University of Kent

Kent Academic Repository

Christina, Chatzipoulka, Raphaël, Compagnon and Marialena, Nikolopoulou (2016) *Urban geometry and solar availability on façades and ground of real urban forms: using London as a case study.* Solar Energy, 138 . pp. 53-66. ISSN 0038-092X.

Downloaded from
https://kar.kent.ac.uk/57972/ The University of Kent's Academic Repository KAR

The version of record is available from
https://doi.org/10.1016/j.solener.2016.09.005

This document version
Author's Accepted Manuscript

DOI for this version

Licence for this version
CC BY-NC-ND (Attribution-NonCommercial-NoDerivatives)

Additional information

Versions of research works

Versions of Record
If this version is the version of record, it is the same as the published version available on the publisher's web site. Cite as the published version.

Author Accepted Manuscripts
If this document is identified as the Author Accepted Manuscript it is the version after peer review but before type setting, copy editing or publisher branding. Cite as Surname, Initial. (Year) 'Title of article'. To be published in *Title of Journal* , Volume and issue numbers [peer-reviewed accepted version]. Available at: DOI or URL (Accessed: date).

Enquiries
If you have questions about this document contact ResearchSupport@kent.ac.uk. Please include the URL of the record in KAR. If you believe that your, or a third party's rights have been compromised through this document please see our Take Down policy (available from https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies).

Urban geometry and solar availability on façades and ground of real urban forms: using London as a case study

Christina Chatzipoulka[a,*], Raphaël Compagnon[b], Marialena Nikolopoulou[a]

[a] *Kent School of Architecture, University of Kent, Marlowe Building, CT2 7NR, Canterbury, United Kingdom*
[b] *Haute Ecole d'Ingénierie et d'Architecture de Fribourg, Pérolles 80, 1700 Fribourg, Switzerland*
[*] *Corresponding author. Phone: +44 7543966550, Email-address: C.Chatzipoulka@kent.ac.uk*

Abstract

Availability of solar radiation in the urban environment is determined to a great extent by urban geometry, namely how densely built-up an area is and how the given built volume is distributed spatially within the site. This paper explores relationships between urban geometry and solar availability on building façades and at the pedestrian level, with implications for buildings' passive potential and outdoor thermal comfort, respectively. The study was based on the morphological and solar analysis of 24 urban forms of London, covering a wide range of built density values found across the city. Two aspects of solar availability were investigated at the neighbourhood scale, through statistical analysis: i) the relationships between urban geometry variables and solar availability indicators in different time periods, and ii) the seasonal solar performance of urban forms' façades and ground.

Apart from the strong, negative effect of density, the analysis revealed that solar availability on ground and façades is significantly affected by urban layout. *Mean outdoor distance*, *site coverage*, *directionality* and *complexity* were the most influential for the solar performance of open spaces; whilst building façades were mostly affected by *complexity*, *standard deviation of building height* and *directionality*. However, direct solar irradiance on ground and façades was found to be influenced by different variables in January and July, which is attributed to the different solar altitude angles. Related to that, urban forms have been identified that present higher irradiance values in January and lower in June when compared to others. Considering temperate climates, these examples highlight the potential for enhancing the seasonal solar performance of existing and future urban developments. Finally, the seasonal effect on solar availability appears to be much more pronounced for ground with its mean direct irradiance value increasing on average by a factor 15, from January to July, while for façades the increase is only by a factor 2.6.

Keywords: solar availability; sky view factor; urban geometry; urban form; density

1. Introduction

With more than the half of the world population living in cities today (Population Reference Bureau, 2015), urban environmental sustainability has become the frame of reference for researchers and practitioners working in the field of urban design and planning. Solar radiation is a major factor to be considered for promoting environmental sustainability in urban settlements, as it is strongly associated with their energy efficiency and liveability. Solar availability on building façades and roofs determines to a great extent their passive and active solar potential; while the insolation of outdoor spaces affects

http://dx.doi.org/10.1016/j.solener.2016.09.005

their microclimate and, in turn, their use (Littlefair, 2001; 2011). Unlike other environmental factors such as wind and temperature, solar exposure of urban surfaces can be accurately simulated due to the directional nature of solar rays, and their predictable interaction with urban geometry. This enables for the causal relationships between urban geometry and solar availability to be explored and defined with great precision. As urban geometry may significantly vary between different cities, as well as within a city, connecting geometrical properties to resulting availability of solar radiation would provide a better understanding of existing urban forms, and facilitate future design and planning decisions.

1.1 Urban geometry and solar availability in urban environments

Referring to urban geometry, the present study makes a distinction between urban density and urban layout. Urban density refers to the magnitude of total built volume in a given site, while urban layout, to the way in which this built volume is distributed spatially within the site, horizontally and vertically. The negative correlation between built density and, solar and daylight availability has been widely reported (Sanaieian et al., 2014) with implications for buildings' energy performance (e.g. Steemers, 2003; Strømann-Andersen & Sattrup, 2011) and, urban microclimate and outdoor thermal comfort (e.g. Ali-Toudert & Mayer, 2006; Emmanuel et al., 2007).

Nonetheless, increased built density is an objective of urban planning as it is associated positively with urban environmental sustainability, especially at the city scale (Jabareen, 2006). Therefore, for temperate and cold climates, where enhancing solar availability is crucial, the counterbalance of the negative impact of increasing density is sought through the deliberate manipulation of urban layout (e.g. Kristl & Krainer, 2001; Lu & Du, 2012). For instance, even given the same density, varying the combinations of site coverage and building height alters the level of solar irradiation (Lee et al., 2016), with decreasing coverage being found beneficial for solar thermal and energy potential on façades and solar availability on the ground (Cheng et al., 2006a; 2006b). Nonetheless, when photovoltaics and solar thermal potential are examined on entire building envelopes, the impact of site coverage is inversed as increasing building footprint area means larger roof area (Li et al., 2015). Another parameter of urban layout that has been found to be influential, especially in urban environments of high-density, is vertical and horizontal randomness, the increase of which may lead to higher solar potential on building envelopes, daylight availability on façades as well as openness of the open space to the sky (Cheng et al., 2006b; Ng & Wong, 2004). It should be pointed out that, until recently, most of the studies examining relationships between urban geometry variables and solar availability indicators were based upon computer-based parametric investigations on generic models of urban canyons, or simple configurations of rectangular building volumes. It is therefore important that such research findings are tested in real urban forms.

1.2 Recent developments in the field

Compared to buildings' solar performance, the study of solar availability in urban environments is considerably more complex, and demanding in terms of computational time and resources. This partially explains why the major researches on this topic have been conducted in the context of collaborative research projects, e.g. Project ZED (1997) and its successor PREcis (2000), up to the ongoing IEA SHC Task 51 Solar Energy in Urban Planning. As included in the conclusions of IEA SHC Task 41 Solar Energy and Architecture (Wall et al., 2012), "[…] *a vast development is needed regarding strategies, methods,* *tools and case studies on the urban level*." However, as computer capabilities increase, studies performing solar radiation simulations at urban scale also increase gradually. Various simulation tools make use of the backwards ray-tracing programme RADIANCE (Ward Larson & Shakespeare, 1998), including CBDM (Mardaljevic, 2010), DIVA (Jakubiec & Reinhart, 2011), and PPF (Compagnon, 2004). Whereas, others simulate holistic urban fluxes employing a Simplified Radiosity Algorithm (Robinson, 2005) for predicting radiant energy flux on building surfaces (e.g. SUNtool and CitySim).

Beyond powerful simulation tools required, the investigation of solar performance of urban areas relies also on the availability of their 3D geometry information. Thanks to recent advances in LIDAR technology and availability of modern GIS-based 3D models of cities, an increasing number of studies deal now with solar availability in real urban forms (Biljecki et al., 2015). A category of those uses 3D urban models of cities in order to evaluate solar energy and passive potential on building envelopes (e.g. Brito et al., 2012; Redweik et al., 2013). There has also been some research which uses data derived from the morphological analysis of cities in order to identify representative typologies and next, based on them, examine how to optimize the solar potential by controlling urban morphological variables. For instance, Sarralde et al. (2015) tested the impact of eight such variables on the solar energy potential analysing different possible scenarios of urban morphology in Greater London. According to the neighbourhood-scale statistical model employed, the optimum combinations of variables could increase the solar irradiation of roofs and façades by 9% and 45%, respectively. Similarly, in the study of A.I. Martins et al. (2014) for the Brazilian city of Maceió, solar energy potential, daylight availability and potential solar gains were assessed on building envelopes of representative urban configurations, varying morphological parameters' values. Building height to street width ratio, average distance between buildings and albedo were identified as the most relevant factors to the solar irradiation and illuminance levels on building surfaces.

1.3 Objectives of the study

The present study combines three distinct objectives, which in turn determine to a great extent the methodology employed. The first objective is to investigate statistically the relationship between urban geometry and solar availability in real urban areas. Unlike aforementioned studies that apply a top-down methodological approach limiting the complexity of urban geometry to some identified as representative urban configurations, this study is based on the analysis of 24 urban forms found across London. The magnitude of the sample implies the acquisition of a tremendous size of raw data, and enables the statistical exploration of relationships between urban geometry variables and solar availability indicators at the neighbourhood scale. A recent study by Mohajeri et al. (2016) focused on the relationship between six density indicators, such as site coverage, plot ratio and population, and buildings' solar potential in 16 neighbourhoods of the city of Geneva (Switzerland).

The second objective is to examine simultaneously the solar availability on building façades and in open spaces, which up to now have received the attention of only few researchers (e.g. van Esch et al., 2012; Zhang et al., 2006). In contrast to solar irradiation of building envelopes, the consideration of solar availability in open spaces does not present an explicitly quantified motivation such those related to reduced energy consumption, CO_2 emissions and cost. Nonetheless, the microclimatic conditions in open spaces do affect the thermal comfort or discomfort levels experienced by people and, thus, the duration and quality of their outdoor activities (Nikolopoulou & Lykoudis, 2007). Such activities may significantly promote individual and collective well-being of inhabitants contributing to more livable as well as, economically and socially, sustainable cities (Nikolopoulou et al., 2001). In order for solar availability on building façades and in open spaces to be studied in equal terms, the solar indicators to be used ought to be common and meaningful in both cases. For this reason, mean sky view factor and mean irradiance were selected to be examined, instead of indicators referring directly to buildings' solar potential and outdoor thermal comfort (e.g. irradiation values above given thresholds and mean radiant temperature, respectively).

Finally, the targets regarding the modification of the solar availability on urban surfaces may vary in time (e.g. seasons), as well as due to different purposes of the solar use (e.g. passive heating, photovoltaics), leading to major conflicts in urban environmental design. In temperate climates, such a conflict results from the seasons' different thermal needs: in general, opting for maximising thermal gains in winter and minimising them in summer, both indoors and outdoors (Littlefair et al., 2000). Considering the above as typical case for London's buildings and open spaces, this study explores the seasonal solar performance of different urban forms of the particular city. For this purpose, solar irradiation of façades and ground is examined for three time periods: the entire year, a winter month (January) and a summer month (July). In addition, the consideration of different months accomplishes another purpose, which is to investigate the impact of solar altitude angles on causal relationships between urban geometry and solar availability.

2. Methodology

The methodology comprises three distinct stages: i) the morphological analysis of three areas of London by computing a set of urban geometry variables, ii) the analysis of solar availability on ground and building façades, and calculation of solar availability indicators for selected urban forms, and iii) the statistical elaboration of the results of the two previous stages. More details about the methodological stages are presented in Section 2.1, 2.2, and 2.3, respectively.

Fig. 1: Right, 3 studied areas on the map of London; left, the DEM of central London's area divided into cells of 500x500m.

http://dx.doi.org/10.1016/j.solener.2016.09.005

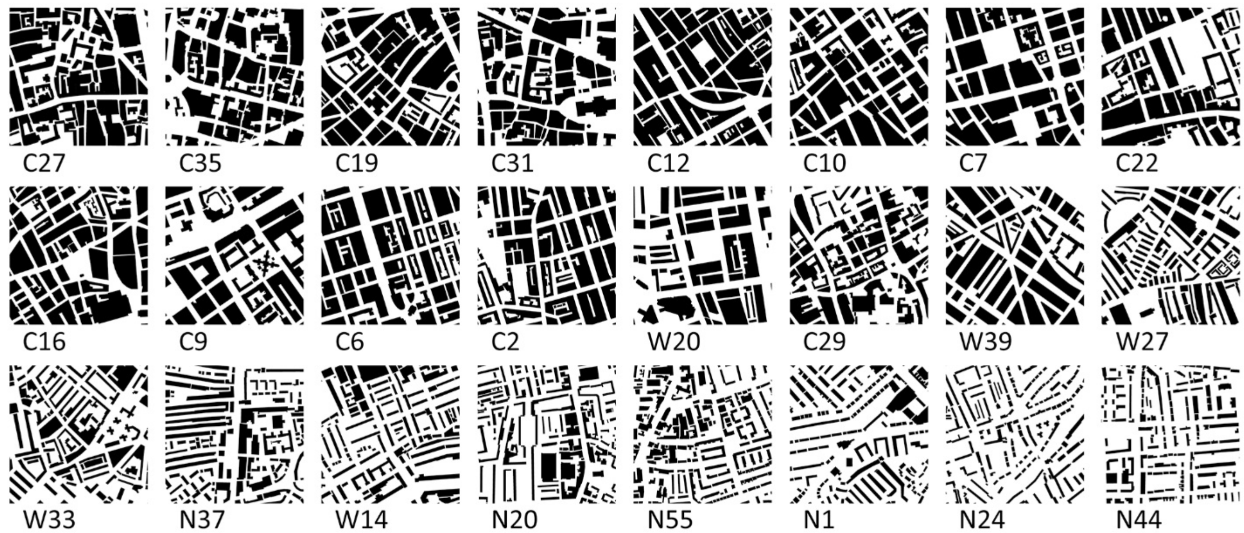


Fig. 2: Twenty-four urban forms from central (C), west (W) and north (N) London, in decreasing order of density.

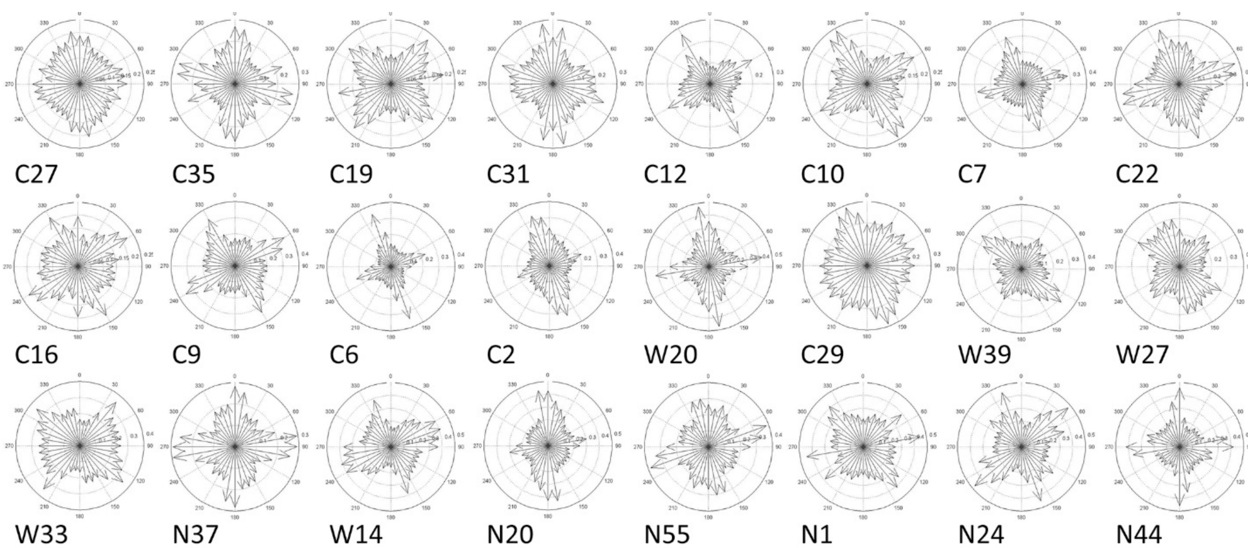


Fig. 3: Polar diagrams showing the variance of ground's permeability of the 24 urban forms in 36 directions.

2.1 Morphological analysis

The 3D information of buildings' geometry in London (51°30'26'N, 0°7'39'W), including building footprints and heights, was obtained in shapefile format from the Centre for Environmental Data Archive. For the purposes of the study, three representative areas of London, of total surface area 37.5 km^2, have been selected: in central, west and north London, which are of high, medium and low built density, respectively. First, the digital elevation models (2.5 DEMs) of the three areas were produced to 0.25m spatial resolution in ArcGIS ArcMap and divided into cells of 500x500m size (Fig. 1). Similar spatial scale has been used by previous studies exploring relevant topics (e.g. A.I. Martins et al., 2014). Next, all the cells were analysed using image processing techniques in Matlab software (Ratti & Richens, 2004) and a representative range of density values for London was obtained. Finally, 24 cells, i.e. urban forms, were selected to be included in the study based on: i) continuity of urban fabric, ii) inclusion of different urban layouts, and iii) the acquisition of a continuity of density values, with most of those to be represented by more than one cells. The final sample is comprised of 6 urban forms from north, 5 from west and 13 from central London (Fig. 2), covering respectively density values between 3-6, 5-11 and 10 -22 m^3/m^2.

Among a great number of variables found in the relevant literature and computed for London's areas, ten of them were identified as the most basic in describing the variation of urban geometry i.e. urban density and nine urban layout descriptors. Urban density expresses the magnitude of total built volume, and is measured as total built volume on a given site over site area [m^3/m^2]. On the other hand, urban layout descriptors describe urban layout, i.e. how the given built volume is spatially allocated into the site, and are presented below:

- *Site coverage* (SCo) – total buildings' footprint area over site area, [%];
- *Mean building height* (MeH) – building height weighted by footprint area, [m];
- *Standard deviation of building height* (StH), [m];
- *Standard deviation of building footprint area* (StF), [m^2];
- *Directionality* (Dir) – standard deviation of ground's permeability in 36 directions weighted by site coverage, [-];
- *Complexity* (Cex) – total façades' surface area over site area, [m^2/m^2];
- *Compactness* (Com) – total buildings surface-to-volume ratio, [m^2/m^3];
- *Number of building volumes* (NOB) within the area;
- *Mean outdoor distance* (MOD) – mean distance of outdoor space from the nearest building façade, [m].

Site coverage and *mean building height* are two major urban planning variables expressing the horizontality and verticality of an urban form respectively. The product of their values is equal to built density; or stated otherwise, for a given density the two variables are inversely proportional. Another important feature of an urban form is the degree of its randomness. *Standard deviation of building height* expresses the degree of vertical randomness, i.e. the higher the StH value the less uniform the urban form's skyline. In the absence of a single variable measuring urban horizontal randomness, the study employs two variables which are associated to it, i.e. *standard deviation of building footprint area* and *directionality*. A higher value of StF demonstrates a less even distribution of total site coverage across the site. *Directionality* expresses the horizontal permeability of an urban form -as a porous medium- at the ground level: the more permeable an urban form at the ground level, the less random its horizontal layout. The particular variable is conceived in the context of this study, but initially inspired by the *variance plot* of Ratti et al. (2006) which is a polar diagram showing the variance of the average urban profile in different directions. The computation of directionality is based on the same algorithm (Ratti, 2001) but instead of DEMs, the ground maps of the urban forms (Fig. 2) are used. Ground permeability values are computed for 36 directions, as shown in Figure 3, and weighted by urban form's *site coverage*. Next, the directionality value is calculated as the standard deviation of ground permeability in these 36 directions. *Complexity* expresses how undulating an urban form is, the more undulating the form the higher the Cex, and it is thus related to *compactness*. The complexity of an urban form is mostly referred in the literature as an attribute defining its aerodynamic properties; while compactness is commonly associated to buildings' potential energy needs. However, both complexity and compactness significantly contribute to the variance of urban geometry and different expressions of them (e.g. convolution index and form factor respectively) have been included as geometric variables in past studies (Arboit et al., 2008; Hii et al., 2011). *Number of building volumes* expresses into how many building volumes the given built density is divided, and is therefore associated to mean building volume, i.e. grain size of an urban form. Last, *mean outdoor distance* is calculated as average Euclidean distance of non-built pixels from the nearest built one (Fig. 8c); so, it is proportional to mean distance between building volumes expressing mean street width.

Pearson correlation analysis (two-tailed) was performed to test the interdependence of the selected urban geometry variables. As seen in Table 1, most of them present a significant correlation with density, which also causes their strong interdependence. It is noticeable that the coefficient of correlation between density, and SCo and MeH variables are similar and particularly high, indicating that urban density in London increases with urban forms being equally expanded in vertical and horizontal means. Table 2 demonstrates the results of repeating the same statistical test but controlling the density variable.

Table 1: Pearson Correlation (two-tailed) results for all urban geometry variables.

	Density	SCo	MeH	StH	StF	Dir	Cex	Com	NOB	MOD
Density		0.931**	0.968**	0.628**	0.898**	-0.663**	0.965**	-0.920**	-0.846**	-0.285
SCo			0.829**	0.546**	0.922**	-0.693**	0.882**	-0.939**	-0.883**	-0.414*
MeH				0.633**	0.824**	-0.581**	0.937**	-0.887**	-0.827**	-0.107
StH					0.484*	-0.307	0.589**	-0.572**	-0.529**	-0.137
StF						-0.563	0.850**	-0.882**	-0.874**	-0.324
Dir							0.706**	0.606**	0.505*	0.575**
Cex								-0.834**	-0.770**	-0.401
Com									0.954**	0.148
NOB										0.053
MOD										

** Correlation is significant at the 0.01 level

* Correlation is significant at the 0.05 level

Table 2: Pearson Correlation (two-tailed) results for all urban layout variables, controlling density.

	SCo	MeH	StH	StF	Dir	Cex	Com	NOB	MOD
SCo		-0.791**	-0.137	0.535*	-0.277	-0.167	-0.574*	0.493*	-0.426*
MeH			0.133	-0.411	0.324	0.049	0.036	-0.061	0.704**
StH				-0.230	0.188	-0.081	0.019	0.005	0.057
StF					0.099	-0.134	-0.324	-0.486*	-0.160
Dir						-0.336	-0.016	-0.141	0.538*
Cex							0.517*	0.328	-0.497*
Com								0.842**	-0.305
NOB									-0.369
MOD									

** Correlation is significant at the 0.01 level

* Correlation is significant at the 0.05 level

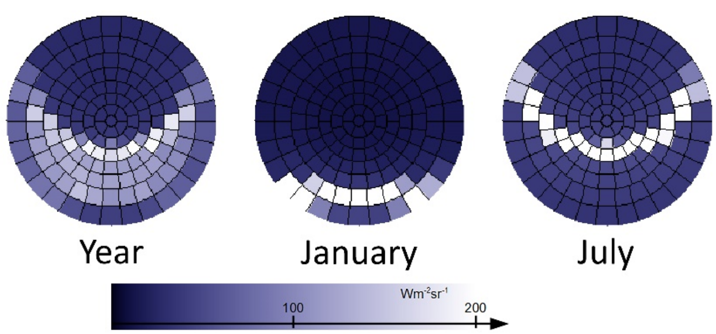
2.2 Solar availability analysis

Solar irradiation availability is related to the openness of an urban form to the sky vault which is decided by its geometry (diffuse solar component), and its exposure to the sun which is decided by its geometry and the orientation of it in relation to the sun path (direct solar component). In this study, solar availability is equally considered at ground level and on building façades. The former is highly related to the thermal conditions experienced by pedestrians and users of open spaces; while, solar irradiation of building façades is mostly linked with the buildings' solar passive potential.

For the assessment of solar availability, mean irradiance [W/m^2] and sky view factor (SVF) [-] values have been selected to be examined. It is noted that SVF is widely used in the literature as indicator of solar availability (Robinson, 2006), both on façades and ground. The simulations have been performed in PPF software, which offers a great flexibility regarding the calculation of solar quantities on buildings' fabrics and ground, and has been employed by several studies, so far (e.g. Cheng et al., 2006a; 2006b; Compagnon, 2000; Montavon et al., 2004). Direct (*Id*), diffused from the sky (*Is*) and reflected by buildings (*Ib*) irradiances are computed separately; while global (*Ig*) irradiance is calculated as the sum of them, as described below:

$$Ig = Id + Is + Ib$$

PPF is based on the RADIANCE ray-tracing programme and uses sky models which represent average radiance distributions of the sky vault for a given time period (Compagnon, 2004). Specifically, for the irradiation simulations, climatic data of London (hourly direct and diffuse irradiance values) were obtained from METEONORM software (Remund et al., 2015) and processed statistically in order to build up three sky models: aggregating weather data of the entire year, January and July (Fig. 4). Only daytime hours were considered, i.e. hours between sunrise and sunset on a day, which are 4317 for the year, 249 for January and 489 for July. The 3D digital models of the urban forms were re-produced in a CAD software including the surrounding buildings, and inserted in PPF (Fig. 5). SVF and irradiance values were computed at each node of a grid of 2-meter spatial resolution, adjusted onto the buildings' surfaces of the models, and on a horizontal plane at 1.1m above the ground corresponding to the average level of the center of gravity of a standing person in Central Europe (Matzarakis et al., 1999).



Year
mean diffuse horizontal irradiance: 120 W/m^2
mean direct horizontal irradiance: 102 W/m^2

January
mean diffuse horizontal irradiance: 52 W/m^2
mean direct horizontal irradiance: 32 W/m^2

July
mean diffuse horizontal irradiance: 136 W/m^2
mean direct horizontal irradiance: 157 W/m^2

Fig. 4: Stereographic views of the sky vault representing sky models generated for the year, January and July, and used in PPF simulations.

http://dx.doi.org/10.1016/j.solener.2016.09.005

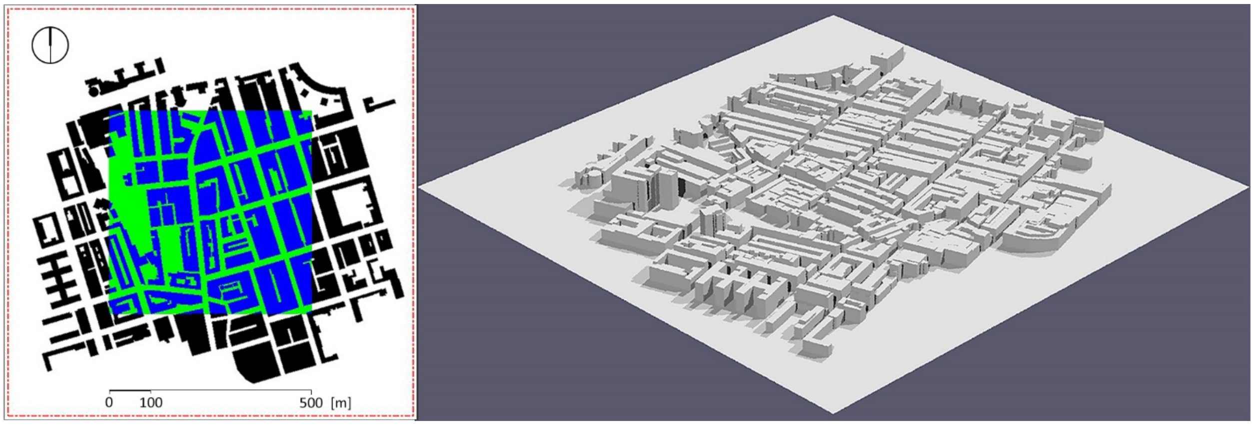


Fig. 5: Left, ground map of a 3D model as seen in PPF: in colour the simulated area (i.e. building volumes in blue, ground in green), in black the surrounding building volumes. Right, perspective view of the same model.

2.3 Statistical analysis

The relationships of urban geometry variables and mean solar indicators' values were explored performing statistical tests in SPSS statistical package. Since these relationships were found to be fairly linear, Pearson Correlation and Linear Regression tests were capable of describing them adequately.

3. Results

3.1 Urban geometry, SVF and irradiance values in twenty-four urban forms

3.1.1 Relationship of urban geometry and mean SVF

The statistical analysis revealed a significantly strong, negative correlation between density and mean ground SVF (r=-0.950) and mean façades SVF (r=-0.958). Furthermore, the correlation between mean ground and façades SVF was even higher (r=0.967), with both decreasing with increasing density (Fig. 6). Controlling for the effect of density, the correlation remained statistically significant but it dropped to 0.637 (p=0.001). This is related to the fact that SVF on ground and vertical urban surfaces was found to be affected by different urban layout descriptors. Indeed, performing partial correlation for urban layout descriptors and mean SVF values with control for density, it was found that the strongest variables for mean ground SVF were MOD (r=0.736, p<0.001), SCo (r=-0.654, p=0.001), Dir (r=0.486, p=0.019) and Cex (r=-0.478, p=0.021); whilst for façades were Cex (r=-0.622, p=0.002), StH (r=0.579, p=0.001) and Dir (r=0.479, p=0.021).

It is observed that, for a given density, mean ground SVF is primarily affected by the quantitative characteristics of the open space itself, namely mean street width (expressed by MOD) and total open space's area (expressed inversely by SCo). However, these two parameters do not present any significant effect on mean façades SVF. Similarly, differentiation of building heights (expressed by StH) was found to influence positively only façades mean SVF value. On the other hand, the variables which affect both ground and façades are Cex and Dir, the former negatively and the latter positively. This indicates that the more undulating the building façades of an urban form the greater the sky obstruction for the open spaces and façades; while increasing the directionality of its horizontal layout increases the overall openness of the urban form to the sky.

Additionally, the MeH variable appears to correlate positively with mean ground and façades SVF, and in the case of the former the correlation is statistically significant (r=0.519, p=0.011). This counter-intuitive finding is explained by the inversely proportional relationship of MeH and SCo variables for a given density (see Table 2), in combination to the fact that SCo is associated negatively to SVF values: higher MeH means lower SCo which in turn is associated with higher mean SVF values. SCo measures an absolute quantity of the urban form (i.e. percentage of the site area covered by buildings), while MeH expresses an averaged one (i.e. mean building height); this makes SCo more accurate in information encapsulated. As shown in Table 3, the relationship of MeH and mean irradiance values was also found positive and, therefore, the relevant results are not further discussed in this paper.

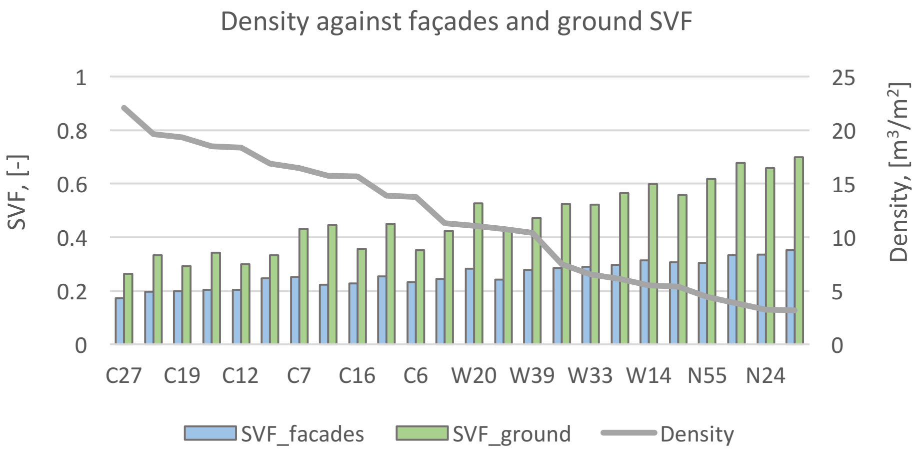
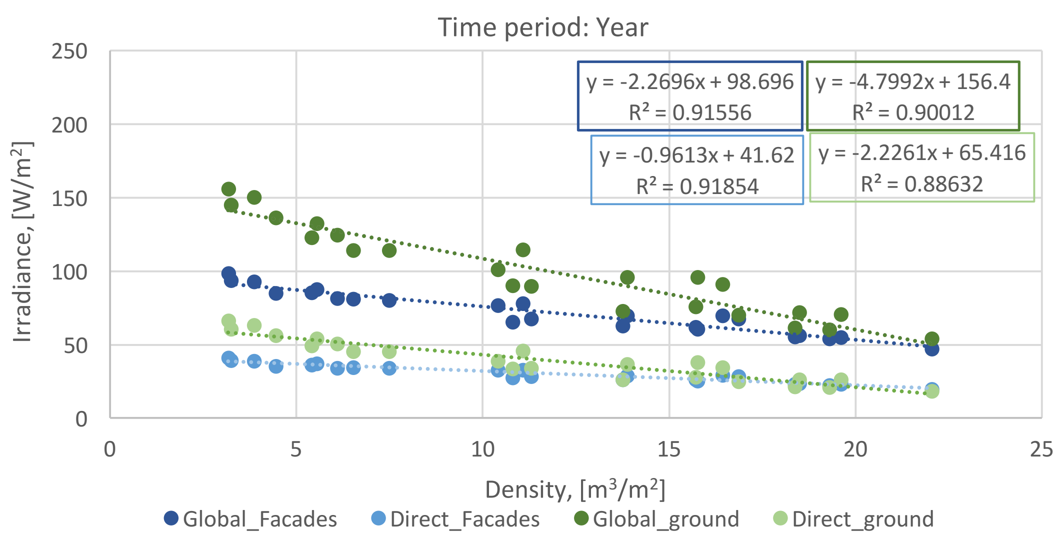
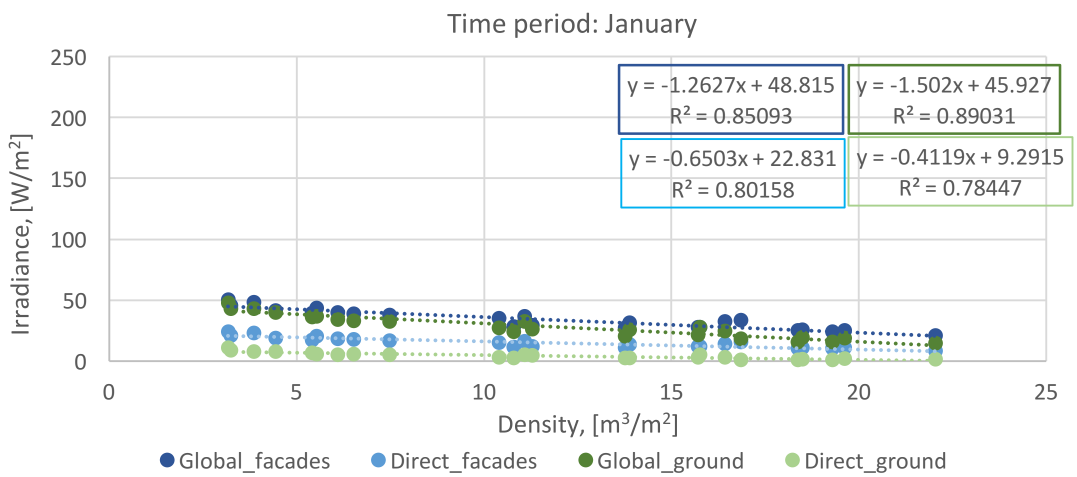


Fig. 6: Density [m^3/m^2] and mean SVF values, of façades and ground, in 24 urban forms.

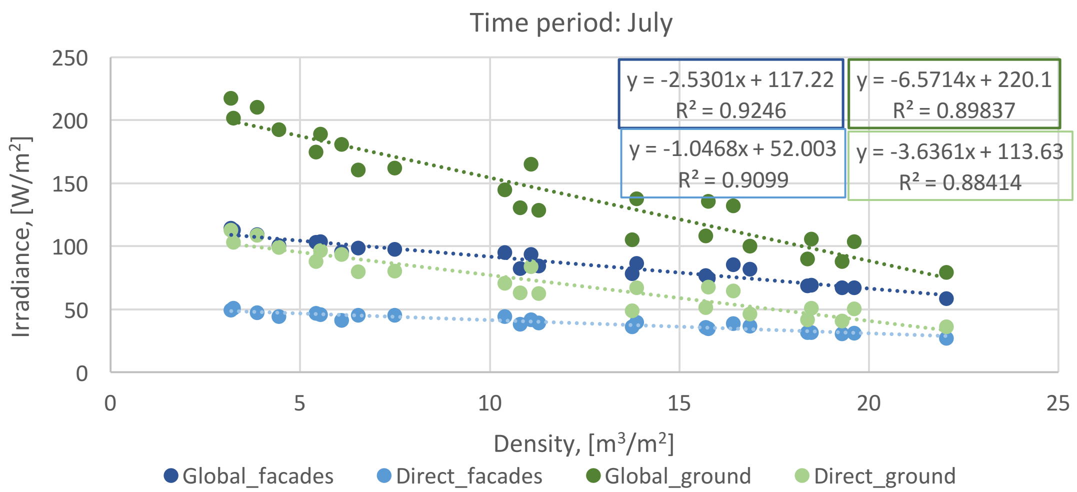


(a)

http://dx.doi.org/10.1016/j.solener.2016.09.005



(b)



(c)

Fig. 7: Linear regression models for density variable and mean global and direct irradiance on ground and façades, over the entire year (a), in January (b), and in July (c).

3.1.2 Effect of the orientation of urban forms on mean irradiance

Since the variables used in the analysis are single numbers and, hence, cannot express the relevant information by azimuth, the effect of urban forms' orientation was first examined in order to be identified and quantified, prior to the investigation of the relationship between urban geometry and mean irradiance. In particular, mean irradiance values were computed for building façades and ground of the urban forms rotating their models by 30° of azimuth from 0°, i.e. actual orientation, to 180°, using the year's sky model. It is noted that targeted analysis has shown that the orientations symmetrical to the N-S axis present very similar results, which allows to consider only half the orientations. In this way, beyond the actual orientation of the urban forms, six more have been computed and studied: 30°, 60°, 90°, 120°, 150° and 180° azimuths.

The results indicated that the impact of orientation is slightly greater on mean ground irradiance compared to mean façades irradiance; however, in both cases, their variance due to varying orientation was limited. For the seven orientation examined, the standard deviation of mean ground direct irradiance in different urban forms varies from 0.1 to 0.9 [W/m^2]; while the relative maximum difference between the mean direct irradiance values computed for each urban form is at a level of 1% to 10%. Respectively, for façades, the standard deviation of mean direct irradiance varies between 0.1 and 0.8 [W/m^2] and the relative maximum difference is at a level of 1% to 8%. Regarding mean diffuse irradiance values, the orientation effect was marginal as expected.

The above results refer to the annual mean irradiance values on ground and building façades and cannot be directly extended to the other two time periods considered in the study. Nonetheless, they provide evidence that, at such a scale, gains and losses in direct solar radiation by varying the orientation of urban forms are counterbalanced resulting in similar mean direct irradiances.

3.1.3 Relationship of urban geometry and mean irradiance

Next, the relationships between urban geometry and mean irradiance values were tested. The correlation between density and mean values of all the components of solar radiation is significantly strong ($|r|>0.880$) with slight differences between façades and ground, and among the time periods considered. It is observed that density correlates better with mean façades irradiance values compared to those of the ground, with only exception this of direct irradiance in January. Furthermore, among the three time periods, the correlation coefficients for January are in general lower than those for the year and July, which are more or less similar. This is attributed to the fact that solar angles affect the strength of the relationship between urban geometry and solar availability, i.e. for lower solar altitude angles the relationship becomes weaker (Chatzipoulka et al., 2015). Figure 7 demonstrates the linear regression models describing the relationship between density and, mean global and direct irradiance for ground and façades, in different time periods.

As in Section 3.1.1, the relationships between nine urban layout descriptors and mean irradiance values were explored by performing partial correlation analysis with control for density. In general, it is observed that the descriptors which were found to affect mean SVF the most are also the strongest variables for predicting mean irradiance. However, this mostly refers to global and diffuse from the sky radiation, since in London's weather file the latter constitutes a great part of the former (Fig. 4). Interestingly, mean direct irradiance was found to be influenced by different urban layout descriptors in different time periods (Table 3). With respect to the ground, the availability of direct radiation is affected by all urban layout descriptors but StH. SCo and Dir present consistently significant correlation with mean direct irradiance; whereas, MOD, StF, Cex, Com and NOB are of significance in different time periods. Compared to the ground, the façades were found to be less affected by urban layout descriptors, i.e. fewer number of them presenting significant correlation with mean direct irradiance. Furthermore, there has not been identified any descriptor being of significance for all three time periods, which may be interpreted in that the relationship between mean façades direct irradiance and urban layout descriptors is more sensitive to different seasons, i.e. solar altitude angles. The effect of StH is statistically significant over the year period, and in January when the sun's position is relatively lower in the sky vault. For winter months, NOB is also found to be affecting the insolation of the façades as well as of the ground; the distribution of a given density into a greater number of building volumes allows a greater range of low solar beams to penetrate into the urban fabric and reach the ground and building façades. On the other hand, in July, mean façades direct radiation is influenced by Cex and MOD variables, which are also among the strongest for ground over the same period.

http://dx.doi.org/10.1016/j.solener.2016.09.005

In order to highlight the relevance of the above results to real urban forms' solar performance, a pair of urban forms in central London, which are of similar density but fairly different layout, was identified, i.e. C6 and C9 (Fig. 8). The location of the two corresponding cells is highlighted in central London's DEM in Figure 1. C6 lies between Regent Park and Oxford Circus; while C9 is situated north-east to the previous, near Euston station. The results of the morphological analysis and solar simulations of the compared urban forms, as well as of the remaining ones, are presented in Appendix. As seen, although they are both of approximately 14m^3/m^2 density, C9 admits more solar radiation incident on its ground and façades, in all different time periods. C9 has lower site coverage (SCo) by 17% and almost double mean outdoor distance (MOD) compared to C6, which may explain higher mean global irradiance on its ground: by 32% over the year, 24% in January, and 31% in July. The effect of directionality (Dir) to which C6 performs slightly better seems to be outbalanced by the tightness characterizing its layout. The only case in which the ground of the two urban forms present similar values is January's mean direct irradiance, for which compactness (Com) and number of building volumes (NOB) have been found earlier to be influential. Regarding the façades, the better performance of C9 is mostly associated to its less uniform vertically form, as expressed by StH, and its higher MOD value; the mean façades global irradiance in C9 is higher by 11%, 15% and 10%, for the year, January and July, respectively. Besides higher mean values, C9 also presents a more even distribution of irradiance values with greater percentage of its façades and ground receiving more global radiation, comparing to C6 (Fig. 9).

Table 3. Pearson correlation analysis (2-tailed) for urban layout descriptors and mean direct irradiance values, controlling for density variable.

	SCo	MeH	StH	StF	Dir	Cex	Com	NOB	MOD
Ground									
Year	**-0.695****	0.496*	0.154	**-0.465***	**0.477***	-0.407	0.258	0.378	**0.656****
January	**-0.593****	0.301	-0.017	-0.229	**0.503***	-0.091	**0.500***	**0.427***	0.403
July	**-0.657****	0.511*	0.142	**-0.478***	**0.479***	**-0.417***	-0.170	0.329	**0.673****
Façades									
Year	-0.303	0.173	**0.530****	-0.206	**0.485***	**-0.544****	0.062	0.039	**0.425***
January	-0.409	0.081	**0.576****	-0.388	0.298	-0.364	0.312	**0.431***	0.187
July	-0.069	0.169	0.345	-0.074	0.337	**-0.509***	-0.168	-0.375	**0.451***

** Correlation is significant at the 0.01 level

* Correlation is significant at the 0.05 level

http://dx.doi.org/10.1016/j.solener.2016.09.005

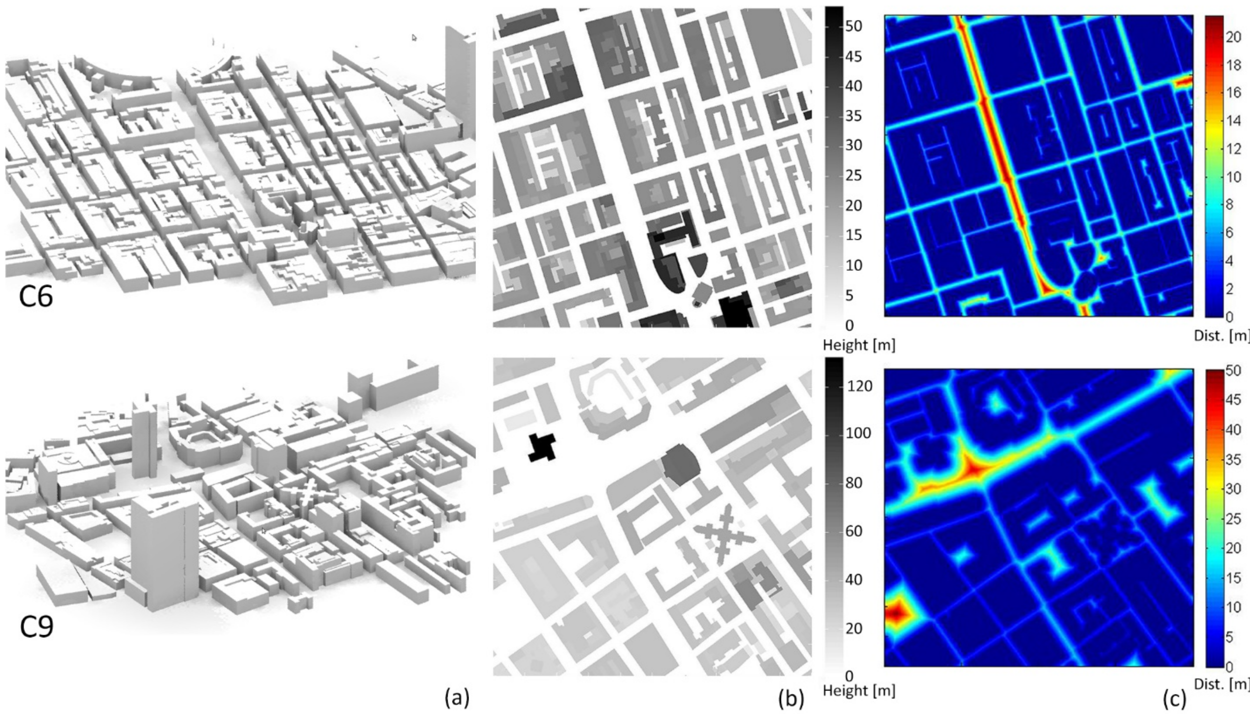
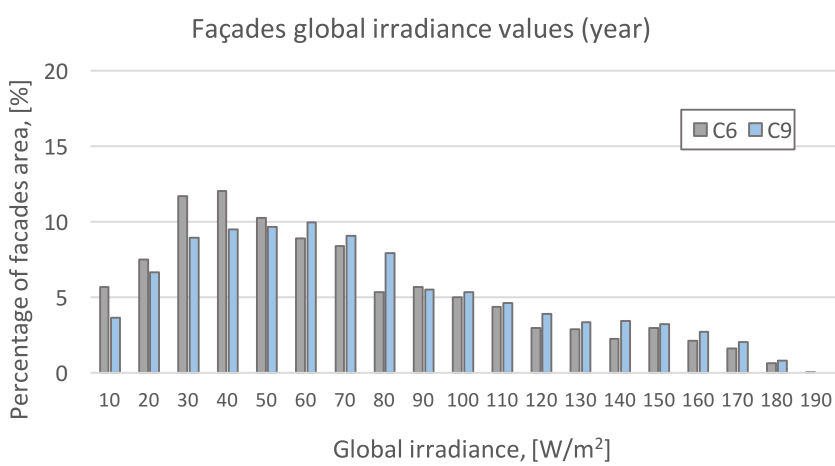
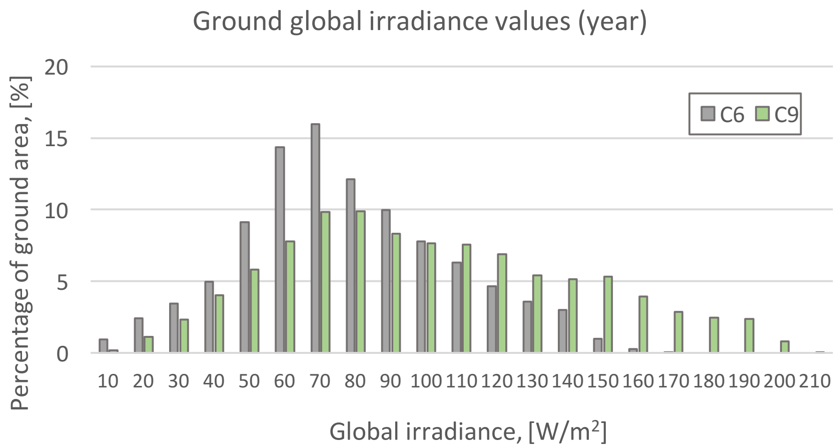


Fig. 8: Perspective views of the models (a), DEMs (b) and maps showing Euclidean distance of outdoor space from the nearest building (c) of C6 and C9 urban forms.



(a)



(b)

Fig. 9: Comparison of distribution of irradiance values computed in C9 and C6, as percentage of total surface area: for façades (a), and ground (b).

3.2 The effect of season on mean irradiance values

3.2.1 Effect on façades and ground

The seasonal effect on solar availability is examined separately for façades and ground in order for this to be associated to the resulting potential for indoor and outdoor environment, respectively. In a representative winter month, such as in January, the excessive overshadowing in urban forms due to low solar angles was found to affect primarily the solar irradiation of open spaces. As seen in Figure 7b, the façades of the urban forms admit more solar radiation, global and direct, compared to the ground. In contrast, in July, as the sun path coincides with higher positions in the sky vault, the open spaces are more exposed to solar radiation, in all urban forms independently of their density (Fig. 7c). Furthermore, the absolute and relative difference between mean irradiance values on ground and façades increases with decreasing density; the lower the density of an urban form, the greater the heat stress exerted over the ground related to that on building façades.

Indicatively, the average value of mean global irradiance for all 24 urban forms in January is 34.1 W/m^2 for façades, and 28.4 W/m^2 for the ground. However, in July, the respective values increase to 87.7 W/m^2 and 143.5 W/m^2. Therefore, the open spaces receive on average about 5 times more radiation in July compared to January, while the solar irradiation of the façades increases by 2.6 times. As far as the direct solar component is concerned, which is highly related to solar angles, the effect of the season is similar for façades but becomes even more pronounced for ground. More specifically, mean direct irradiance incident on ground is on average 15 times higher in July than in January, i.e. increasing from 4.4 to 71.2 W/m^2; whereas that incident on building façades increases by 2.6 times, i.e. from 15.2 to 39.8 W/m^2. Combining the above findings, it can be argued that the seasonal solar effect is much more pronounced for open spaces rather than for building façades, with open spaces suffering from excessive overshadowing in the winter and prolonged solar exposure in the summer.

http://dx.doi.org/10.1016/j.solener.2016.09.005

3.2.2 Seasonal performance of twenty-four urban forms

This last part of the study investigates the extent to which urban forms with higher mean irradiance in January also admit more solar radiation in July. The relationship between mean global irradiance values in January and July is almost perfect linear with R^2 being particularly high, 0.945 for façades and 0.983 for ground (Fig. 10). Regarding direct irradiance, the respective values are 0.825 and 0.878. Therefore, there is a great tendency for urban forms with higher irradiance values in January to also present higher values in July, and inversely. However, this linear relationship becomes less strong when referring to direct irradiation and when considering the solar performance of façades. In fact, some exceptions to this general tendency have been identified among the urban forms studied, which reveal the potential for achieving comparatively greater solar exposure in winter and lower in summer. For instance, with respect to façades performance, urban form C10 achieves higher mean direct irradiance in January and lower in July, compared to C7, C9, C2 and C29 (see Appendix). Indicatively, comparing C10 to C29, the former is more densely built up by 56%; its façades receive on average more direct radiation in January by 36% and less in July by 4%. Considering the findings presented in Section 3.1.3, it can be argued that the above is achievable because mean façades direct irradiance is affected by different urban layout descriptors in different seasons. In the particular case, it is C10's much higher standard deviation of building height (StH) that explains its better performance in January, while its better performance in July is associated to its higher complexity (Cex) and lower mean outdoor distance (MOD) values. An example of an urban form whose seasonal ground performance stands out is C22. Compared to N37, C22 has higher density by 160% and while in January the two urban forms present similar mean irradiance values, in July C22's ground receives on average 28% less direct radiation.

Overall, it is of great importance that a better seasonal performance is achieved by urban forms of medium-high density, i.e. C10 and C22, of density 16.9 and 15.8 m^3/m^2, respectively. It becomes apparent that an adequate amount of built volume (i.e. density) is necessary for securing overshadowing in summer and, simultaneously, its carefully planned configuration within the site may limit direct radiation losses in winter. Nonetheless, the above argument is valid if assuming that cold and warm periods have the same weighting in terms of duration and harshness. Otherwise, the optimum density values range may be adjusted to prioritise the major objective, either of maximising or minimising ground's and/or façades' solar exposure.

http://dx.doi.org/10.1016/j.solener.2016.09.005

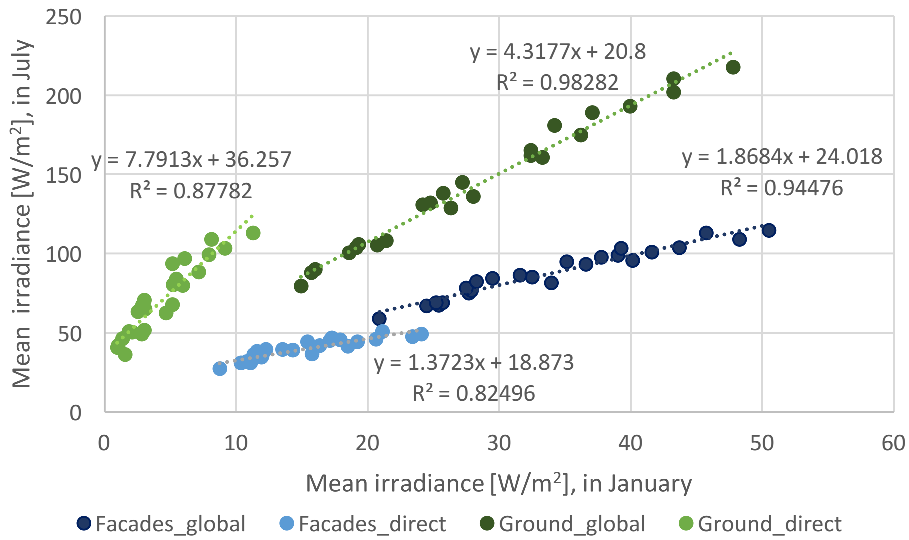


Fig. 10: Linear regression models of mean global (a) and direct (b) irradiance values in January (x axis) and July (y axis) for façades and ground.

4. Discussion

In previous parametric investigations on the particular topic, the importance of built density, usually expressed by plot ratio (total built floor area to site area), is equated methodologically to these of other urban geometry variables such as site coverage, building height, compactness, etc. (e.g. A.I. Martins et al. 2014; Nault et al., 2015). The present study distinguishes the density variable from those quantifying geometric characteristics of urban layout, and argues that this distinction is necessary when relationships between urban geometry and resulting solar performance are explored. The causal relationship between density and solar availability in the urban environment is straightforward: the more the built volume in a given site, the more the sun and sky obstruction, and thus the less solar radiation reaching ground and vertical surfaces. (Roofs may be unaffected under special circumstances, i.e. flat roofs and constant building height.) Nonetheless, as demonstrated by the research findings, the way in which this built volume is being configured in an area might amplify or conversely, offset density's effect.

Reflecting on the findings, there are several issues which have not been mentioned in previous sections and are worth being highlighted. Firstly, the relationship between *density* and solar availability was found to be slightly weaker for ground compared to façades, which is directly linked to the fact that the level of solar availability on ground is more dependent upon variations of urban layout (more urban layout descriptors affecting it, presenting higher coefficient of correlation). Secondly, mean irradiance values of ground and façades are generally affected by different urban layout descriptors; however, for those affecting them both, the nature of the effect is constant independently of the time period (positive or negative on both ground and façades irradiance values). Therefore, the particular descriptors act synergistically in maximising or minimising solar availability on ground and façades. Thirdly, following on findings of an earlier work (Chatzipoulka et al., 2015) the present study highlights

http://dx.doi.org/10.1016/j.solener.2016.09.005

that the relationship between urban geometry and solar availability varies depending on solar altitude angles. In this context, the location (i.e. latitude) of case studies used for exploring such relationships becomes significant and the comparison across different cities critical.

Based on SVF and irradiance findings for London's urban forms, it can be argued that *site coverage* is a key urban layout parameter for ground solar availability as it affects negatively both its diffuse and direct irradiation in all time periods. This is in partial agreement with a study for São Paulo, Brazil, in which variations of site coverage were found to affect both ground and façades solar performance (Cheng et al., 2006a; 2006b). A potential association of site coverage with façades solar performance may be explained by the fact that lower site coverage can lead to higher mean distance between buildings, especially in generic urban models when open space is usually evenly distributed across the site. Indeed, *mean outdoor distance* was found to significantly affect the direct solar radiation incident on building façades over the year time and in July, which seems to confirm the results of another study for London (Sarralde et al., 2015).

Furthermore, the analysis provided evidence for the positive relationship of vertical randomness and façades solar performance which has been studied before for cities in the tropics (Cheng et al., 2006b; Ng & Wong, 2004). Unlike vertical randomness, horizontal randomness was found to have a detrimental effect on solar availability. Increasing *directionality*, which is negatively associated to horizontal randomness, was found to be beneficial both for ground and façades solar availability; while increasing *standard deviation of building footprint area*, positively related to horizontal randomness, affected negatively ground's exposure to direct radiation in two out of three time periods studied. It is pointed out that this is a first attempt to quantify the particular attribute of urban layout in existing urban areas; and therefore, the variables used need to be further tested, as well as others to be considered.

Complexity was found to affect negatively both façades and ground solar availability, with its influence being more significant for the former. In contrast, in the study of A.I. Martins et al. (2014) for a Brazilian city the relationship between façades solar irradiation and surface area was positive which was linked to the effect of vertical surfaces inter-reflections. At this point, it is also worth saying that the nature of the effect of complexity may totally change depending on which criterion is used for assessment i.e. whether it is the solar availability on façades (irradiance or irradiation) or solar potential per unit floor area (irradiation divided by total floor area). Increasing façades surface area, while retaining total floor area constant, results in higher total irradiation of façades and, therefore, higher solar potential per unit floor area (e.g. Hii et al., 2011). Nonetheless, the consideration of potential usefulness of solar availability for buildings and in outdoor spaces is beyond the scope of this study.

Unlike *complexity*, *compactness* does not present any significant correlation except with mean ground direct irradiance in January. In general, there is no sufficient evidence in the literature that the particular variable affects urban solar availability. On the other hand, as it is a measure that associates building surface area (i.e. building solar radiation receptor) to building volume (i.e. internal living space), compactness turns into a key geometric factor when solar availability is examined in relation to building energy needs (e.g. Nault et al., 2015; Ratti et al., 2005). Finally, distributing built density into more volumes was found to affect positively ground and façades insolation in January. The number of built volumes variable is first introduced by the present study and thus, its relevance to solar availability needs to be further tested.

5. Limitations and further research

This study employs image processing techniques for analysing the geometry of urban forms based on their DEMs. The particular technique presents some advantages as well as limitations compared to the other method used for this purpose, which is based on vectorial models. The main difference of the two methods is that, in the latter, buildings volumes are recognized as objects, i.e. shapes of particular attributes such as perimeter, area, etc.; while, in the former, urban 3D information is stored in 2D matrices of elevation values, i.e. images in which each pixel represents building height. Therefore, some simple calculations which in vectorial models are straightforward, using DEMs they may be complicated, and less accurate, e.g. this of building perimeter (Ratti & Richens, 2004). On the other hand, processing DEMs offers a considerable freedom and flexibility in computing more sophisticated variables, such as *directionality* and *mean outdoor distance* used in this study.

The relationships between urban layout descriptors and indicators of solar availability have been investigated by performing partial Pearson Correlation tests, controlling the density variable. The particular test was identified as a simple and effective way to cope with the strong interrelation of urban layout descriptors with density, as revealed in Section 2.1. The findings provide a considerable insight into the role of urban layout in modifying the solar environment in urban forms, and practical guidance for urban designers and planners practicing in London, or locations of similar latitude. However, it is acknowledged that more research is required in order for the interdependence of the effects of urban geometry variables to be examined in depth. For instance, in the parametric study of Li et al. (2015) the effect of site coverage was found to decrease in increased site densities. The investigation of such speculations in real urban forms would require a greater sample and/or different methodological approach.

In most European cities, and especially in historic ones such as London, it is rare that entire urban areas are built by the repetition of a built unit, i.e. block, over a strict grid pattern with fixed orientation. In contrast, they tend to be more or less heterogeneous. Studying solar availability in real urban forms allows the investigation of aspects of urban solar availability associated to the complexity of actual built environments; however, it may entail some methodological restrictions. For instance, the fact that within London's urban forms building height is not constant does not allow the impact of increasing site coverage and increasing building height -i.e. the two ways of increasing density- to be investigated comparatively. As explained in Section 3.1.1, by averaging buildings' heights in an urban form, a crucial part of the height information is suppressed and, thus, the results for the mean building height (MeH) variable was found to be governed by those of site coverage (SCo).

Another issue, which is not regarded a restriction but related to the heterogeneity of urban forms' layout as well as the scale of the study, is that the impact of the orientation of the urban forms on their overall solar availability was found to be limited. The particular topic has been studied extensively for more than half a century now, starting from the pioneering work of Knowles (1974; 1981) who studied the effect of orientation on building and urban forms' solar performance. On the urban scale, the significance of the orientation parameter for ground and façades solar availability has been ascertained by numerous researchers, either focusing on urban street canyons (e.g. Ali-Toudert & Mayer, 2006; van Esch et al., 2012), or strictly orthogonal layouts (e.g. Kristl & Krainer, 2001; Li et al., 2015). The findings of this study do not conflict with the above since they are based on totally different case studies. They

http://dx.doi.org/10.1016/j.solener.2016.09.005

indicate though that examining entire urban areas of non-orthogonal street layouts, such as the studied urban forms, the effect of orientation on the total irradiation of ground and façades may be reduced due to counterbalanced gains and losses in direct radiation occurred when varying their orientation. However, it is important to highlight that the particular findings are derived from annual solar simulations, for the specific sample of urban forms, and cannot be generalised but require further research.

Finally, apart from the latitude to which the findings of this research are highly sensitive, London's weather file should also be considered when referring to them. As implied by mean diffuse and direct horizontal irradiance for an unobstructed point in Figure 4, the diffuse solar component constitutes a great part of the global irradiance experienced in London, all over the year and especially in the winter period. Reflecting on the current results, it is anticipated that a sunnier weather file would not change the nature of the relationships identified but possibly the strength of them. Nonetheless, this remains a speculation which requires to be tested by studying locations of similar latitude to this of London but higher frequency of clear sky weather conditions.

6. Conclusions

This paper presents an investigation on the causal relationships between urban geometry and solar availability on building façades and at the ground level, considering three time periods: the entire year, January and July. Urban geometry is expressed by ten variables, i.e. *density* and nine urban layout descriptors; while mean SVF and irradiance values have been selected as indicators of solar availability on vertical surfaces and in open spaces. All urban geometry variables and indicators of solar availability were computed for 24 urban forms of London, of different built density, and their relationships were statistically examined performing Pearson Correlation and Linear Regression tests. The most important findings are summarized below:

- The strong negative effect of density on the solar irradiation of ground and façades can be modified to an important degree by urban layout, namely the way in which the given built density is distributed, horizontally and vertically, within an area. For instance, comparing a pair of urban forms of similar density but fairly different layout, ground and façades of the one was found to be receiving more global irradiation by 32% and 11%, respectively.
- Mean ground SVF and diffuse irradiance are significantly affected by *mean outdoor distance*, *site coverage*, *directionality*, and *complexity*; whilst for façades the strongest urban layout variables were *complexity*, *standard deviation of building height* and *directionality* (given in effect's decreasing order). Most of the above variables are also influential for mean direct irradiance values over the year period.
- However, urban layout descriptors affecting mean direct irradiance the most are found to be different in time periods considered, especially in January and July. This differentiation is attributed to the occurrence of different ranges of solar altitude angle which are, in general, lower in January and higher in July.
- Considering a temperate climate, such as of London, the fact that the level of solar availability on urban surfaces is influenced by different urban layout descriptors in winter and summer presents the possibility of enhancing urban forms' seasonal solar performance.

http://dx.doi.org/10.1016/j.solener.2016.09.005

- Finally, the seasonal effect on solar availability appears to be much more pronounced for ground rather than for building façades, with open spaces suffering from excessive overshadowing in the winter and prolonged solar exposure in the summer.

The environmental, and thus solar design of our cities should apply to multiple principles formulated at a global, national and local level. In London Plan Chapter 5, *London's response to climate change*, these principles are hierarchised as follows: 1. Be lean: use less energy; 2. Be clean: supply energy efficiently; 3. Be green: use renewable energy. Whereas, in Chapter 7, it is highlighted that "[…] *public and private open spaces, and the building that frame those spaces, should contribute to the highest standards of comfort* […]". Table 4 associates the findings of the study to different solar design goals for ground and façades by demonstrating which solar indicator and which sky model is relevant to each goal, when designing a masterplan in temperate climates.

Table 4. Solar indicators and sky models relevant to different design goals applied to façades and ground.

Optimisation goals	Year sky model	January sky model (i.e. winter)	July sky model (i.e. summer)
Thermal comfort in open spaces		Mean ground global irradiance	Mean ground global irradiance
Passive solar gains through buildings' façades		Mean façades global irradiance	
Buildings' overheating limitation			Mean façades global irradiance
Active solar energy collection on buildings' façades	Mean façades global irradiance		

Red colour for indicators to be maximised

Blue Colour for indicators to be minimised

The present study adopts a particular perspective focusing on the thermal implications of solar radiation, i.e. thermal gains on building façades and heat in open spaces, the desirability of which differs from winter to summer. In this context, interpreting the research findings in design and planning guidelines for London would first suggest to opt for developments of medium density as they present a greater potential for promoting mutually the different seasonal objectives. Since in such developments shading in summer would be partially ensured by overshadowing occurred due to building volumes, designers should prioritise to enhance solar availability in winter. This could be achieved by breaking the given built volume into smaller blocks, which is beneficial both for façades and ground. The winter solar performance of façades could be also enhanced by differentiating considerably the height of the buildings; while this of ground by increasing buildings' compactness. Site coverage and directionality of the development should be considered carefully, as they affect ground's solar availability both in winter and summer. Regarding summer solar protection, increasing the undulations of built forms and decreasing the distance between buildings could be an option; however, these may affect significantly the overall (annual) insolation of the development and thus, an optimum value should be sought. Finally, emphasis should be put on the solar design of open spaces as their insolation in winter and solar protection in summer are more difficult to be achieved. On the other hand, in the case that the recommendations aim at increasing façades' solar potential for generating electricity or heating water, then these should focus on the urban layout descriptors found to be influential for mean façades irradiance values over the entire year.

Overall, the contribution of the study on the solar performance of urban forms is deemed two-fold. Beyond the specific results concerning the city of London, the study reveals a series of wider issues governing the relationship of solar availability with urban geometry, and solar altitude angles. In fact, it demonstrates that a more sophisticate understanding of how these three factors are interrelated to each other may open up significant opportunities towards a more effective, and sensitive solar design of our cities.

Acknowledgements

This study has been funded by a Research Scholarship from the Kent School of Architecture and a travel grant from the Kent Institute of Advanced Studies in the Humanities (KIASH).

References

A.l. Martins, T., Adolphe, L., E.g. Bastos, L., 2014. From solar constraints to urban design opportunities: Optimization of built form typologies in a Brazilian tropical city. Energy Build. 76, 43–56.

Ali-Toudert, F., Mayer, H., 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. Build. Environ. 41, 94–108.

Arboit, M., Diblasi, A., Fernández Llano, J.C., de Rosa, C., 2008. Assessing the solar potential of low-density urban environments in Andean cities with desert climates: The case of the city of Mendoza, in Argentina. Renew. Energy 33, 1733–1748.

Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S., Çöltekin, A., 2015. Applications of 3D City Models: State of the Art Review. ISPRS Int. J. Geo-Information 4, 2842–2889.

Brito, M.C., Gomes, N., Santos, T., Tenedório, J.A., 2012. Photovoltaic potential in a Lisbon suburb using LiDAR data. Sol. Energy 86, 283-288.

Centre for Environmental Data Archive. Online database: http://www.ceda.ac.uk/ [Accessed 25 March 2016]

Chatzipoulka, C., Nikolopoulou, M., Watkins, R., 2015. The impact of urban geometry on the radiant environment in outdoor spaces, ICUC9: 9th Int. Conf. Urban Clim. Toulouse, France. Available at: https://kar.kent.ac.uk/52695/

Cheng, V., Steemers, K., Montavon, M., Compagnon, R., 2006a. Compact cities in a sustainable manner. 2nd Int. Sol. Cities Congr. Oxford, UK.

Cheng, V., Steemers, K., Montavon, M., Compagnon, R., 2006b. Urban Form, Density and Solar Potential. PLEA2006 - 23rd Conf. Passiv. Low Energy Archit. Geneva, Switz.

Compagnon, R., 2000. PRECis: Assessing the Potential for Renewable Energy in Cities. Annexe 3: Solar and Daylight availability in urban areas. Cambridge.

Compagnon, R., 2004. Solar and daylight availability in the urban fabric. Energy Build. 36, 321–328.

Emmanuel, R., Rosenlund, H., Johansson, E., 2007. Urban shading - A design option for the tropics? A study in Colombo, Sri Lanka. Int. J. Clim. 27, 1995–2004.

Hii, D.J.C., Heng, C.K., Malone-Lee, L.C., Zhang, J., Ibrahim, N., Huang, Y.C., Janssen, P., 2011. Solar radiation performance evaluation for high density urban forms in the tropical context. BS2011: 12th Conf. of Int. Build. Perform. Simulat. Assoc. Sydney, Australia.

IEA SHC Task 51 Solar Energy in Urban Planning (2013-2017). International Energy Agency: Solar Heating Cooling programme (http://task51.iea-shc.org/).

Jabareen, Y.R., 2006. Sustainable Urban Forms: Their Typologies, Models, and Concepts. J. Plan. Educ. Res. 26, 38–52.

Jakubiec, J.A., Reinhart, C.F., 2011. DIVA 2.0: Integrating daylight and thermal simulations using Rhinoceros 3D, Daysim and EnergyPlus, BS2011: 12th Conf. of Int. Build. Perform. Simulat. Assoc. Sydney, Australia.

Knowles, R.L., 1974. Energy and Form. The MIT Press, Cambridge, Massachussetts.

Knowles, R.L., 1981. Sun Rhythm Form. The MIT Press, Cambridge, Massachussetts.

Kristl, Ž., Krainer, A., 2001. Energy evaluation of urban structure and dimensioning of building site using iso-shadow method. Sol. energy 70, 23–34.

Lee, K.S., Lee, J.W., Lee, J.S., 2016. Feasibility study on the relation between housing density and solar accessibility and potential uses. Renew. Energy 85, 749–758.

Li, D., Liu, G., Liao, S., 2015. Solar potential in urban residential buildings. Sol. Energy 111, 225–235.

Littlefair, P.J., Santamouris, M., Alvarez, S., Dupagne, A., Hall, D., Teller, J., Coronel, J.F., Papanikolaou, N., 2000. Environmental site layout planning: solar access, microclimate in urban areas, BRE308. BRE, Garston.

Littlefair, P., 2001. Daylight, sunlight and solar gain in the urban environment. Sol. Energy 70, 177–185.

Littlefair, P. 2011. Site layout planning for daylight and sunlight: A Guide to good practice, BRE209. 2nd ed. BRE, Garston.

London Plan. Online source, available at: https://www.london.gov.uk/what-we-do/planning/london-plan/current-london-plan

Lu, M., Du, J., 2012. Assessing the daylight and sunlight availability in high-density residential areas: a case in North-east China. Archit. Sci. Rev. 56, 168–182.

Mardaljevic, J., 2010. Multi-Scale Climate-Based Daylight Modelling, SEUS - Solar Energy at Urban Scale, Compiègne, France. Available at: https://www.utc.fr/fileadmin/user_upload/SITE-UTC/documents/Presse/Evenements/abstract_seus.pdf

Matzarakis, A., Mayer, H., Iziomon, M.G., 1999. Applications of a universal thermal index: physiological equivalent temperature. Int. J. Biometeorol. 43, 76–84.

Mohajeri, N., Upadhyay, G., Gudmundsson, A., Assouline, D., Kämpf, J., Scartezzini, J.-L., 2016. Effects of urban compactness on solar energy potential. Renew. Energy 93, 469–482.

Montavon, M., Compagnon, R., Scartezzini, J.-L., 2004. Comparison of the solar energy utilisation potential of different urban environments. PLEA2004 – 21st Int. Conf. Passiv. Low Energy Archit. Eindhoven, The Netherlands.

Nault, E., Peronato, G., Rey, E., Andersen, M., 2015. Review and critical analysis of early-design phase evaluation metrics for the solar potential of neighborhood designs. Build. Environ. 92, 679–691.

Ng, E., Wong, N.H., 2004. Better daylight and natural ventilation by design. PLEA2004 - 21st Int. Conf. Passiv. Low Energy Archit. Eindhoven, The Netherlands.

Nikolopoulou, M., Baker, N., Steemers, K., 2001. Thermal comfort in outdoor urban spaces: Understanding the Human parameter. Sol. Energy 70, 227–235.

Nikolopoulou, M. & Lykoudis, S., 2007. Use of outdoor spaces and microclimate in a Mediterranean urban area, Build. Environ. 42, 3691–3707.

Population Reference Bureau, World Population Data Sheet, 2015. Available at: http://www.prb.org/Publications/Datasheets/2015/2015-world-population-data-sheet.aspx

Project PREcis: Assessing the Potential for Renewable Energy in Cities. Final report, Project no. JOR3-CT97-0192, 2000.

Project ZED: Towards Zero Emission Urban Development. Final report, Project no. APAS-RENA CT94-00016, 1997.

Ratti, C., 2001. Urban analysis for environmental prediction. PhD Thesis, University of Cambridge, UK.

Ratti, C., Richens, P., 2004. Raster analysis of urban form. Environ. Plan. B Plan. Des. 31, 297–309.

Ratti, C., Baker, N., Steemers, K., 2005. Energy consumption and urban texture. Energy Build. 37, 762–776.

Ratti, C., Di Sabatino, S., Britter, R., 2006. Urban texture analysis with image processing techniques: Winds and dispersion. Theor. Appl. Climatol. 84, 77–90.

Redweik, P., Catita, C., Brito, M., 2013. Solar energy potential on roofs and façades in an urban landscape. Sol. Energy 97, 332–341.

Remund, J. Müller, S. Kunz, S. Huguenin-Landl, B. Studer, C. Klauser, D. Schilter, C., Lehnherr, R., 2015. METEONORM – Global Meteorological Database, Handbook Part I & II, Version 7. Meteotest & Swiss Federal Office for Energy, Bern. Available at: http://www.meteonorm.com/en/downloads/documents [Accessed 25 March 2016]

Robinson, D., 2005. A simplified radiosity algorithm for general urban radiation exchange. Build. Serv. Eng. Res. Technol. 26, 271–284.

Robinson, D., 2006. Urban morphology and indicators of radiation availability. Sol. Energy 80, 1643–1648.

Sanaieian, H., Tenpierik, M., Linden, K. Van Den, Mehdizadeh Seraj, F., Mofidi Shemrani, S.M., 2014. Review of the impact of urban block form on thermal performance, solar access and ventilation. Renew. Sustain. Energy Rev. 38, 551–560.

Sarralde, J.J., Quinn, D.J., Wiesmann, D., Steemers, K., 2015. Solar energy and urban morphology: Scenarios for increasing the renewable energy potential of neighbourhoods in London. Renew. Energy 73, 10–17.

Steemers, K., 2003. Energy and the city: Density, buildings and transport. Energy Build. 35, 3–14.

Strømann-Andersen, J., Sattrup, P.A., 2011. The urban canyon and building energy use: Urban density versus daylight and passive solar gains. Energy Build. 43, 2011–2020.

Van Esch, M.M.E., Looman, R.H.J., De Bruin-Hordijk, G.J., 2012. The effects of urban and building design parameters on solar access to the urban canyon and the potential for direct passive solar heating strategies. Energy Build. 47, 189–200.

Wall, M., Probst, M.C.M., Roecker, C., Dubois, M.-C., Horvat, M., Jørgensen, O.B., Kappel, K., 2012. Achieving solar energy in architecture – IEA SHC Task 41. Energy Procedia 30, 1250–1260.

Ward Larson, G., Shakespeare, R., 1998. Rendering with Radiance: The Art and Science of Lighting Visualisation, Morgan Haufmann, San Francisco.

Zhang, J., Heng, C.K., Malone-Lee, L.C., Hii, D.J.C., Janssen, P., Leung, K.S., Tan, B.K., 2012. Evaluating environmental implications of density: A comparative case study on the relationship between density, urban block typology and sky exposure. Autom. Constr. 22, 90–101.

Appendix. Urban geometry variables and mean SVF, global and direct irradiance values for twenty-four urban forms.

	Urban Geometry										Façades							Ground						
	Density $[m^3/m^2]$	SCo [%]	MeH [m]	StH [m]	StF $[m^2]$	Dir $(*10^{-2})$	Cex $[m^2/m^2]$	Com $[m^2/m^3]$	NOB	MOD [m]	SVF	Global Irradiance (W/m^2)			Direct Irradiance (W/m^2)			SVF	Global Irradiance (W/m^2)			Direct Irradiance (W/m^2)		
												Year	Jan.	Jul.	Year	Jan.	Jul.		Year	Jan.	Jul.	Year	Jan.	Jul.
C27	22.0	59.7	36.9	12.0	196.7	2.041	2.245	0.126	57	5.0	0.173	47.2	20.9	58.8	19.9	8.8	27.3	0.264	54.1	14.9	79.3	18.6	1.6	36.4
C35	19.6	53.3	36.8	13.0	144.9	5.246	2.032	0.128	66	6.6	0.196	55.0	25.4	67.3	23.3	11.1	31.0	0.333	70.7	19.2	103.7	26.3	2.1	50.3
C19	19.3	61.3	31.5	11.1	183.0	3.581	1.818	0.123	68	4.5	0.199	54.0	24.5	67.1	22.4	10.4	30.9	0.291	60.4	15.7	87.9	21.2	1.0	40.6
C31	18.5	54.6	33.9	12.7	130.5	4.331	1.841	0.126	62	6.7	0.205	56.1	25.7	69.0	23.5	11.1	31.5	0.342	71.9	19.3	105.6	26.3	1.9	50.9
C12	18.4	64.2	28.6	10.3	173.9	4.658	1.888	0.135	53	5.1	0.205	55.5	25.2	68.9	23.2	10.8	31.8	0.300	61.6	16.0	89.9	21.7	1.0	41.8
C10	16.9	59.9	28.1	26.3	143.9	4.216	1.731	0.135	57	4.6	0.248	67.7	34.0	81.7	28.3	15.8	36.8	0.334	70.2	18.6	100.4	25.1	1.4	46.3
C7	16.4	56.4	29.1	10.2	164.8	5.143	1.562	0.127	45	8.5	0.253	69.9	32.5	85.3	29.5	14.3	38.9	0.432	90.9	24.8	132.2	34.5	3.1	64.9
C22	15.8	49.8	31.7	9.6	135.0	6.261	1.600	0.130	48	9.4	0.224	60.7	27.7	75.0	25.6	11.9	34.5	0.445	96.0	28.1	135.8	38.1	5.2	67.6
C16	15.7	58.3	27.0	7.2	123.1	3.236	1.630	0.137	75	5.7	0.227	61.9	27.9	76.7	26.1	12.0	35.5	0.357	75.8	21.4	108.2	28.2	3.0	51.6
C9	13.9	46.9	29.6	16.1	133.7	5.925	1.509	0.139	48	9.0	0.254	69.7	31.6	86.4	29.1	13.5	39.6	0.451	95.9	25.8	138.0	36.6	2.9	67.4
C6	13.8	56.3	24.5	7.6	226.5	6.329	1.593	0.152	55	5.0	0.232	62.8	27.5	78.3	26.4	11.3	36.3	0.352	72.9	20.8	105.1	26.2	2.9	49.0
C2	11.3	54.3	20.8	4.9	132.6	5.794	1.423	0.169	59	6.2	0.246	67.7	29.5	84.3	28.7	12.3	39.3	0.424	89.9	26.3	128.8	34.2	4.7	62.5
W20	11.1	43.8	25.3	10.6	100.6	8.952	1.192	0.147	59	9.7	0.284	77.9	36.6	93.4	32.8	16.3	41.8	0.526	114.7	32.4	165.2	46.0	5.5	84.0
C29	10.8	46.5	23.2	5.5	108.7	2.750	1.436	0.170	71	6.1	0.243	65.6	28.3	82.3	27.6	11.6	38.2	0.429	90.2	24.2	130.7	33.9	2.6	63.4
W39	10.4	48.6	21.4	5.3	120.9	5.110	1.121	0.154	60	6.8	0.279	76.9	35.1	95.0	32.7	15.4	44.5	0.472	101.3	27.2	144.8	39.0	3.0	70.7
W27	7.5	38.6	19.4	6.8	50.4	5.042	1.208	0.213	101	6.9	0.286	80.1	37.8	97.8	34.2	17.1	45.3	0.525	114.3	32.4	161.9	45.5	5.2	80.4
W33	6.5	34.5	18.9	7.1	57.1	5.272	1.243	0.243	105	6.9	0.290	81.2	39.0	98.7	34.7	17.9	45.5	0.521	114.1	33.3	160.7	45.5	5.9	79.8
N37	6.1	36.8	16.6	6.9	34.4	5.580	1.120	0.233	132	5.8	0.297	81.5	40.1	95.7	34.0	18.5	41.4	0.564	124.4	34.2	180.9	50.5	5.2	93.4
W14	5.5	33.0	16.8	5.7	30.5	7.999	1.038	0.247	131	7.0	0.313	87.5	43.7	103.6	37.1	20.6	45.9	0.599	132.5	37.1	188.8	54.3	6.1	96.8
N20	5.4	32.7	16.6	5.0	54.6	8.240	1.135	0.257	121	6.4	0.306	85.3	39.3	103.3	36.2	17.3	46.9	0.558	122.8	36.2	174.8	49.4	7.1	88.2
N55	4.4	33.0	13.5	4.5	28.3	5.860	1.028	0.289	175	6.0	0.304	84.8	41.6	100.7	35.6	19.2	44.5	0.618	136.2	40.0	192.8	56.5	8.0	99.3
N1	3.9	27.1	14.2	3.9	39.5	6.580	0.830	0.271	159	7.6	0.334	92.8	48.3	109.1	38.8	23.4	47.6	0.677	150.3	43.3	210.5	63.4	8.2	109.0
N24	3.2	20.3	15.9	4.2	15.7	8.290	0.950	0.338	162	7.9	0.337	93.6	45.8	113.0	39.4	21.1	50.9	0.658	144.9	43.3	201.8	60.5	9.1	103.2
N44	3.2	23.9	13.3	7.5	22.0	8.890	0.790	0.305	167	7.5	0.353	98.6	50.5	114.7	41.2	24.1	49.4	0.699	155.8	47.8	217.4	66.2	11.3	113.1

http://dx.doi.org/10.1016/j.solener.2016.09.005