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URBAN MORPHOLOGY AND ENERGY PERFORMANCE: THE DIRECT AND INDIRECT CONTRIBUTION IN MEDITERRANEAN CLIMATE

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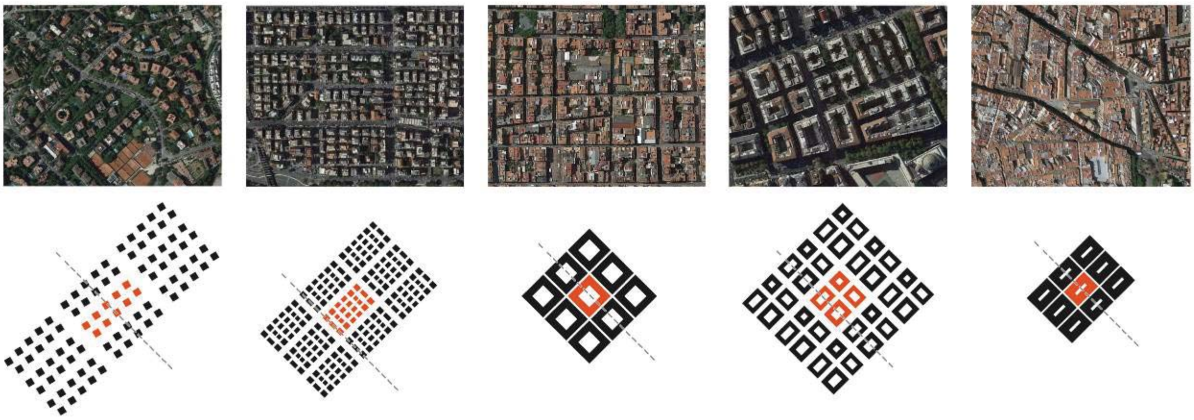

Fig 1: Urban textures and digital models

WHICH ARE YOUR ARCHITECTURAL (R)SOLUTIONS TO THE SOCIAL, ENVIRONMENTAL AND ECONOMIC CHALLENGES OF TODAY?

Research summary

The combined effects of urban heat island (UHI), urban population growth and energy overexploitation are undermining the safety of urban areas. Urban morphology plays a prominent role in this context, because it affects building's energy demand and local climate at urban scale. However, this contribution is recurrently neglected. The present contribution seeks to investigate the direct and indirect effect of urban morphology on buildings energy performance in the Mediterranean climate. Urban morphology affects energy demand by modifying two relevant variables: outdoor air temperatures and incident radiation. The relevance of these effects were studied on a sample of urban textures of Rome and Barcelona. The study is parametric in approach. The textures were modelled and parameterized and their performances were compared. The UHI in different urban textures was calculated, by Urban Weather Generator tool. Then a sensitivity analysis of the building energy demand to the outdoor air temperatures and the incoming solar radiation was carried out, by EnergyPlus engine. Results confirm the relevance of urban morphology to the UHI intensity. Warmer temperatures lead to an average increase of energy demand from 10% to 35%, according to different urban densities. At the same time, the incident radiation reduction due to urban obstruction is desirable in Mediterranean climate; it allows a reduction of annual energy demand up to the 19% compared to an unobstructed environment. Therefore, relevant errors may occur if urban morphology's contribution to energy demand is neglected, approximately 89% for space heating and 131% for space cooling calculations, depending on the texture density and the building orientation.

Keywords: Urban Morphology, urban textures, energy performance, Urban Heat Island

1. Introduction

Urban Heat Island and energy overexploitation are, nowadays, one of the major threats to the safety and the sustainability of European cities. It is well known that buildings are responsible for a large proportion of global energy demand, approximately 40% of energy end-use, of which 50% is due to the growth in HVAC systems (Pérez-Lombard, Ortiz, & Pout, 2008). At the same time, urban areas experience a substantially different climate than their rural environment, for the so-called Urban Heat Island (UHI) phenomenon. In a context of climate change and urban population growth, these issues are extremely relevant, especially in Mediterranean basin. Urban morphology plays a prominent role in this context, as it directly affects energy demand and urban climate. The topic of the relationship between urban form and energy consumption has been long debated. Some preliminary attempts to face the issue in mathematical and measurable terms has been introduced by Martin and March (1972). Nowadays, by different modeling approaches, several studies have investigated the effect of urban block geometry on the thermal behavior inside and outside the building, to highlight the variation in energy performance induced by different urban textures (Morganti, Coch, & Cecere, 2012; Ratti, Baker, & Steemers, 2005; Rode, Burdett, Robazza, & Schofield, 2014; Salat, 2009; Zhang et al., 2012). Almost none of these theoretical investigations took into account the UHI effect and its spatial variability in relation to urban geometry. In a densely built area, the UHI is enhanced through three processes: the solar radiation absorption is increased because of multiple reflections; the turbulent sensible heat transfer out of the canyon is reduced due to shelter; the long-wave radiation loss from within the canyon is reduced due to the screening by the flanking buildings (Oke, 1988). Moreover, urban warming has relevant impact on energy consumption at urban scale (Santamouris, 2014), especially in hot climates. Different works have investigated the relevance of urban morphology on UHI, focusing on two variable: the ratio height to width of the canyon or the surfaces' Sky View Factor (Oke, 1988; Stewart, Oke, & Krayenhoff, 2014; Theeuwes et al., 2014). Outcomes cannot be easily compared, because of different approaches and climatic condition in which the studies have been conducted (Res & Unger, 2004). The effect of urban morphology on energy demand and Urban Heat Island is strictly climate-dependent and both effects should be carefully investigated as part of the major challenge of achieving more sustainable urban environment.

2. Research objectives and method

The present work starts from the hypothesis that urban morphology affects the building energy demand by a direct and an indirect contribution; the direct one is the obstruction of the incoming radiation, the indirect one is the UHI induced by different urban densities, which results in a variation of the energy demand. The present study aims at highlighting the effect of these two energy processes in Mediterranean climate, in particular:

1. The relevance of urban morphology to the UHI intensity and the consequence on building's thermal behaviour
2. The consequence of incoming radiation reduction on building's thermal behaviour.

The study is parametric in approach. Five building configurations were identified in Rome and Barcelona (figure 2), which share the same latitude and Mediterranean climate. The chosen fabrics represent a typical range of recurrent urban densities (Morganti et al., 2012). A digital model for each fabric was built, based on “normalization and replication” approach (Zhang et al., 2012). The models were thus theoretically homogenous urban textures, composed of the same type of built form, in an urban grid structure similar to that of the existing one and average-oriented (45°N). The models were the basis for the textures’ morphology parameters calculation. The reference urban textures were Centocelle and Don Bosco districts in Rome and Borrel y Soler, Gracia and Raval districts in Barcelona.

2.2 Urban Heat island calculation

The urban heat island intensity in the different urban textures was calculated by means of Urban Weather Generator (UWG) tool (Bueno, Norford, Hidalgo, & Pigeon, 2013). The UWG calculates hourly values of urban air temperature given the weather data measured at an operational weather station located outside the city. The model is based on the town energy balance scheme (Masson, 2000), including a building energy model (Bueno, Pigeon, Norford, Zibouche, & Marchadier, 2012). The solar radiation received by walls and road is calculated by assuming an average urban canyon orientation. The longwave radiation among walls, road, urban canyon air and the sky is computed by linearization of the Stefan–Boltzmann equation, accounting for the transmittance of the urban canyon air and assuming only one bounce of radiative heat fluxes between surfaces (Bueno et al., 2013).

The reference weather data for the calculation were those of Ciampino airport (Rome). The UHI intensity was estimated keeping constant all the parameters, except the morphological ones, which were changed according to the different urban textures. The morphological parameters involved in the calculation were (Bueno et al., 2013):

- *Average Building height* (hbld): the average building height in the urban area, normalized by building footprint
- *Site coverage ratio* (ρurb): ratio of the building footprint to the site area.
- *Façade to site ratio* (VHurb): ratio of the vertical surface area (walls) to the urban plan area

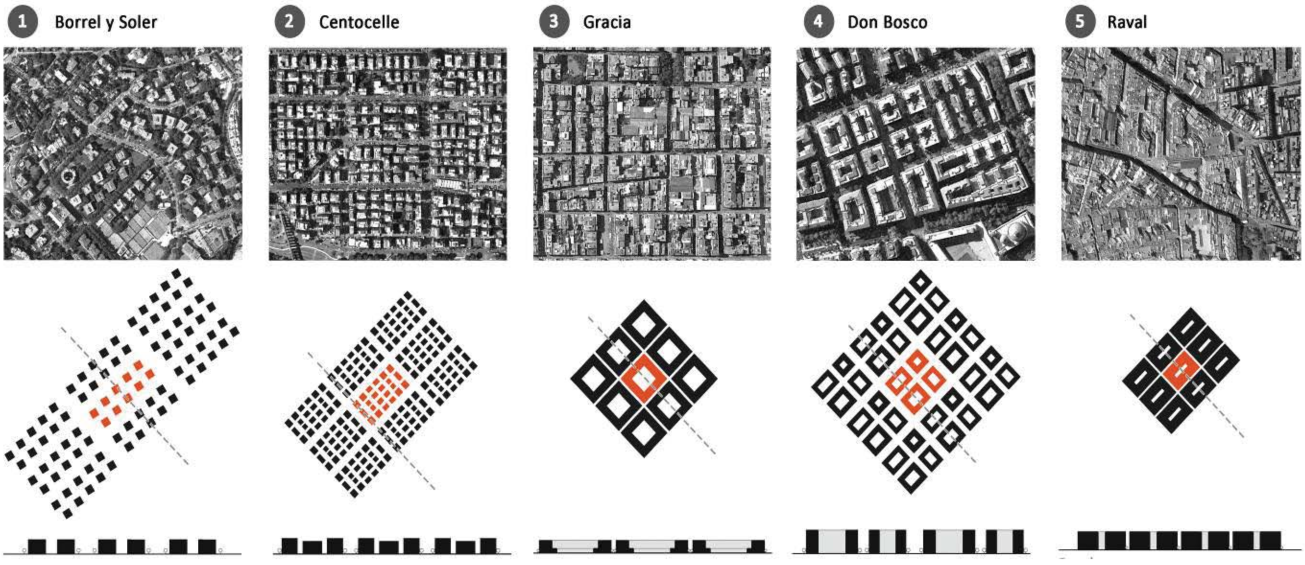

Fig 2: Reference urban textures and corresponding models

2.3 Sensitivity analysis of the energy demand to air temperature and incoming solar radiation

In order to quantify the effect of the outdoor air temperature and the incoming solar radiation on the building's energy demand, a sensitivity analysis was carried out. Several simulations were performed by means of EnergyPlus engine and Design Builder interface (v 2.2.5). Ciampino's weather data were used as reference weather file; To test the sensitivity of the building energy demand to the above-mentioned variables, the hourly air temperatures were increased from +1 to +4°C and both the direct and indirect normal radiation were decreased from the 80% to the 20% of the available radiation. The test for the energy demand calculation was a 70mq dwelling, double exposed, in four possible orientations (NE-NW, NW-SW, SW-SE, and SE-NE) and with the following model assumptions:

- Wall transmittance: 1.6 W/mq K
- Window transmittance: 4.5 W/mq K
- Façade glazing ratio: 30 %
- Ventilation rate: 2 vol/h
- Infiltration rate: 0.2 vol/h
- Winter set Point: 20°C
- Summer set point: 26 °C
- Store Height : 3.3 m
- Internal gains: 5 W/mq
- Occupancy: Family type

As a basis for comparison, another set of simulations was performed. In this further analysis, the air temperatures range were the different urban weather files calculated by UWG according to each urban texture, and the incoming radiation range was simulated by modelling the different urban morphological environment according to the chosen urban textures.

3. Results

URBAN TEXTURES	MORPHOLOGY PARAMETERS			AVERAGE UHI		
	Hbld	ρurb	VHurb	Annual average UHI	Summer average UHI	Winter average UHI
Borrel	15.00	0.20	1.04	1	1.5	0.9
Centocelle	14.67	0.34	1.35	1.3	2.0	1.0
Gracia	11.60	0.64	2.18	2.1	2.5	1.9
Don Bosco	25.50	0.43	1.68	1.5	3.0	1.2
Raval	19.50	0.80	2.98	3	3.4	2.7

Fig 3: Summer and winter average air temperature increase in different urban textures

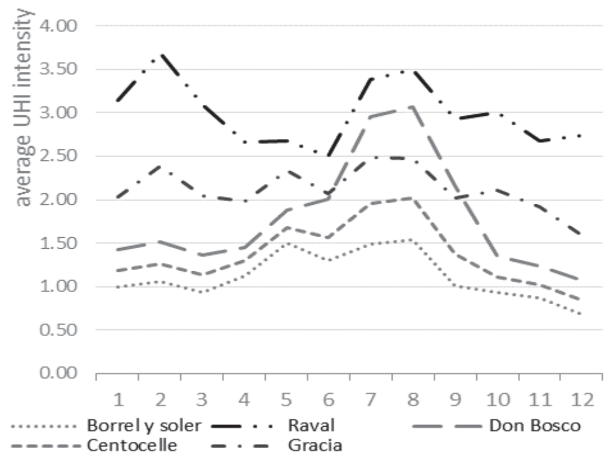

Fig 4: Monthly average temperature increase in different urban textures

3.1 Urban heat island in different urban textures

Results show a consistent variation of the average UHI intensity according to different urban morphologies (fig 3 and fig 4). Here, the average UHI intensity is defined as the monthly average difference between the temperatures calculated by UWG and those of Ciampino weather station. The difference in the average UHI intensity between the most favourable and unfavourable urban morphology comes up to 2.6 °C in February and 1.9 °C in August. In both winter and summer, higher average temperatures were predicted in Raval, the case with higher *Site coverage ratio* and *Façade coverage ratio* value. Tuscolano's morphology, the case with greater *average height* among the others, presented a variable behavior during the year, with much higher UHI intensity in summer than in winter. The lowest UHI intensity was predicted in the low-density texture of Borrel y Soler.

3.2 Sensitivity analysis of the building energy demand to the air temperature increase

Figures 5 and 6 show, respectively, the heating and cooling demand outcomes for each orientation and for each degree of the outdoor air temperature increase. Unfilled points represent the results for a progressive constant increase of air temperature (from +1 to +4); filled points represent outcomes for the simulations performed with the urban weather files calculated by UWG, which takes into account the daily variability of the UHI intensity.

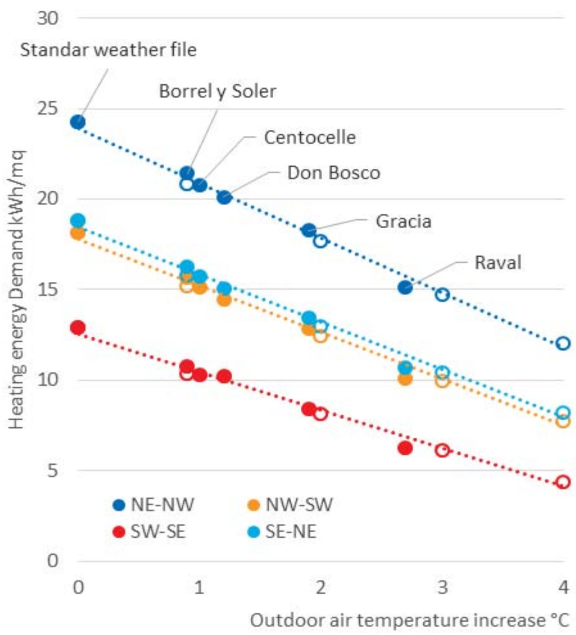

Fig 5: Temperature increase and heating demand: theoretical approach and urban textures

As expected, heating demand decreases when outdoor temperatures increase (figure 5). Moreover, the trend was roughly the same for all the studied orientations. Among the studied urban textures, the maximum decrease occurred in NE-NW orientation with Raval's weather file, where the heating energy demand decreased of 9,2 kWh/mq, 38% less than the one calculated with the Ciampino weather file. On the contrary, the effect of warmer temperatures on the cooling demand was clearly detrimental (figure 6).

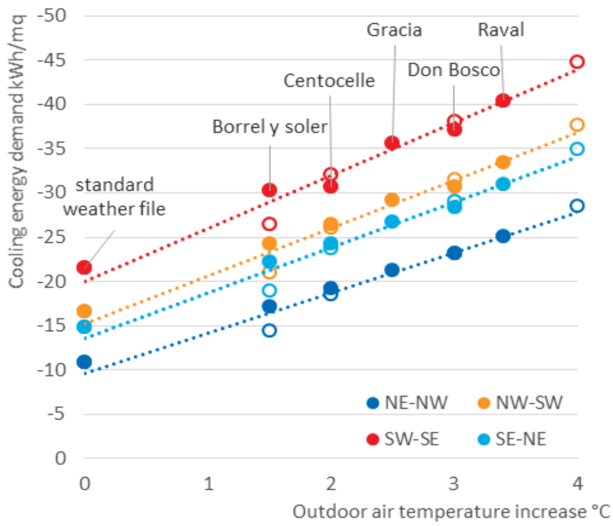

Fig 6: Temperature increase and cooling demand: theoretical approach and urban textures

URBAN TEXTURES	HEATING DEMAND (KWh/mq)			COOLING DEMAND (KWh/mq)			ANNAUL ENERGY DEMAND (KWh/mq)		
	Standard weather file	Urban Weather file	ΔE	Standard weather file	Urban Weather file	ΔE	Standard weather file	Urban Weather file	ΔE
NE-NW orientation									
Borrel	24.3	21.43	-12%	-10.91	-17.27	58%	35.21	38.7	10%
Centocelle	24.3	20.79	-14%	-10.91	-19.22	76%	35.21	40.01	14%
Gracia	24.3	18.27	-25%	-10.91	-21.29	95%	35.21	39.56	12%
Don Bosco	24.3	20.13	-17%	-10.91	-23.22	113%	35.21	43.35	23%
Raval	24.3	15.12	-38%	-10.91	-25.16	131%	35.21	40.28	14%
NW-SW orientation									
Borrel	18.16	15.64	-14%	-16.61	-24.37	47%	34.77	40.01	15%
Centocelle	18.16	15.14	-17%	-16.61	-26.54	60%	34.77	41.68	20%
Gracia	18.16	12.85	-29%	-16.61	-29.18	76%	34.77	42.03	21%
Don Bosco	18.16	14.51	-20%	-16.61	-30.8	85%	34.77	45.31	30%
Raval	18.16	10.09	-44%	-16.61	-33.52	102%	34.77	43.61	25%
SW-SE Orientation									
Borrel	12.94	10.74	-17%	-21.56	-30.27	40%	34.5	41.01	19%
Centocelle	12.94	10.25	-21%	-21.56	-30.74	43%	34.5	40.99	19%
Gracia	12.94	8.41	-35%	-21.56	-35.69	66%	34.5	44.1	28%
Don Bosco	12.94	9.78	-24%	-21.56	-37.12	72%	34.5	46.9	36%
Raval	12.94	6.24	-52%	-21.56	-40.46	88%	34.5	46.7	35%
SE-NE Orientation									
Borrel	18.84	16.29	-14%	-14.95	-22.22	49%	33.79	38.51	14%
Centocelle	18.84	15.77	-16%	-14.95	-24.27	62%	33.79	40.04	18%
Gracia	18.84	13.47	-29%	-14.95	-26.77	79%	33.79	40.24	19%
Don Bosco	18.84	15.09	-20%	-14.95	-28.44	90%	33.79	43.53	29%
Raval	18.84	10.72	-43%	-14.95	-31	107%	33.79	41.72	23%

Fig 7: UHI effect on annual energy demand for different urban textures

What deserve to be highlighted is that the overall energy demand rises because of UHI effect, because the increase in the cooling energy demand was always more onerous than the heating energy saving (fig 7). As an example, the SW-SE oriented dwelling with Raval's temperatures reached an increase up to 18,9 kWh/mq on the cooling demand, with respect to a winter saving of only 6.7 kWh/mq. Finally, no substantial differences were observed between the results for the constant temperature increase and the hourly variable UHI intensity calculated by UWG.

3.3 Sensitivity analysis of the building energy demand to the incoming radiation

Figures 8 and 9 show the variation of the building energy demand with respect to a theoretical radiation reduction (from 80% to 20% of the total radiation available). Figures 10 and 11 show the results for runs performed with the different urban morphological environments surrounding the dwelling test, according to the studied urban textures. In that case, the percentage of the incoming radiation reduction has been indirectly obtained considering the difference in the solar gains of the test model with or without the urban environment. In both winter and summer, the effect of radiation obstruction on energy demand was quite different among the four studied orientations. SW-SE orientation was largely the most affected, because it receives the maximum passive thermal gains when unobstructed. As an example, the SW-SE oriented dwelling in the Raval's morphological context reached an increase in heating energy demand from 12.94 kWh/mq up to 24,4kWh/mq, if compared to an unobstructed environment. In effect, the dense urban structure of Raval district produces a decrease of the incoming radiation up to the 80% at the lower floors, which entails a relevant increase in heating energy demand. In the NW-NE expositions, the variation in incoming radiation

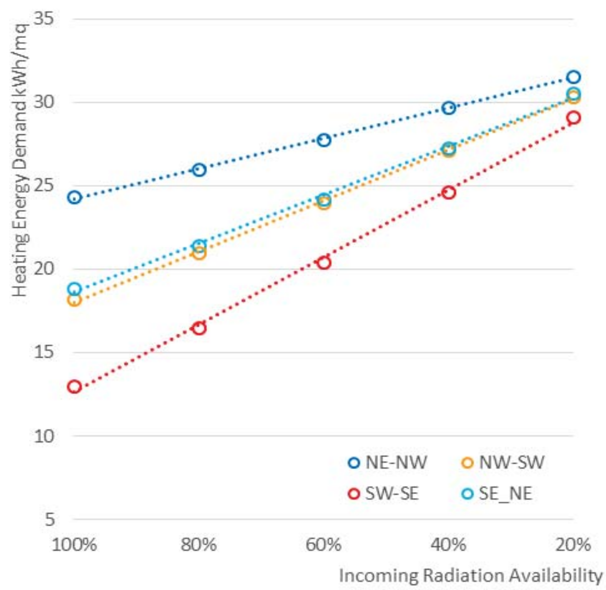

Fig 8: radiation obstruction and heating demand: theoretical approach

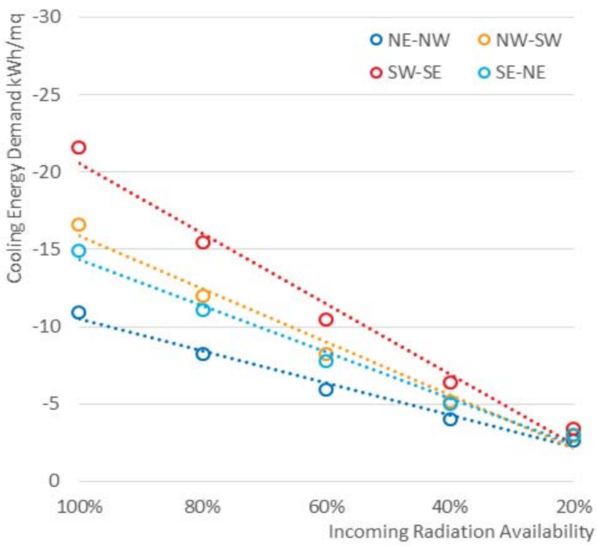

Fig 9: radiation obstruction and cooling demand: theoretical approach

did not produce substantial variation, since it almost never receives direct solar radiation in winter in the latitude of Rome. Results were reverse for what concern the cooling demand; in summer the reduction of incident radiation was desirable for each orientation and it allowed a reduction of energy demand from 12% (Borrel y Soler, SW-SE orientation) to 70%

(Raval, NW-SW) if compared to the performance in an unobstructed environment.

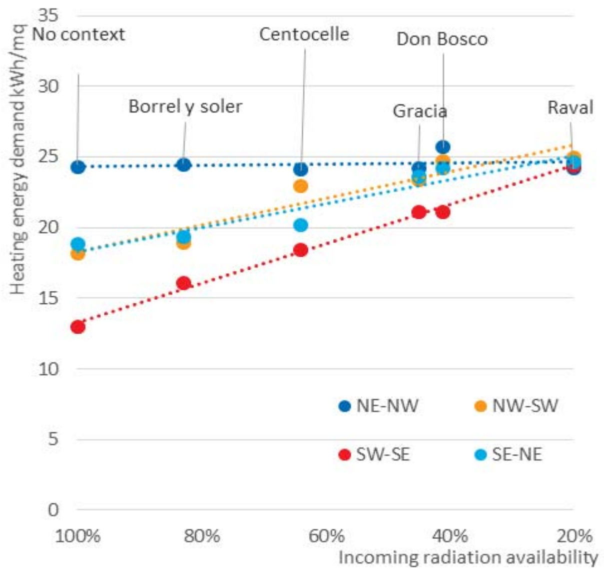

Fig 10: radiation obstruction and heating demand: urban textures

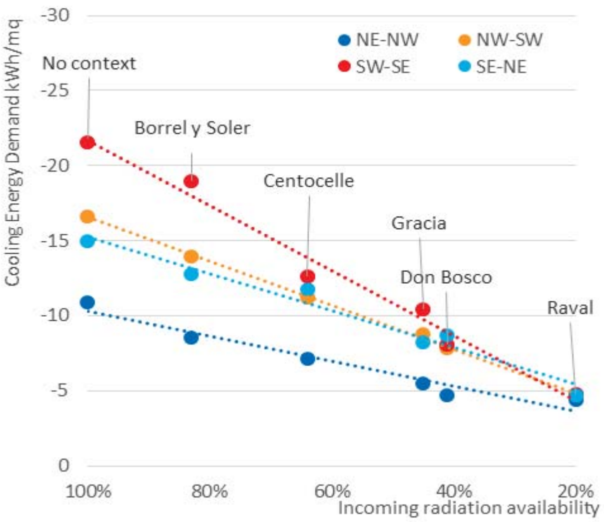

Fig 11: radiation obstruction and cooling demand: urban textures

At the light of the results, the overall direct effect of urban morphology on energy demand is thus positive in Mediterranean context: it allows a decrease of annual energy demand in all the orientations up to the 19 % if compared to an unobstructed environment (figure 12).

URBAN TEXTURES	HEATING DEMAND (KWh/mq)			COOLING DEMAND (KWh/mq)			ANNAUL ENERGY DEMAND (KWh/mq)		
	No Context	With Urban Context	ΔE	No Context	With Urban Context	ΔE	No Context	With Urban Context	ΔE
NE-NW orientation									
Borrel	24.3	24.46	1%	-10.91	-8.52	-22%	35.21	32.98	-6%
Centocelle	24.3	24.09	-1%	-10.91	-7.14	-35%	35.21	31.23	-11%
Gracia	24.3	24.24	0%	-10.91	-5.52	-49%	35.21	29.76	-15%
Don Bosco	24.3	25.71	6%	-10.91	-4.74	-57%	35.21	30.45	-14%
Raval	24.3	24.2	0%	-10.91	-4.4	-60%	35.21	28.6	-19%
NW-SW orientation									
Borrel	18.16	18.96	4%	-16.61	-13.94	-16%	34.77	32.9	-5%
Centocelle	18.16	22.92	26%	-16.61	-11.21	-33%	34.77	34.13	-2%
Gracia	18.16	23.36	29%	-16.61	-8.82	-47%	34.77	32.18	-7%
Don Bosco	18.16	24.67	36%	-16.61	-7.83	-53%	34.77	32.5	-7%
Raval	18.16	24.95	37%	-16.61	-4.7	-72%	34.77	29.65	-15%
SW-SE Orientation									
Borrel	12.94	16.04	24%	-21.56	-18.97	-12%	34.5	35.01	1%
Centocelle	12.94	18.44	43%	-21.56	-12.63	-41%	34.5	31.07	-10%
Gracia	12.94	21.08	63%	-21.56	-10.46	-51%	34.5	31.54	-9%
Don Bosco	12.94	21.13	63%	-21.56	-8.09	-62%	34.5	29.22	-15%
Raval	12.94	24.4	89%	-21.56	-4.81	-78%	34.5	29.21	-15%
SE-NE Orientation									
Borrel	18.84	19.36	3%	-14.95	-12.75	-15%	33.79	32.11	-5%
Centocelle	18.84	20.17	7%	-14.95	-11.75	-21%	33.79	31.92	-6%
Gracia	18.84	23.6	25%	-14.95	-8.27	-45%	33.79	31.87	-6%
Don Bosco	18.84	24.24	29%	-14.95	-8.7	-42%	33.79	32.94	-3%
Raval	18.84	24.59	31%	-14.95	-4.75	-68%	33.79	29.34	-13%

Fig 12: Urban Morphology direct effect on annual energy demand

Conclusions

Results confirm that urban morphology does matter to urban energy issues in Mediterranean climate, both in winter than in summer. The relevance of urban morphology on UHI intensity was confirmed. Warmer temperatures, due to UHI effect, led to an average increase in energy demand from 10% up to 35%, according to different urban densities. The energy rise is especially concerning in summer in the densest urban textures, where an increase up to 131% of the cooling load is estimated with respect to rural environments. Temperature mitigation strategies should be highly recommended in the denser neighborhoods of Mediterranean cities. At the same time, the obstruction of solar radiation induced by surrounding urban morphology is desirable in these latitudes, because it allows a consistent reduction of the cooling load, especially for southern orientations. Even if during winter the effect is opposite, the overall effect of radiation obstruction allows a reduction of the annual energy demand up to the 19% if compared with an unobstructed environment. Therefore, the omission of these two contributions may entail relevant errors in the energy assessment at city scale, up to the 89% for the heating loads and the 131% for the cooling loads, depending on urban texture's density and building orientation. Future implementations should deeper the relationship between morphology, microclimate and energy performance (thermic and lighting); The direct and indirect effect of urban morphology should be evaluated as a whole, in order to develop useful tools of energy analysis and design which could steer the actions of urban planners and stakeholders toward more energy-sustainable cities.

5. Acknowledgments

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