: the buildings' heating energy-uses are lower with darker surfaces in the surrounding outdoor spaces (i.e. with new asphalt: A=0.07). Finally, knowing how the buildings' heating energy-use varies with the different urban variables BCR, H/W, MOS, H/Hav and A, a further analysis was performed considering all the buildings' heating consumption results. Starting from Equation 1, the aim of this analysis was to define a correlation that allows calculating the buildings heating energy-use as a function of the urban parameters, specifically for the Turin case study. For this purpose, a multiple regression analysis was performed, considering the urban variables mentioned in paragraph 2, minimizing the differences between measured and calculated energy consumption data:

heating energy-use intensity [kWh/m^3/year] =
$-0.40*(BCR)^2 + 1.23*BCR - 0.05*(H/W)^2$
$+1.95*H/W - 1.96*H/H_{av} - 3.52*MOS$
$+0.63*A + 0.12*G + 17.78.$ (2)

In Equation (2), the G value is a discrete variable that indicates the presence of greenery: equal to 1 when the surrounding ground surface is green or equal to 0 if there are no green outdoor surfaces. In Fig. 8 the influence of the different urban variables of Equation 2 is represented for the analysed urban layouts. The aspect ratio H/W, the solar exposure H/Hav, and the main orientation of the streets MOS are the most energy-consumption related variables. This demonstrates the high influence of the urban canyon phenomenon and the solar exposure in space heating energy consumptions.

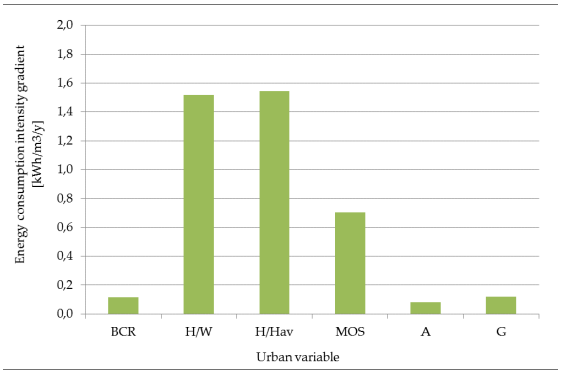

Fig. 8 – Heating intensity gradients related to variations in the urban variables (on 199 buildings' simulations)

Fig.s 7 and 8 reveal also how the surrounding environment can play an important role in energy sustainability. It is possible to guide the urban design with compensatory measures, to reduce energy consumptions; for example, the high buildings density requires high values of H/W and then high heating consumptions, but with a good solar exposure (high MOS and H/H_{av}) the energy-use decreases. Also the selection of materials for outdoor spaces (i.e. A and G) can help in increasing the energy sustainability of a district.

4. Discussion and Conclusions

Reducing buildings' energy consumption is one of the crucial problems that architects and urban planners are called to solve every time they face the design of new buildings or the renovation of existing parts of the city. The initial goal was to demonstrate the incidence of the urban form on buildings' space heating demands. The results show that the heating energy-use trend, as a function of BCR and H/W parameters, is parabolic. In a very dense urban context, in fact, solar gains are lower and the shadows, generated by the buildings, cause a lowering of the outdoor air temperature, and so, an increase of the buildings' heating demand. In less dense urban contexts, instead, the buildings are more exposed to solar radiation but there is no urban canyon effect, i.e. the incident solar radiation is not trapped in the urban texture and the outside air temperature is not increased. For this case study, the optimum values of BCR, in order to reach a reduction in heating demand, is 0.3, which means an urban context in which the built area is the 30 % of the total site area. Moreover, very high values of the H/W parameter (considering the buildings' height constant) indicate the presence of very narrow streets. In these conditions too, there is not the urban canyon effect and the solar radiation cannot penetrate. For very low Aspect Ratio values, however, the roads are very wide and, even in this case, the effect of the urban canyon does not occur, since the solar radiation is not trapped within the external walls of the buildings. The optimal situation is when H/W values are equal to 0.9, a situation in which the street width is approximately equal to the building height. Additionally, the results show that the best orientation of the streets is West-East, which means that if a census parcel (or a building block, or a district) has that main orientation, the building energy efficiency is optimal. The trend of energy consumption as a function of Albedo is increasing linear, which means that very dark surfaces (characterized by low values of Albedo) absorb more solar radiation and cause a rise in the outside air temperature. This corresponds to a decrease of the thermal gradient between the buildings' internal air temperature and the outside air, and a reduction of heat losses. This study doesn't want to be the arrival point in the definition of new urban strategies to reduce the buildings' energy consumptions, in fact it tries to define a common methodology. The future developments of this research may provide for the application of the illustrated methodology in situations of hot or arid climates. In South America or Saudi Arabian cities, in fact, the control of the incident solar radiation plays an important role in the reduction of buildings' cooling energy demands. By analyzing how the urban parameters influence the buildings'

cooling demand, a complete picture of the problem could be delineated, because the rules found for a temperate climate (such as the case of Turin) may not be valid for an arid context.

This research tries to define a method for the determination of the urban form influence on the buildings' heating demands. In this sense, the illustrated methodology could be useful for the design of the new Zero Energy Building districts as it could provide a valuable tool to increase the buildings' energy efficiency, since it would not only optimize the envelope or system performances, but also the form of the urban context in which the building is located.

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