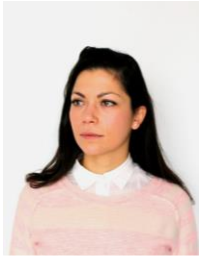

The impact of urban geometry on the radiant environment in outdoor spaces

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1. Introduction

Urban geometry, namely the quantitative relationship of building volumes and open spaces (i.e. built density) and their spatial configuration (i.e. urban layout), is a major modifier of urban microclimate. As urban geometry may significantly vary between different cities, as well as within a city, connecting geometrical properties to resulting environmental quality would provide a better understanding of existing urban forms and facilitate design and planning decisions on future developments. Recent advances in LIDAR technology and increasing availability of modern GIS-based 3D models of cities allow the measurement and description of geometry across entire urban areas and its association with environmental indicators (Gal et al., 2006). This study explores the impact of urban geometry across London on the radiant environment in outdoor spaces, at the urban district scale. In particular, the paper will focus on the relationships between urban geometry, expressed by urban geometric variables, and average values of Sky View Factor, Ground View Factor (mean shadow fractions on the ground) and Mean Radiant Temperature at the pedestrian level.

The urban radiant environment close to the ground is highly related to the thermal conditions experienced by pedestrians and users of open spaces, such as streets and squares. The sum of all radiation fluxes to which the human body is exposed governs thermal comfort, expressed by mean radiant temperature (T_{mrt}). Irradiation availability in outdoor spaces depends on their openness to the sky vault (diffuse solar and sky component) which results from the geometry of the urban fabric, and their exposure to the sun (direct solar component) which is decided by the urban geometry as well as the orientation of it in relation to the sun path. Sky view factor (SVF) and ground view factor (GVF) are measures of the openness to the sky and the sun, respectively. For a given point, SVF value is constant and ranges from 0 to 1, with zero denoting a completely obstructed point. Unlike SVF GVF value varies in time as it depends also on the sun's position. For a given point and time of the day, its value can be either 0 (in shade) or 1 (sunlit). Computing GVF values for each point in the outdoor space results in a common shadow pattern and thus, the mean GVF value expresses the percentage of the outdoor space which is seen by the sun.

How densely built is an urban area affects directly the radiant environment as increasing density means more obstructed outdoor spaces. There have been numerous studies of the relationship between density and urban microclimate or outdoor thermal comfort. However, the vast majority of them investigate it at the urban micro-scale focusing on the geometry of urban canyons (e.g. Ali-Toudert and Mayer, 2006; Bourbia and Boucheriba, 2010; Johansson, 2006). Beyond density, urban layout can influence significantly radiant conditions in the urban fabric. For instance, site coverage has been found to be a crucial urban parameter as its increase affects negatively solar potential and mean SVF values both on ground and building façades; while the randomness of urban layout was found to enhance them (Cheng et al., 2006). Up to now, most studies on the impact of urban layout are parametric using generic urban models and/or their emphasis is primarily put on solar and illuminance performance of buildings' fabrics.

The availability of a GIS-based 3D model of London allowed this study to examine the impact of density and urban layout on the radiant conditions of outdoor spaces studying real urban forms. Moreover, the number of the urban forms examined made feasible the statistical exploration of the characteristics of these relationships. The above in combination with the spatial scale at which the topic is being investigated are unique features of the methodology of the present study and relatively new in the literature. The work of Lindberg and Grimmond (2011) can be considered an important precedent as they employ a similar methodology to investigate the influence of building morphology and nature of vegetation on shadow patterns and mean radiant temperature in London. Nonetheless, the morphological analysis conducted is limited considering only two urban parameters, these of mean building height and site coverage.

2. Methodology

Three representative areas of London were selected to be studied; in central, west and north London which are of high, medium and low built density, and of 2 x 6km, 1.5 x 6.5km and 2.5 x 6km surface area, respectively (Fig. 1). Each of these areas was first divided into cells -*squares*- of 500 x 500m size. From these, squares were selected for analysis based on two major criteria successively applied: continuity of urban fabric and representativeness of different typologies. In total the final sample includes 72 squares: 28 squares of central London, 25 of west London and 19 of north London, which cover density values between approximately 9-33, 4-14 and 3-6 m^3/m^2, respectively.

The methodology comprises three distinct stages: (i) the morphological analysis of the squares using image processing techniques in Matlab software (Ratti and Richens, 2004), ii) radiation simulations with the use of SOLWEIG software, and (iii) the statistical analysis of the results of the two previous stages investigating potential correlations. Both in the morphological analysis and SOLWEIG simulations, urban geometry is represented in DEM format (Digital Elevation Model) which is a compact way of storing urban 3D information using a 2D matrix of building height values. The DEM of the studied area in central London is shown in Figure 1.

Figure 1: Right, 3 studied areas on the map of London. Left, the DEM of central London's area divided into squares of 500 x 500m.

2.1 Morphological analysis

The morphological analysis consists of the computation of a set of urban geometric variables for which special algorithms were written and executed in Matlab. The present study makes a distinction between density and urban layout. *Density* refers to the magnitude of built volume in a given site while urban layout to the way in which this built volume is distributed spatially, horizontally and vertically. It is measured as total built volume on a given site over site area [m^3/m^2]. Urban layout is described through measurements of geometrical characteristics of an urban form, i.e. urban form descriptors. Here, eight such descriptors have been included in the analysis and are as follows:

- *Site coverage* (Coverage) – buildings' footprint area over site's area, [m^2/m^2]
- *Standard deviation of building height* (sHeight) – weighted by footprint area, [m];
- *Frontal area density* (FAD) – buildings' façades area over site's area, [m^2/m^2];
- *Number of built volumes* (NoB) – attached buildings considered as one volume;
- *Mean distance between built volumes* (mDistance) – on the ground level, [m];
- *Standard deviation of distance between built volumes* (sDistance), [m];
- *Standard deviation of built volumes' footprint area* (sFootprint), [m^2];
- *Standard deviation of built volumes' volume* (sVolume), [m^3].

In order to determine the correlation of the above variables, the Pearson correlation test was performed and the results are demonstrated in Table 1. As seen, density presents a strong correlation with most of the urban form descriptors, except for mDistance and sDistance.

Table 1: Pearson Correlation results for density and urban form descriptors considered in the analysis.

Correlations

		Density	Coverage	sHeight	FAD	NoB	mDistance	sDistance	sFootprint	sVolume
Density	Pearson Correl.	1								
	Sig. (2-tailed)									
Coverage	Pearson Correl.	.901**	1							
	Sig. (2-tailed)	.000								
sHeight	Pearson Correl.	.805**	.582**	1						
	Sig. (2-tailed)	.000	.000							
FAD	Pearson Correl.	.944**	.830**	.794**	1					
	Sig. (2-tailed)	.000	.000	.000						
NoB	Pearson Correl.	-.757**	-.829**	-.531**	-.691**	1				
	Sig. (2-tailed)	.000	.000	.000	.000					
mDistance	Pearson Correl.	-.306**	-.389**	-.208	-.364**	-.019	1			
	Sig. (2-tailed)	.009	.001	.079	.002	.876				
sDistance	Pearson Correl.	-.070	-.063	-.135	-.144	-.283*	.905**	1		
	Sig. (2-tailed)	.559	.600	.257	.227	.016	.000			
sFootprint	Pearson Correl.	.790**	.839**	.504**	.639**	-.762**	-.155	.079	1	
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.193	.507		
sVolume	Pearson Correl.	.715**	.633**	.584**	.524**	-.569**	-.087	.038	.865**	1
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.466	.752	.000	

**. Correlation is significant at the 0.01 level (2-tailed).

2.2 Radiation and mean radiant temperature simulations

The solar and longwave environmental irradiance geometry (SOLWEIG) model simulates spatial variations of 3D radiation fluxes (incoming to / outgoing from the ground, direct and reflected) and mean radiant temperature (T_{mrt}) as well as shadow patterns in complex urban settings (Lindberg and Grimmond, 2008). All the above along with sky view factor values are computed at the pedestrian level, at 1.2m height above the ground, taking into account the 3-D urban geometry (in DEM format), a 24-hour weather file of a specific day (temperature, humidity, global, direct and diffuse solar radiation) and geographical information (latitude, longitude and elevation of London: 51.5^o, -0.17^o and 0m). Optional parameters like emissivity for walls and ground and albedo are set to default values.

Simulations were run for 8 days of a typical year in London (21 Jun, 26 Jul, 23 Apr, 20 Mar, 19 Oct, 23 Nov, 19 Jan and 29 Dec). Sunny and cloudy days have been considered, evenly distributed in the year in order for the effect of solar elevations to be examined. The weather file used is from Islington weather station in North London. Each square's original area was extended by 100m in all directions to include the surrounding buildings. The spatial resolution of DEMs was set to 0.5m.

The present paper focuses on three SOLWEIG outputs: (i) sky view factor (SVF), (ii) hourly shadow fractions or, as named in SOLWEIG, ground view factor (GVF) and (iii) hourly mean radiant temperature (T_{mrt}), and in particular their mean value in the outdoor spaces of squares' original area (i.e. 500 x 500m) (Fig.2). The extraction of the respective values and their averaging are both done in Matlab.

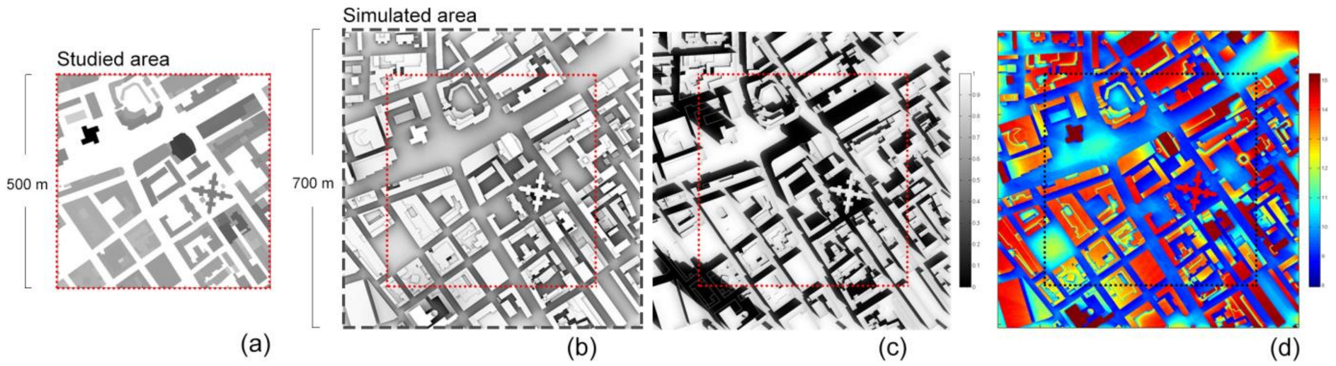

Figure 2: Square in central London (highlighted in Fig. 1): a) square's DEM, b) SVF values map, c) shadow pattern at 9am on 23 April (GVF) and d) T_{mrt} values map at 9am on 23 April (cloudy hour).

3. Results

The relationships between urban geometry, as expressed by density and eight urban form descriptors, and mean values of SVF, GVF and T_{mrt} have been investigated performing correlation and linear regression tests in SPSS statistics software. All the statistical results mentioned in the paper are statistically significant ($p < 0.05$).

3.1 Sky view factor results

First, the relationship between density values and mean SVF (mSVF) values was examined. The results reveal a strong negative correlation (r=-0.940).The curve estimation test showed that the best fit is achieved by a logarithmic curve (R^2=0.906), while the linear relationship was also very strong (R^2=0.884) described by the function: mSVF= 0.685 - 0.017 * Density. To investigate which descriptors affect mean SVF values the most, partial correlation analysis was performed, controlling the density variable. It was found that the strongest variables were Coverage (r= -0.698), mDistance (r= 0.526) and FAD (r= -0.468). Less strong but still statistically significant was the correlation of mSVF with sVolume (r= 0.372), sHeight (r= 0.358), sDistance (r= 0.317) and NoB (r=0.291). Only the sFootprint variable was found to be of non-significance. Therefore, among the urban form descriptors considered, Coverage and FAD were found to affect the mSVF value on the ground negatively, while all the rest variables - except for sFootprint – positively. Finally, in a stepwise linear regression test including all the 8 urban form descriptors, it was found that a linear model with the three strongest variables achieves almost a perfect correlation with R^2 equal to 0.984 (mSVF= 0.847 - 0.005*Coverage - 0.135*FAD + 0.006*mDistance) which is significantly higher than that achieved by the density variable alone (R^2=0.884).

In order to examine the effect of the spatial scale of the study on the results, the above tests have been conducted considering the initial squares divided into 4 squares of 250m x 250m size. The urban form descriptors as well as mSVF values in the outdoor spaces of 288 in total squares were first computed and next the statistical tests were repeated. The results showed a slight decrease in the strength of the correlation between density and mSVF from r= -0.940 to r= -0.892.The strongest variables remain the same three, i.e. mDistance (r=0.661), Coverage (r=-0.659) and FAD (r=-0.517).

3.2 Ground view factor results

SOLWEIG computes hourly shadow patterns on the ground, i.e. hourly GVF values for each point in the outdoor space of the squares, taking into account the urban geometry and the location, but not the weather file. Thus, the mean GVF (mGVF) value expresses the percentage of the outdoor space which would be seen by the sun at that time of the day, independently of whether it is sunny or not. Linear regression analysis was performed for each daytime hour of the 9 days considered in the study, to investigate the relationship between hourly mGVF values and urban geometry as well as mean SVF values. Figure 3 demonstrates the strength of the correlation, expressed by coefficient of determination (R^2), between hourly mGVF and mSVF. As can be seen, the strength of the correlation varies with the sun's altitude angle; the higher the altitude, the higher the correlation (i.e. days closer to summer solstice and hours closer to midday). Exactly the same pattern appears when the relationships of hourly mGVF with density and urban form descriptors were tested. Nonetheless, comparing their performance in predicting the solar availability on ground, SVF and urban form descriptors perform consistently better than density, with one of the former always presenting the highest correlation.

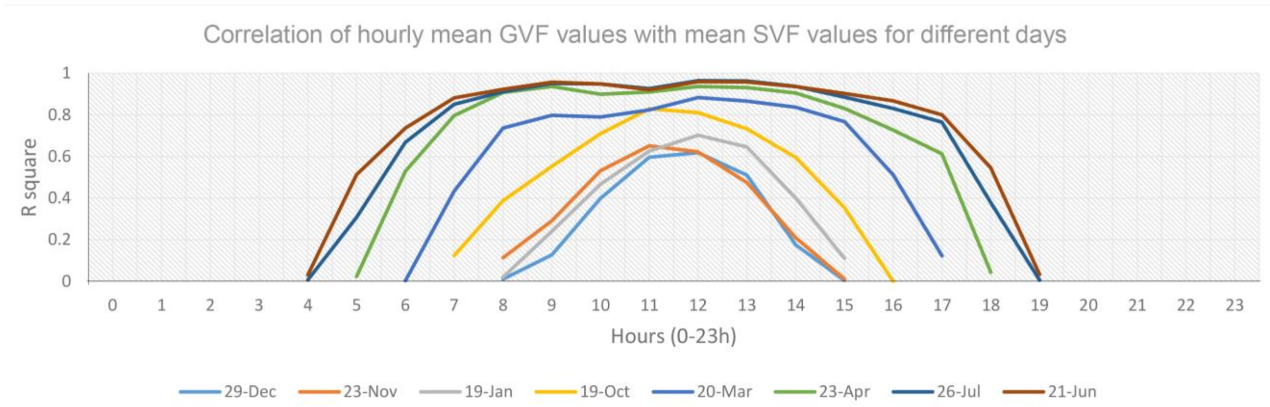

Figure 3: Correlation of hourly mean ground view factor (mean shadow fractions on ground) with mean sky view factor for the 8 days studied.

As previously, in order to investigate which descriptors affect hourly mGVF values the most, partial correlation analysis was performed for the daytime hours of 21st June (summer solstice), controlling the density variable. According to the results for that day, during the morning and late afternoon hours (i.e. approximately 7 am. to 9 am. and 3 pm. to 6 pm.) the strongest variable was found to be Coverage with a correlation coefficient (r) varying between -0.473 and -0.771. Between 10 am. and 2 pm. the variable which presents the highest correlation to mGVF is either mDistance or FAD. In general, Coverage, mDistance and FAD, which found to be the strongest variables for mSVF, appear to be the most important for hourly mGVF as well. Furthermore, the relationship of mGVF with sDistance, sVolume and sHeight, all referring to the homogeneity of the urban form, was found to be significant in the different hours of the 21st of June.

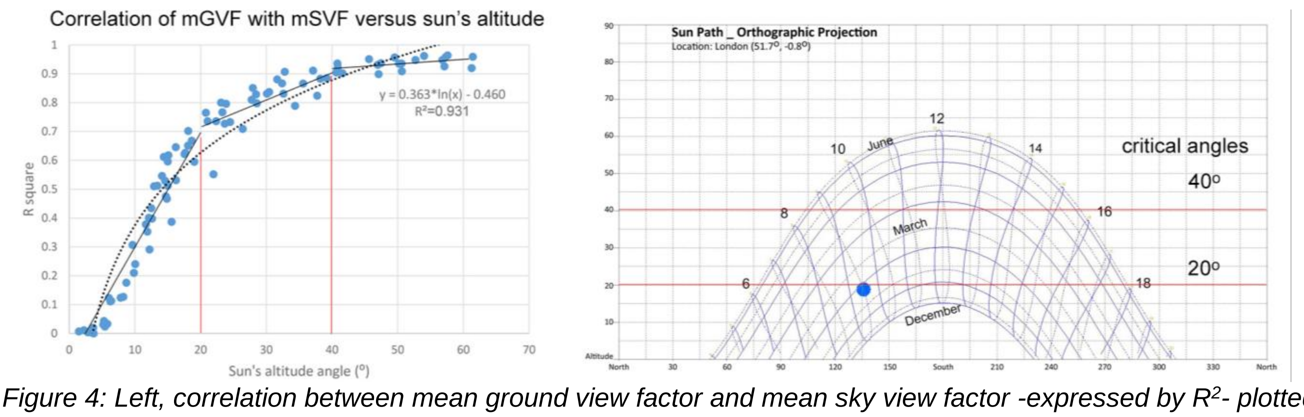

Figure 4: Left, correlation between mean ground view factor and mean sky view factor -expressed by R^2- plotted against sun's altitude. Right, the sun path for London's location in orthographic projection. The crucial sun's altitude angles of 20º and 40º are highlighted by red lines.

Plotting the R^2 values - from the linear regression analysis done for hourly mean ground view factor and mean sky view factor - against sun altitude angles, two critical angles can be identified by observation. At 20º, the impact of the altitude on the correlation between mGVF and mSVF begins to reduce significantly; for angles larger than 40º the value of R^2 tends to stabilise above 0.9 denoting an almost perfect linear relationship between mGVF and mSVF (Fig.4). Overall, the relationship is well described by a logarithmic model (R^2=0.931), according to which the rate of change of R^2 at 20º is already of order 10^{-2}.

3.3 Mean radiant temperature results

The mean radiant temperature results show that at night-time and in fully overcast conditions, the outdoor spaces of central London's urban squares are warmer than those of west and north London, due to greater longwave radiation emitted and reflected by building volumes. In contrast, on sunny days, average daytime T_{mrt} values have been found to be higher in North London's urban squares due to the larger insolation of their outdoor spaces. In the night-time, the difference between minimum and maximum mean T_{mrt} in the 72 squares is consistently about 5-6 ºC. In cloudy daytime hours, the difference was found to decrease with increasing sun altitude angle, with the smallest difference being at midday (i.e. 1.9 ºC at 12 am. on 19 January – cloudy day) (Fig. 5a). In contrast, in sunny daytime, the difference between the warmest and coolest squares varies with the sun's altitude as well as intensity of direct solar radiation. The biggest difference in hourly mean T_{mrt} value is18.3 ºC at 10 am. on 26th July (sunny day; global, direct normal and diffuse radiation: 621, 608 and 186 W/m^2) (Fig. 5b).

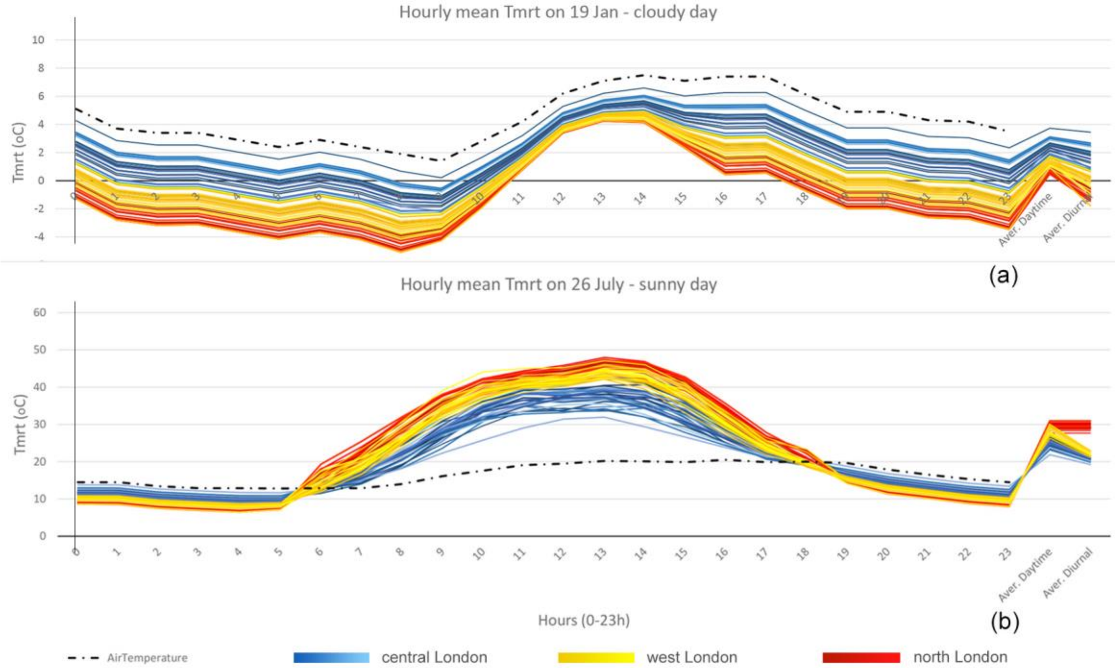

Figure 5: Hourly mean T_{mrt} values in outdoor space of 72 squares, (a) on a cloudy day and (b) on a sunny day

Additionally, the statistical analysis has shown that in the absence of direct solar radiation, the correlation between urban geometry and hourly mean T_{mrt} is very high, resulting from the almost perfect linear relationship of mean SVF values with density as well as urban form descriptors. In the presence of direct solar radiation, meaning when the T_{mrt} value is highly related to whether a point is sunlit or not, the strength of the correlation increases with increasing sun altitude angle, as found for hourly mean GVF values (Fig. 6).

4. Discussion and conclusions

Sky view factor is a widely used indicator in a variety of studies on urban climate and thus, the relevant findings could be useful beyond the scope of the present study. In particular, the statistical analysis has revealed a strong negative correlation between mean sky view factor values and density (r=-0.940). The repetition of the tests considering 288 squares of 250 x 250m size instead of the 72 initial squares of 500 x 500m size has shown that the sensitivity of the statistical results on the spatial scale is limited. Therefore, the general findings can be confidently used for spatial scales between 250m and 500m. In Lindberg and Grimmond (2011), a strong negative correlation was identified between site coverage and mean ground SVF value (R^2=0.830). (Conducting the same test in this study, R^2 was found to be rather higher at 0.903.) However, here, because site coverage as well as most of the urban form descriptors were found to be highly correlated with density, the correlation of the urban form descriptors with mean SVF value has been tested controlling the density variable. Indeed, site coverage was found to be the strongest variable (r=-0.698) followed by mean distance between building volumes (r= 0.526) and frontal area density (r=-0.468). Translating this into urban planning guidelines would suggest that for a given density target, reducing site coverage and increasing mean building height can result in a higher mean SVF value at the ground level.

Lindberg and Grimmond (2011) have studied the relationship between daytime mean shadow fractions on the ground from buildings (i.e. daytime mean ground view factor) and, site coverage and mean sky view factor, analysing the shadow patterns on a sunny autumn and a sunny summer day. They found an almost perfect fit between daytime mean shadow fractions and SVF (summer: R^2=0.99, autumn: R^2=0.99). Also, the correlation between daytime mean shadow fractions and site coverage was found to be high (summer: R^2=0.85, autumn: R^2=0.87). In this study, the relationship between hourly mean shadow fractions and urban geometry have been extensively investigated analysing the hourly shadow patterns on 8 days of the year. The days selected were evenly distributed in the year to allow the impact of the sun's altitude to be examined. It was found that the strength of the correlation between mean ground view factor and, density, urban form descriptors and mean SVF value varies significantly with the sun's altitude: the higher the altitude, the higher the correlation. The results may be explained by noting that the higher the sun is in the sky vault, the more the exposure of the urban form to the sun approximates to that of the sky. Thus, the relationship between urban geometry and mean shadow fractions is dominated by the relationship of urban geometry with mean SVF values. As urban geometry is strongly correlated with mean SVF values, when mean SVF values correlate well with mean GVF values, urban geometry will also. Moreover, the relationship between the correlation of mGVF with mSVF, and the sun's altitude was found to fit very well in a logarithmic model with the impact of the latter on the former to reduce progressively with increasing sun's elevation. Two critical angles have been identified on the relevant plot (Fig. 4) these of 20º and 40º: at 20º the rate at which the correlation between mGVF and mSVF changes as a function of sun's altitude starts to reduce significantly. Above 40º, the correlation stabilises and tends to be very high (R^2>0.9). As regards the relationship of urban layout with mean shadow fractions, site coverage, mean distance between building volume and frontal area density were found to be the strongest variables like for mean SVF values. Also, urban form descriptors capturing the randomness of urban layout also present significant positive correlation on particular hours of the day studied (21st June). This is in general agreement with those studies (e.g. Cheng et al., 2006) arguing that increasing urban randomness enhances the solar availability in the urban fabric.

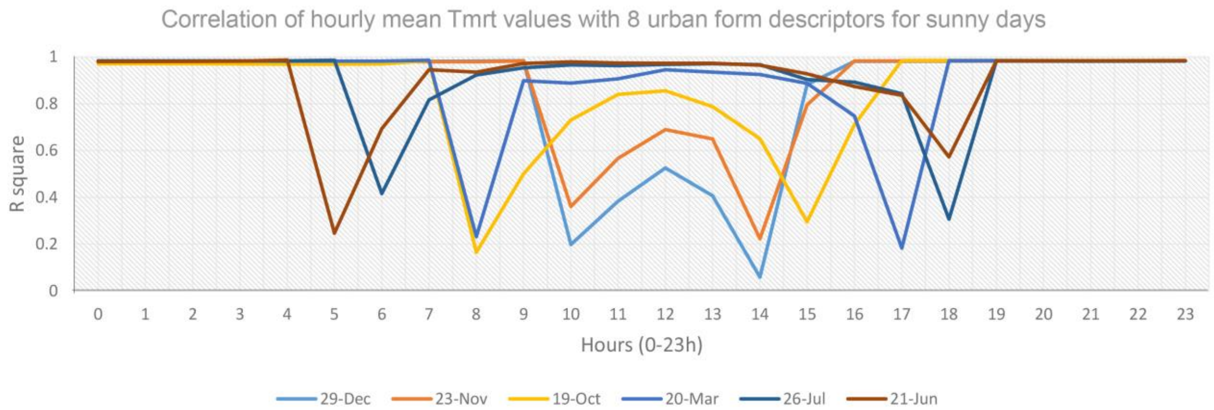

Figure 6: *Correlation of hourly mean T_{mrt} values with 8 urban form descriptors on the sunny studied days.*

As expected from the above, in the absence of solar radiation, the relationship of urban geometry with mean radiant temperature in outdoor spaces is almost perfectly linear, as the latter is decided by the sky view factor values. In contrast, in daytime sunny conditions, in which the spatial variations of T_{mrt} are highly affected by the shadow patterns, the correlation of urban geometry with mean T_{mrt} values follows the same pattern as for mean GVF values, meaning it increases with the sun's altitude. As a consequence, at night-time, the squares in Central London were found to be warmer than those in west and north London due to lower SVF values, with the difference between the coolest and the warmest squares being consistently between 5-6ºC. In cloudy daytime hours, the squares of Central London remain warmer but the difference between maximum and minimum mean T_{mrt} value among the squares drops due to the diffuse solar radiation which is in greater supply in squares of lower density (higher mean SVF). Finally, in sunny hours, the squares in North London, of generally lower density, were warmer than those of the other areas and the difference between the warmest and coolest squares can reach up to 18ºC depending on the intensity of direct solar radiation.

Overall, the present study has shown that the radiant environment at the district level can be predicted to a great degree by urban geometry and thus, is amenable to being modified through urban planning. Beside the mean SVF values, the availability of direct solar radiation on ground was found to correlate well with density and urban layout, depending on the sun's altitude angle. The critical angles identified by the present study are essentially independent of location; thus, they could be advised for other parts of the world. However, it is very likely that they would be affected by the mean building height of the urban form which has not been investigated as yet.

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