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Urban morphology indicators for solar energy analysis

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Abstract

Within the variation of energy performance at urban scale, the relation between solar irradiation and urban form takes a central role. The solar availability on façades which is influenced by the morphology of the urban context, is strictly related to building energy performance indeed. In this paper, we aim at identifying a set of urban morphology indicators (UMIs) that show the most accurate relations with the solar availability on façades (SI_y) in the Mediterranean context. The analysis that relates to 14 urban textures of Rome and Barcelona comprises seven UMIs: gross space index, floor space index, façade-to-site ratio, average building height, volume-area ratio, building aspect ratio and sky factor of building façades. The SI_y in each texture has been calculated with *Heliodon2* software, using normalised models; the relation between SI_y and UMIs were investigated using least-square regression analysis. Results suggest that gross space index, façade-to-site ratio and sky factor show very good correlation with SI_y ($R^2 = 0,91$) and could be used to develop a comparative assessment tool of solar performance at fabric scale. This could ease the work of urban planners and architects in the early stage of design, reducing both data and time normally needed to perform solar analyses at urban scale.

Keywords: urban form; urban morphology indicators; density; solar irradiation; façades.

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1. Introduction

It is widely agreed that solar energy availability is a key variable to assess buildings energy performance in urban environment. On one hand, building's solar gains account for a significant part of the energy balance during both winter and summer; on the other hand, the potential for harvest solar energy in the urban context is directly connected to the potential for renewable energy systems to enhance energy efficiency at urban scale. Besides, solar availability in the urban context could vary significantly, according to different cities but especially to the morphology of urban texture [1–3]. Thus, it is essential to deeply explore the causal relation between urban geometry and solar energy, to provide a better understanding of our cities and ease planning decisions for a sustainable renovation process.

In this context, the solar performance of building façades is important not only because façades exceed roofs in terms of available area to harvest renewable energy, but above all because it is highly related to urban morphology. The building façade is one of the most important variable in relation to solar performance indeed, but inadequate if considered alone. Urban layout is well described by several urban morphology indicators (UMIs) that clearly express and measure the different properties of the texture. The UMIs are usually calculated as a ratio of urban quantities, surfaces, volumes or lengths and describe different aspects of urban geometry and physical density of built environment.

The aim of this paper is to identify the most suitable set of UMIs for the analysis of solar availability on façades in the Mediterranean compact city. It focuses on the solar performance of the vertical surfaces, since they are directly related to the building's solar gains which account for most part of the energy demand in the Mediterranean latitudes. The assessment of solar availability through UMIs could ease the implementation of solar analysis at urban scale, since the data required for the calculation are generally used in urban planning practice and are easily accessible for many cities.

2. Urban solar energy analysis

Referring to urban scale, this study characterizes for the Mediterranean compact city the causal relation urban morphology-solar energy through UMIs. Several studies reported the effect of each variable on solar performance [3–7]. Some of them consider real urban areas and related data in order to predict their solar potential using UMIs to better characterize the layout of the case studies [1,2,5,8]. Other studies focused on understanding the influence of urban morphology, described and controlled through UMIs, to optimize the solar potential of urban areas. The latter use normalised models derived from representative urban textures [9–11].

To perform solar energy analysis at urban scale, experts use specialised tools recently developed for the purpose, for example Radiance, DIVA, CitySim and SUNtool. These tools fostered the implementation of solar analysis in design practice. However, two factors still limit their widespread to urban planning and design: the specialist knowledge required to set up the simulation and the amount of time needed to realize the model at urban scale. For these reasons, this study focuses on defining a method that could reduce time and data necessary to carry out solar energy analyses at urban scale useful in the early stage of design process; this method is intended for architects and decision makers since do not require specialist knowledge.

3. Methodology

The analysis is carried out on 14 urban textures of Rome (Italy) and Barcelona (Spain) and comprises seven UMIs: 1) gross space index, 2) floor space index, 3) façade-to-site ratio, 4) average building height, 5) volume-area ratio, 6) building aspect ratio and 7) sky factor of building façades (Figures 1-2). Each index gives information on some qualitative aspects of the urban form, such as the shape of the buildings or the patterns of the street network. It has been already proven that the above-mentioned indicators have a causal relation with energy performance at urban scale [12–17].

Gross space index (GSI) and *floor space index* (FSI) are two of the most common density indicators. They describe respectively the compactness and the intensity of buildings in the urban textures. The GSI is defined as the ratio of the built-up area to the urban site area; the FSI is the ratio of the gross floor area to the urban site area. *Façade-to-site ratio* (VH$_{urb}$) is an index of vertical density for the urban texture that is the ratio of the building façades area to the

urban site area. Thus, VH$_{urb}$ is proportional to the amount of vertical surfaces in the urban area which depends on form and height of buildings. *Average building height* (H$_{bld}$) in the urban site area is calculated as the ratio of the buildings volume to the built-up area. *Volume-area ratio* (V/A) expresses the building density in the urban area similarly to FSI, but in terms of volume units: it is measured as the ratio of the buildings volume to the urban site area. *Building aspect ratio*, instead, is more related to compactness of shape of a single building; it defines the amount of exposed envelope per unit volume which is related to various component of the energy balance of the building [12]. This index is indeed commonly used for energy analysis at the building scale rather than at fabric scale.

Finally, sky factor of façades (SF) is calculated as the mean value of the ratio of the solid angle of visible sky from each point of the façades to the sky vault. This is an index commonly used in relation to different kinds of energy analyses in the so-called "urban canyon", such as solar access, daylight availability and urban heat island effect. Despite it is not a morphological indicator, SF has been considered in this study because it is directly related to façade solar access and depends on position and morphology of surrounding buildings which determine obstructions to direct and indirect solar irradiation.

Rome and Barcelona have been chosen as survey sites to identify the relations between the seven UMIs and the solar availability on building façades (SI$_y$) in the Mediterranean context. Fourteen urban textures were identified as case studies according to three criteria:

- uniformity of the urban morphology;
- wide range of urban layout;
- typical urban patterns in the Mediterranean context.

The range of variation of the seven UMIs and the SI$_y$ have been calculated over simplified digital models of the 14 urban textures during a year (Figure 2). The models represent typological characterization of the real urban textures, based on a process of normalisation and repetition of the sample urban block [18]. The simplified models have thus the same orientation and the same values of GSI and FSI than the real textures, but are composed by 9 identical and regular urban blocks. The solar irradiation on building façades has been assessed for the central block of each digital model using *Heliodon2* software, considering urban obstructions [19]. *Heliodon2* calculates the spatial and temporal distribution of solar energy on building façades, considering a cloudless sky condition during whole year. Calculations have been carried out on the base of the latitude of the city of Barcelona (41°23′ N, 2°10′ E). The SI$_y$ of the central block has been related to each of the seven UMIs that describe density and morphology of the urban texture; least-square regression models have then allowed to find the most accurate correlations between SI$_y$ and UMIs, taken separately or in combination.
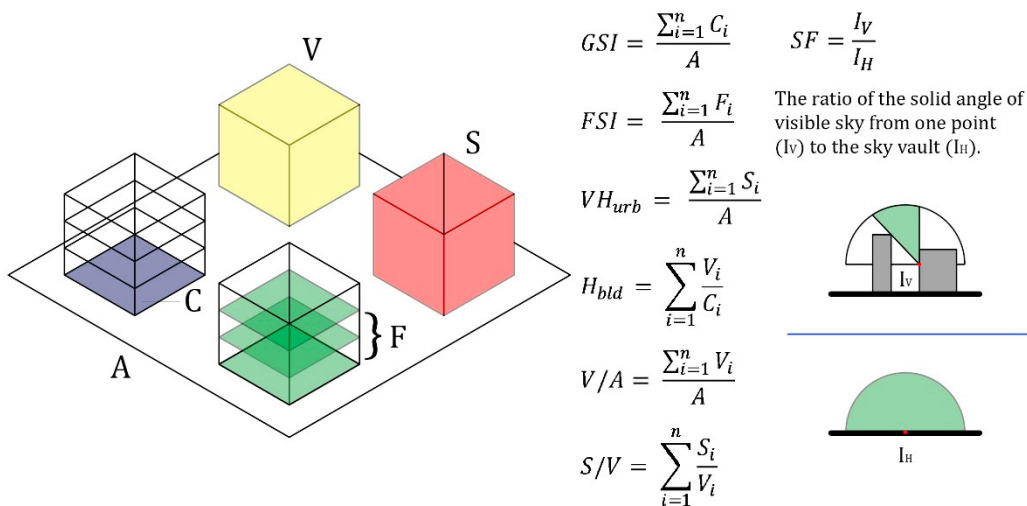

$$GSI = \frac{\sum_{i=1}^{n} C_i}{A} \qquad SF = \frac{I_V}{I_H}$$

$$FSI = \frac{\sum_{i=1}^{n} F_i}{A}$$

The ratio of the solid angle of visible sky from one point (I$_V$) to the sky vault (I$_H$).

$$VH_{urb} = \frac{\sum_{i=1}^{n} S_i}{A}$$

$$H_{bld} = \sum_{i=1}^{n} \frac{V_i}{C_i}$$

$$V/A = \frac{\sum_{i=1}^{n} V_i}{A}$$

$$S/V = \sum_{i=1}^{n} \frac{S_i}{V_i}$$

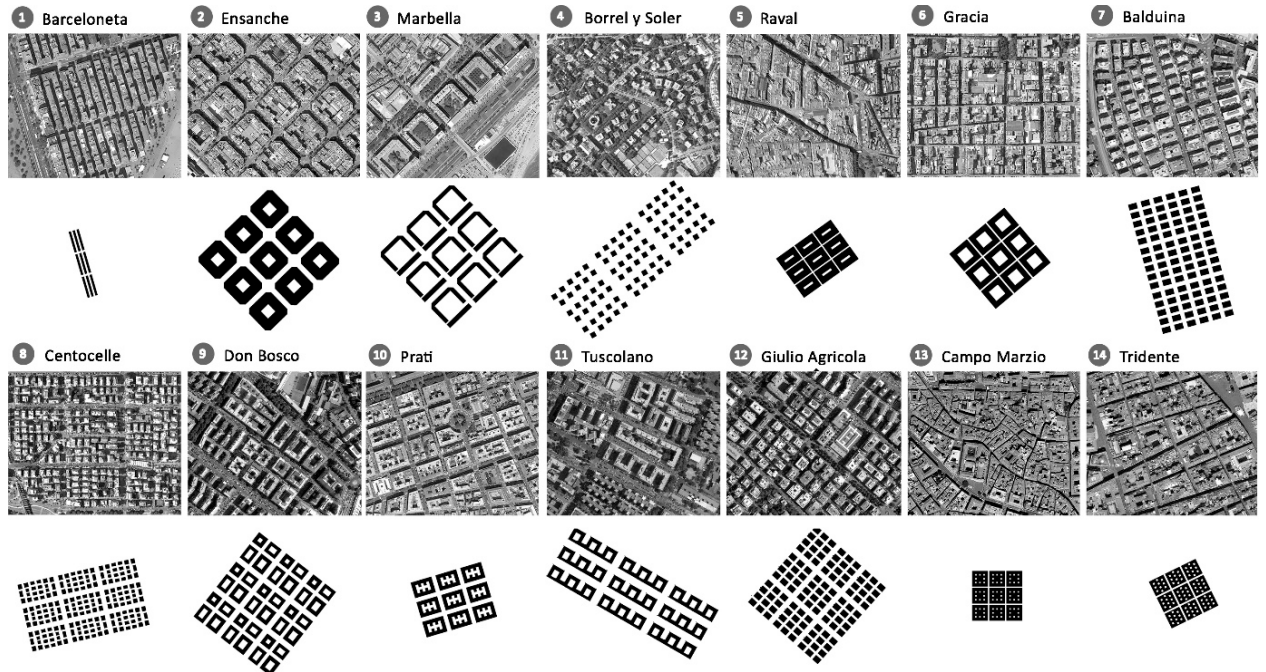Fig. 1. Definitions of Urban morphology indicators (UMIs).

Fig. 2. Aerial views of urban textures and normalised models taken as case studies.

4. Results

The main results as regards the UMIs evaluation and the solar irradiation on building façades (SI_y) for fourteen compact urban textures are here presented and discussed. The results have general implications to solar energy analysis at urban scale in the Mediterranean climate. Table 1 shows the computation of the indicators selected for the study. The normalised models of compact urban textures show, in general, medium-high values for each UMIs with a range of variability between 2,14 (S/V) and 5,08 (V/A). In comparison with other urban morphologies, these cases stand out because of higher compactness and plot ratio [2]. UMIs that are directly related to density (FSI, GSI, VH_{urb} and SF), roughly show constant range of variability (3,5-4), although they describe different aspects.
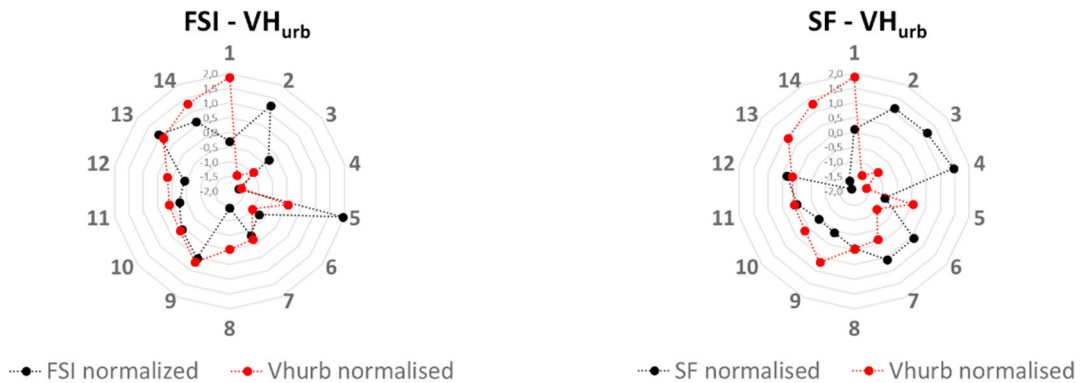

Fig. 3. Trends and comparison of normalised values of 3 significant UMIs as case studies; (a) floor space index – façade to site ratio; (b) sky factor – façade to site ratio.

Table 1. Values of "Urban Morphology Indicators " and "solar availability of the façades" regarded to the selected case studies.

		GSI (m^2/m^2)	FSI (m^2/m^2)	VH$_{urb}$ (m^2/m^2)	H$_{bld}$ (m^3/m^2)	V/A (m^3/m^2)	S/V (m^2/m^3)	Sky Factor	SI$_y$ $(khWm^{-2}y)$
1	Barceloneta	0,52	2,59	2,23	16,50	8,55	0,38	0,29	258,12
2	Eixample	0,62	4,09	0,71	15,95	9,90	0,20	0,38	489,69
3	Mar Bella	0,33	2,60	0,92	19,52	6,42	0,25	0,38	474,79
4	Borrel y Soler	0,20	1,23	0,63	15,00	3,07	0,34	0,41	540,34
5	Raval	0,80	4,80	1,38	19,50	15,62	0,19	0,20	190,81
6	Gracia	0,64	2,17	0,89	11,60	7,47	0,29	0,33	369,30
7	Balduina	0,43	2,57	1,28	19,50	8,35	0,26	0,33	397,00
8	Centocelle	0,34	1,48	1,35	14,67	4,95	0,41	0,28	393,46
9	Don Bosco	0,43	3,41	1,68	25,50	10,88	0,23	0,24	407,62
10	Prati	0,49	2,96	1,43	19,50	9,62	0,25	0,24	351,88
11	Tuscolano	0,36	2,64	1,41	25,51	4,31	0,23	0,28	369,30
12	Giulio Agricola	0,41	2,47	1,44	21,00	8,63	0,26	0,31	359,33
13	Campo Marzio	0,79	3,94	1,77	17,34	13,67	0,24	0,11	166,60
14	Tridente	0,70	3,50	1,96	16,50	11,55	0,29	0,14	201,29
-	*Mean value*	*0,50*	*2,89*	*1,36*	*18,4*	*8,79*	*0,27*	*0,28*	*355,0*
-	*Standard deviation*	*0,18*	*0,99*	*0,46*	*3,9*	*3,50*	*0,06*	*0,09*	*113,94*
-	*Variation factor*	*4,00*	*3,90*	*3,53*	*2,20*	*5,08*	*2,14*	*3,68*	*3,24*

Moreover, Figure 3(a) underlines that in many cases, normalised FSI and VH$_{urb}$ values are directly proportional. But two couples – 1-8 and 2-5 cases – constitute an exception: the former shows higher VH$_{urb}$ values with lower FSI, while the latter has high FSI with lower VH$_{urb}$. Reasons could be found in S/V values – higher in the former and lower in the latter – that describe a different building width. If we compare VH$_{urb}$ to SF, a general inverse proportionality could be easily assumed: taken an area, the higher the façade surface is the lower the mean extent of the sky observed by façades becomes (Figure 3(b)).

Annual solar irradiation on façades SI$_y$ (kWhm^{-2}y) is lower in the cases with a combination of high-density-related UMIs values (GSI, FSI, VH$_{urb}$) and low SF values; while we found the highest rate of solar irradiation for low UMIs values correlated to high SF values.

In order to test the effect of urban compactness on solar energy, we compare the seven above-mentioned UMIs with the annual solar irradiation as shown in Figure 4. We found negative linear correlation for SI$_y$ and GSI, FSI, VH$_{urb}$,V/A and a positive linear correlation between SI$_y$ and SF. In fact, compact urban forms with denser layout reduce the ratio of visible sky from façades, due to mutual obstruction of buildings.

The coefficient of determination between solar irradiation and UMIs varies from about 0 to 0,79. The best correlations with solar performance are shown by V/A ratio (R^2 0.53), VH$_{urb}$ (R^2 0.59), GSI (R^2 0.60) and SF (R^2 0.79). Generally, comparing the linear correlation graphs is useful also to understand how case studies perform (Figure 4). Cases 2, 3, 4 and 9 receive more solar irradiation than the average – represented by trend lines – while cases 1, 5, 6, 13 and 14 receive less.

Multiple linear regression analysis applied to the results, provide an accurate analytical formulation to express the solar irradiation on façades as function of the three main UMIs (GSI, VH$_{urb}$ and SF) (1):

$$y = -0.43\,X1 - 0.38\,X2 + 0.32\,X3 \tag{1}$$

where y represents the normalised value of annual solar irradiation, and *X1, X2, X3* the normalised values of the independent variables, respectively GSI, VHurb and SF (see also Table 2). The coefficients of the multiple linear regression function also demonstrate that façade solar irradiation is more dependent by density indicators (GSI and VH$_{urb}$) rather than by SF.
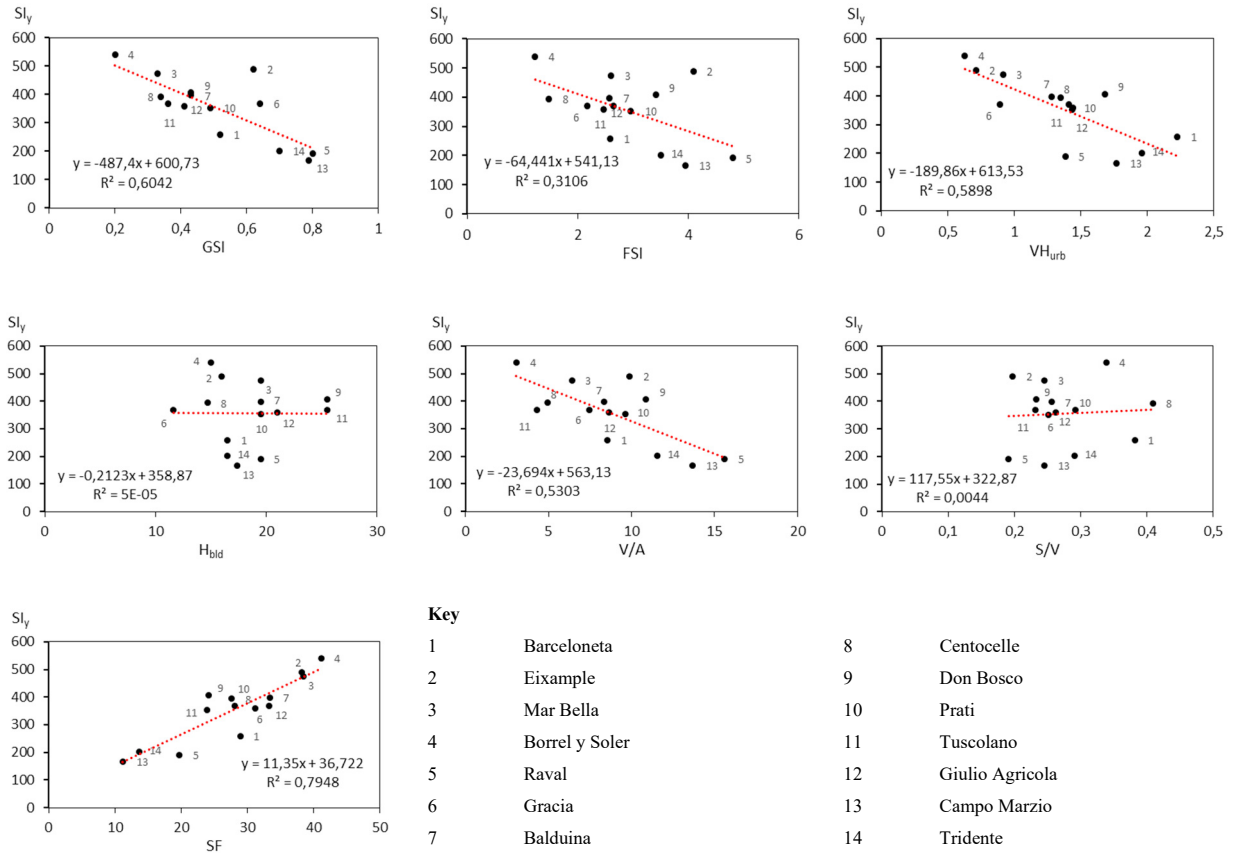
Fig. 4. Relations between Solar availability on building façades and different Urban Morphology Indicators regarded to case studies.

5. Discussion

The four UMIs (V/A ratio, VH_{urb}, GSI and SF) provide the best description of the façades solar performance because of their strict relation to urban density and building envelope features. FSI has a relative low coefficient of determination (R^2 0.31) because it considers the floor space of a given building, that does not have a direct relation with façade solar performance. Moreover, H_{bld} and S/V may not be reliable indicators for solar analysis ($R^2 \simeq 0$); this could be explained because the former is insufficient to represent the three-dimensional urban geometry and the latter does not have effect on the variation of façade solar energy performance, despite its importance for building energy performance.

Table 2. Regression statistics of multiple linear regression (1).

Regression statistics	
Multiple R	0,95
R squared (Coefficient of Determination)	0,91
Adjusted R square	0,88
Standard Error of the regression	0,34
Observations	14

In some urban textures, reasons of a better solar access than the average, are due to specific morphological features: very low urban density (case 4), optimal façades orientation combined with courtyard (cases 2, 3, 9). Instead solar performance is in general poor for cases with high urban density (as described by each UMIs). Case 1 constitutes an exception due to its very uncommon urban form compared with other cases: high aspect ratio and dominant orientations (E and W) strongly influence the façades solar access.

Based on these results, it can be argued that gross space index, façade-to-site ratio and sky factor are key urban layout indicators for solar availability on façades in historical urban fabrics in Mediterranean climate. Besides, there are several issues that are worth being underlined. According to analysis, sky factor shows the best correlation with urban solar performance; however, it is quite difficult to be calculated by architects: it requires knowledge on specific tools generally managed by researchers and specialist on the field. For this reason, to a first approximation, it is possible to take into account GSI and VH_{urb} as reliable key indicators for solar performance at urban scale. In fact, since they are much more common in planning practice and easier to be determined through accessible tools or simple direct analyses.

Our study proposes a comparison of the most widespread UMIs in the state of the art on the topic of urban geometry variables in solar analysis, specific for Mediterranean context and focusing on the performance of the vertical surfaces. In fact, compared to roofs, façade solar performance is the most affected by urban obstructions and, at the same time, shows more consistent relation with UMIs – in general roofs are less affected by the urban geometry. Besides, to find a better correlation morphology-solar energy, we propose a selection of case studies based on homogeneous urban layout, instead of defining them using administrative boundaries or urban cell of a given dimension [1,2]. In this way, UMIs used to characterize the urban texture are unaffected by the presence of different building typologies.

4. Conclusions

Our paper presents an investigation on the assessment of different UMIs useful to define the most suitable set of indicators for urban solar analysis in the Mediterranean context. Focusing on annual façade solar gains, results demonstrate the reliability of GSI, VH_{urb} and SF to predict the solar performance of different urban layouts. All UMIs and solar energy indicator were computed on fourteen urban textures of Rome and Barcelona, which represent some typical layouts of the Mediterranean compact city. Their causal relations were analysed using linear statistical correlations.

The multiple linear regression showed a strong correlation between the annual solar irradiation and the three indicators. Findings also suggest that the first couple of indicators, even if considered separately, could allow for a preliminary analysis of solar performance of different urban morphologies. The above-mentioned correlation could be useful for both planning guidelines and urban renovation process of the Mediterranean compact city. On one hand, they can support policy maker decisions according to the performances of urban morphology, in order to differentiate public investments and incentives. On the other hand, they should be integrated in the early stage of design process, taking into account the solar availability of urban areas to guide strategies for harvesting solar energy and fostering solar energy technologies [20] as well as helping architects understand façades solar irradiation implications of urban morphology. The proposed methodology could lead to define urban transformation strategies that brace other innovative technologies in the field of solar energy, and so integrate other scales of intervention (e.g. city and building) that improve global energy efficiency of urban environment, such as smart solar grids or new building materials to reduce UHI effect [21].

Further development should firstly consider an extension of the number of the case studies able to find a more precise linear regression and, above all, a validation of the model through experimental data.

Acknowledgements

References

[1]   Chatzipoulka C, Compagnon R, Nikolopoulou M. Urban geometry and solar availability on façades and ground of real urban forms: using London as a case study. Sol Energy 2016;138:53–66. doi:10.1016/j.solener.2016.09.005.

[2]   Mohajeri N, Upadhyay G, Gudmundsson A, Assouline D, Kämpf J, Scartezzini JL. Effects of urban compactness on solar energy potential. Renew Energy 2016;93:469–82. doi:10.1016/j.renene.2016.02.053.

[3]   Morganti M, Coch Roura H, Cecere C. The effect of urban obstructions in Mediterranean climates: Built form typology, density and energy. Archit City Environ 2012:13–26. doi:http://dx.doi.org/10.5821/ace.v7i19.2559.

[4]   Morganti M. Sustainable Density: Form, Built Environment, Energy. 2013. doi:http://www.tdx.cat/handle/10803/365041.

[5]   Compagnon R. Solar and daylight availability in the urban fabric. Energy Build 2004;36:321–8. doi:https://doi.org/10.1016/j.enbuild.2004.01.009.

[6]   Cheng V, Steemers K, Montavon M, Compagnon R. Urban Form, Density and Solar Potential. In: Antoine Compagnon Peter Haefeli WW, editor. PLEA2006 - 23rd Conf. Passiv. Low Energy Archit., Geneve: PLEA; 2006.

[7]   Curreli A, Serra-Coch G, Isalgue A, Crespo I, Coch H. Solar Energy as a Form Giver for Future Cities 2016. doi:10.3390/en9070544.

[8]   Carneiro C, Morello E, Desthieux G, Golay F. Urban environment quality indicators: application to solar radiation and morphological analysis on built area. Adv Vis Imaging Simul 2010:141–8.

[9]   Sanaieian H. Review of the impact of urban block form on thermal performance, solar access and ventilation. Renew Sustain Energy Rev 2014;38:551–60. doi:http://dx.doi.org/10.1016/j.rser.2014.06.007.

[10]   Li D, Liu G, Liao S. Solar potential in urban residential buildings. Sol Energy 2015;111:225–35. doi:10.1016/j.solener.2014.10.045.

[11]   Košir M, Capeluto IG, Krainer A, Kristl Ž. Solar potential in existing urban layouts-Critical overview of the existing building stock in Slovenian context. Energy Policy 2014;69:443–56. doi:10.1016/j.enpol.2014.01.045.

[12]   Ratti C, Baker N, Steemers K. Energy consumption and urban texture. Energy Build 2005;37:762–76. doi:https://doi.org/10.1016/j.enbuild.2004.10.010.

[13]   Morganti M, Pages-Ramon A, Isalgue A, Cecere C, Coch Roura H. Urban Fabric Performance in the Mediterranean City: A Typology Based Mass-Energy Analysis, Lausanne: EPFL; 2013, p. 581–6.

[14]   Salvati A, Cecere C, Coch H. Microclimatic response of urban form in the Mediterranean context. In: Strappa G, Amato AD, Camporeale A, editors. City as Org. New Vis. urban life, 22nd ISUF Int. Conf. - 1, Rome: U+D Edition; 2016, p. 719–28.

[15]   Salvati A, Coch H, Cecere C. Urban Morphology and Energy Performance : the direct and indirect contribution in Mediterranean Climate. In: Cucinella M, Pentella G, Fagnani A, D'Ambrosio L, editors. PLEA2015 Archit. (R)Evolution - 31st Int. PLEA Conf., Bologna, Italy: 2015.

[16]   Strømann-Andersen JB, Sattrup PA. The urban canyon and building energy use: Urban density versus daylight and passive solar gains. Energy Build 2011;43:2011–20. doi:https://doi.org/10.1016/j.enbuild.2011.04.007.

[17]   Morganti M, Pages-Ramon A, Isalgue A, Coch H, Cecere C. Built-form, mass and energy : Urban fabric performance. Proc - 28th Int PLEA Conf Sustain Archit + Urban Des Oppor Limits Needs - Towar an Environ Responsible Archit PLEA 2012 2012.

[18]   Zhang J, Heng CK, Malone-Lee LC, Hii DJC, Janssen P, Leung KS, et al. Evaluating environmental implications of density: A comparative case study on the relationship between density, urban block typology and sky exposure. Autom Constr 2012;22:90–101.

[19]   Beckers B, Masset L. Heliodon2 documentation 2011.

[20]   Nastasi B, Di Matteo U. Solar Energy Technologies in Sustainable Energy Action Plans of Italian Big Cities. Energy Procedia 2016;101:1064–71. doi:10.1016/j.egypro.2016.11.136.

[21]   Morini E, Castellani B, Presciutti A, Filipponi M, Nicolini A, Rossi F. Optic-energy performance improvement of exterior paints for buildings. Energy Build 2017;139:690–701. doi:10.1016/j.enbuild.2017.01.060.