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Effects of urban compactness on the building energy performance in Mediterranean climate

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Abstract

This work explores the double effect of urban compactness on building energy performance in a Mediterranean climate, namely the increase of urban heat island (UHI) intensity and the decrease of solar radiation availability on building façades. The energy demand of a test apartment has been calculated under varying conditions of UHI intensity and solar radiation for different urban textures. Results show robust relationships between the energy demand and the 'site coverage ratio' of the buildings. This demonstrates that compact urban textures are more energy efficient than less dense urban patterns in a Mediterranean climate.

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Keywords: Urban compactness; Mediterranean climate; Heat island; Solar radiation; Heating demand, Cooling demand, Urban energy modelling

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1. Introduction

Urban areas are the main source of emissions responsible for climate change, the major part of which is due to the energy consumption for heating and cooling needs of buildings. The challenge of reducing the environmental impact

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of the built environment has thus boosted research into the modelling of building energy consumption at the urban scale [1,2], considering the energy phenomena that affect the energy performance of buildings in urban environments. This is aimed at developing urban analysis tools able to inform decision makers on the most effective policies and design strategies to improve the performance of the built environment at urban scale, instead of focusing on retrofitting the single building.

This paper contributes to this wider aim through the assessment of the impact of urban compactness on the energy performance of buildings in a Mediterranean climate. Urban compactness modifies building energy demand in two ways; on the one hand, it may contribute to the increase of the UHI effect [3,4], which entails an indirect impact on the energy demand. On the other hand, it modifies the solar radiation availability on the building façade, which is a key variable of energy demand in a Mediterranean context [5].

Several studies have investigated the relationship between compactness and solar access in urban textures [6–11] highlighting the possibility of enhancing solar collection on the building's envelope through the optimization of urban form. Many other studies have analysed the relationship between urban compactness and heat island intensity, using both experimental data and modelling tools [4,12–15]. According to these results, it is generally agreed that an increase of urban compactness entails a decrease of solar energy availability within the urban texture and an increase of heat island intensity in the urban area, especially at night.

Notwithstanding the extensive knowledge developed on this topic, a quantitative analysis of the global impact of urban compactness on building energy performance is still lacking. Urban compactness may have contrasting outcomes as regards the energy performance of buildings, especially in a Mediterranean climate, where cooling and heating demand are equally significant. The increase of urban compactness enhances the UHI intensity, which is positive for the heating and negative for the cooling; conversely, the decrease of solar radiation due to the increase of urban compactness has a positive impact on the cooling demand but is detrimental to the heating demand [5].

It is generally accepted that the UHI effect causes an overall increase of the energy demand in both hot and temperate climates [15–19], however the combined effect of increased UHI intensity and decreased solar gains has not yet been investigated. This paper aims at filling this gap, presenting an analysis of the global impact of urban compactness on the annual energy demand of residential buildings in a Mediterranean urban context.

2. Materials and method

The analysis is based on calculations of the energy demand for heating and cooling of a test apartment in different urban contexts, considering both the solar obstructions and the heat island intensity determined by the compactness of the urban structure.

A sample of urban textures was identified in Rome (Italy) and Barcelona (Spain) to represent the range of urban compactness in Mediterranean urban areas. The reference textures are: Borrel y Soler, Gracia and Raval in Barcelona and Centocelle and Don Bosco in Rome (Figure 1).

The compactness of the textures was measured using the 'Site Coverage Ratio' (ρ_{bld}), given by the ratio of the ground surface occupied by buildings to the total site area.

A normalised model was built for each urban texture; the normalised models are theoretical homogenous textures composed of simplified urban blocks repeated in a regular urban structure [20], with the same values of 'site coverage ratio' of the real urban textures. The simplified textures were modelled in Design Builder in order to perform energy simulation of the test apartment with EnergyPlus (v 8.1) as follows:

1) without urban context and using the standard weather file of Rome-Ciampino
2) within the different urban textures and using a specific weather file for each texture

The first simulation is representative of an apartment in a rural environment; the second takes into account the solar radiation obstruction and the UHI intensity determined by the urban context. To carry out the latter set of simulations, an urban weather file was created for each urban texture using the Urban Weather Generator (UWG) model [21,22]. The calculation of UWG model is based on a rural weather file (Rome-Ciampino in this case) and a parametric description of the urban area, which considers the morphological features of the fabric. Therefore, different urban weather files have been created using constant average values for all the urban parameters except the morphological ones, which were changed according to the different urban textures [5].

In either kind of simulation, the energy demand was calculated considering the test apartment at the first floor (+4.00m from ground level) in 4 orientations: NW-NE, NE-SE, SE-SW and SW-NW. Results have been analysed in relation to the texture's site coverage ratio, in order to investigate the existence of significant relationships between the energy demands and the compactness of the urban structure. The comparative analysis of results is based on the average demands among the four orientations, so as to be representative of an average oriented apartment in an urban area. The values for the main parameters of the energy model are reported in Table 1.

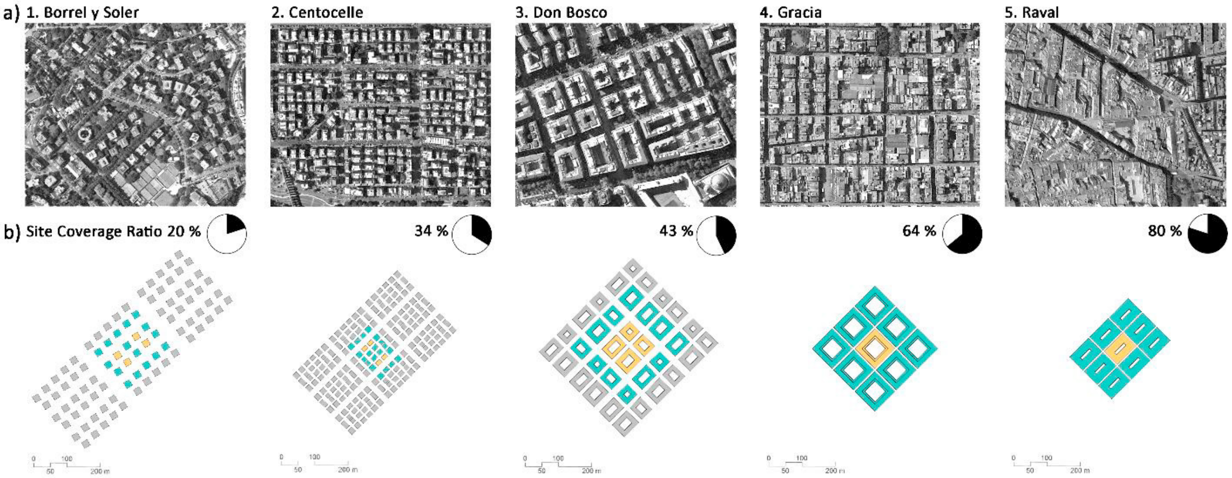

Fig. 1. (a) Orthographic pictures of the real urban textures, (b) Values of "Site Coverage ratio" and top view of the normalised models of the urban textures modelled in Design Builder; the test apartment was in the four corners of the yellow buildings, surrounded by the blue buildings to consider the effect of shadows on the energy demand

Table 1. Values of the main parameters of the energy model

Parameter	Value
Density	0.03 person m^2
Occupancy schedule	weekday: 12-9am; 4pm-12am– Weekend: on
Heating Set point	20 °C
Heating schedule	November-March - Weekday: 7-9am; 4-23pm, Weekend: 7am-23pm
Cooling Set point	26 °C
Cooling schedule	April- October; - Weekday: 7-9am; 4-23pm, Weekend: 7am-23pm
Natural ventilation	2 ac/h
Infiltration	0.5 ac/h
Wall type and Transmittance	Masonry wall - 1.59 $W/m^2 K$
Glazing ratio	20%
Glazing type and Transmittance	Single glazing – 4.5 $W/m^2 K$
Shading device	None

3. Results and discussion

In Table 2 the average solar obstruction and the UHI intensities for the five urban textures are reported. The percentage of solar obstruction was obtained as the ratio of the apartment's solar gains without urban context to the ones within the urban textures (with the apartment at 4.0 m from ground level). The average values of UHI intensity in summer, winter and during the entire year have been calculated using data from the weather files generated with UWG.

Table 2. Site coverage ratio, average UHI intensity and energy demand for the apartment for the five case studies

Urban texture	Site Coverage Ratio (ρ_{bld}),	Solar Obstruction	Avg Summer UHI	Avg Winter UHI	Avg Annual UHI	Heating Demand kWh/m^2	Cooling Demand kWh/m^2	Annual Demand kWh/m^2
Rural Environment	0.0	0%	0	0	0	18.56	-16.01	34.57
Borrel Y Soler	0.2	17%	1.5	0.9	1.0	16.92	-20.72	37.64
Centocelle	0.34	36%	2.0	1.0	1.3	17.77	-19.26	37.03
Don Bosco	0.43	59%	3.0	1.2	1.5	19.18	-18.86	38.04
Gracia	0.64	55%	2.5	1.9	2.1	16.18	-18.18	34.36
Raval	0.80	80%	3.4	2.7	3.0	13.36	-16.51	29.87

Results confirm that an increase of urban compactness determines a proportional decrease of solar radiation on the building façades. The direct proportion between site coverage ratio and solar obstruction is clear for Borrel Y Soler, Centocelle and Raval. The cases of Don Bosco and Gracia show different ratios, due to the height of the buildings in the two textures: in Don Bosco buildings are very tall, so the solar obstruction is enhanced, while in Gracia the buildings are low and the obstruction of solar radiation is reduced despite the high compactness of the texture. With regard to the UHI intensity, a proportion with the site coverage ratio is also recognisable; the UHI intensity is higher in the most compact textures. However, there are some exceptions, in particular on the summer UHI intensity, that may be explained in the light of other morphological features of the textures, such as 'vertical surface density'. This parameter measures the density of façades in urban area, which varies a lot for different typology and height of the buildings and highly affects UHI intensity during summer, as commented in other works [4].

3.1. Urban compactness and building's energy demands

The trend lines in Figure 2 represent the variability of the average heating and cooling demands of the apartment as a function of the urban compactness. The red line identifies the energy demand of the same apartment located in the rural environment, without UHI effect or solar obstructions. The variation of the demand due to the increase of the site coverage ratio is thus the result of decreasing solar radiation and increasing UHI intensity and identifies the overall impact of the urban compactness on the energy demand.

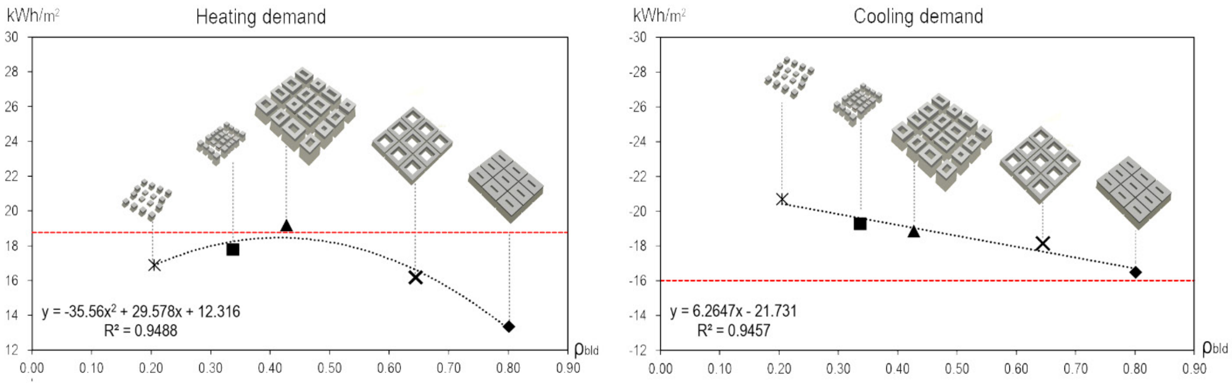

Fig. 2. Relationships between the texture's site coverage ratio and the apartment's heating demand and cooling demand for five case studies.

Urban compactness and cooling demand are linearly correlated, with a robust R^2 =0.95. The increase of urban compactness entails a proportional decrease of the cooling demand for the test apartment. Therefore, according to these findings, a high degree of compactness is beneficial during summer in a Mediterranean climate, due to the importance of the reduced solar radiation being greater than the increased heat island. However, the cooling demand for the apartment in the urban context is necessarily higher than the corresponding one in a rural environment, because of the impact of the UHI intensity.

As regards the heating demand, a nonlinear relationship has been found with respect to the texture's compactness (R^2= 0.95). The heating demand is generally lower in the urban textures than in the rural environment, due to the beneficial effect of the UHI intensity, even in the texture with the lowest value of site coverage ratio. An increase of the texture's compactness entails, at the beginning, a similar increase of the heating demand, because of the progressive decrease of solar radiation. However, there is a threshold value of the texture's coverage ratio (ρ_{bld}=0.4) beyond which the heating demand resumes decreasing. This happens because the energy saving deriving from a strong UHI intensity becomes more important than the reduction of solar gains during winter time.

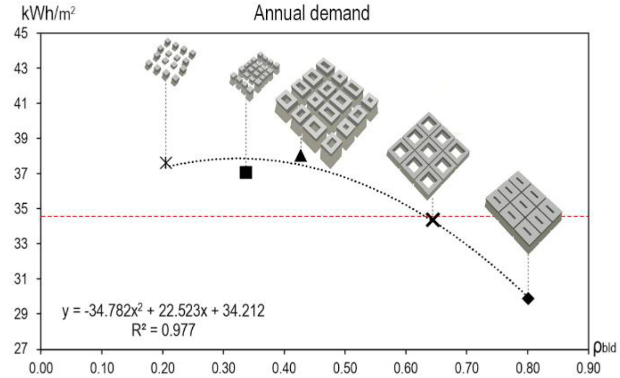

Fig. 3. Relationship between the texture's site coverage ratio and the apartment's annual energy demand for five case studies

Figure 3 shows the trend of the annual energy demand in relation to the texture's site coverage ratio; the annual demand is the sum of the heating and cooling demands.

These results indicate that the urban context is detrimental to the energy performance of the buildings if the urban structure is scattered. For low values of site coverage ratio, the apartment's energy demand is higher than in a rural environment. However, the increase of urban compactness determines a decrease of the annual energy demand in the urban context. Furthermore, the contrasting impacts of urban compactness on energy demand compensate themselves in very compact urban textures (ρ_{bld} around 0.63), determining the same energy demand of a rural environment. In the most compact urban texture among the case studies (Raval, ρ_{bld}=0.8), the annual energy demand is even lower than a rural environment. Therefore, these findings demonstrate that compact urban textures (ρ_{bld} higher than 0.5) are more energy efficient in a Mediterranean climate compared to scattered and discontinuous urban patterns, because compactness allows UHI intensity to be taken advantage of during winter time, while reducing the cooling demand thanks to a huge reduction of solar radiation on the building façades.

The validity of the results is affected by the limitation of the energy model, the assumptions on the test apartment and the simplified modelling of the urban textures; further research would be required to provide empirical validation of these findings.

4. Conclusion

This work explores the contrasting effects of urban compactness on building energy demand in a Mediterranean climate. The energy demand of a test apartment has been calculated considering concurrently the UHI intensity and the solar obstruction determined by different urban textures.

The results confirm that compact urban textures, with a site coverage ratio above 0.5, contribute to reduce energy consumption in a Mediterranean climate, by decreasing annual energy demand as opposed to the performance of an isolated building; this holds true despite the UHI intensity determined by compact urban structures, because the increase of air temperature is counterbalanced by a decrease of solar radiation during summer time. Therefore, this analysis suggests that the most compact and dense urban textures, such as the historic fabric of many city centres, are more energy efficient than sparser and less dense urban patterns, typical of more recent urban developments.

The relationships identified in this study allow for a preliminary assessment of the energy performance of urban textures, based on a common density parameter such as the 'site coverage ratio'. The opportunity of performing rapid assessments at the district scale and providing maps of the energy vulnerability within the city would certainly ease the work of designers, planners and decision makers in identifying a priority of interventions on the built environment.

Future lines of investigation would concern the identification of the most appropriate and effective interventions at the building scale, according to the solar access and the climatic performance expressed by each urban texture. In this way, the analysis of the energy performance at the urban scale could translate into operational tools for design at the building scale, fostering the work of architects and urban planners in the field of urban renewal and energy efficiency.

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