# Urban Geometry, SVF and Insolation of Open Spaces


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Abstract: The radiant environment in open spaces is very sensitive to the surrounding built form, which determines their openness to the sky and exposure to the sun. This paper presents the analysis of 132 urban forms in London and Paris, two cities at similar geographical latitude, but of different urban geometry, focusing on the relationship between urban geometry and insolation of open spaces at neighbourhood scale. The methodology consists of three stages: (i) the geometric analysis of the urban forms, (ii) their solar access analysis, and (iii) the statistical exploration of the results. Special emphasis is on average ground SVF which is employed as an integrated geometry variable and environmental performance indicator. The comparative analysis of the two cities underlines the significance of urban layout for modifying the outdoor radiant environment, and reveals temporal characteristics of the relation of urban geometry with insolation of urban forms, induced by the varying solar geometry. Indicatively, average ground SVF was found to be primarily affected by the quantitive characteristics of the open space, and able to predict average daytime insolation on 21 March and 21 June ($R^2$>0.8), in both cities.

# **Urban Geometry, SVF and Insolation of Open Spaces:** the case of London and Paris

The radiant environment in open spaces is very sensitive to the surrounding built form, which determines their openness to the sky and exposure to the sun. This paper presents the analysis of 132 urban forms in London and Paris, two cities at similar geographical latitude, but of different urban geometry, focusing on the relationship between urban geometry and insolation of open spaces at neighbourhood scale. The methodology consists of three stages: (i) the geometric analysis of the urban forms, (ii) their solar access analysis, and (iii) the statistical exploration of the results. Special emphasis is on average ground SVF which is employed as an integrated geometry variable and environmental performance indicator. The comparative analysis of the two cities underlines the significance of urban layout for modifying the outdoor radiant environment, and reveals temporal characteristics of the relation of urban geometry with insolation of urban forms, induced by the varying solar geometry. Indicatively, average ground SVF was found to be primarily affected by the quantitive characteristics of the open space, and able to predict average daytime insolation on 21 March and 21 June ($R^2$>0.8), in both cities.

Keywords: urban geometry, urban microclimate, SVF, solar access, London, Paris

## Introduction

It is widely acknowledged that urban geometry plays a key role in addressing the significant environmental challenges posed by the increasing urbanisation of the world population and resulting intensification of the built environment. As a major modifier of the urban climate (Oke, 2006), it is directly related to the thermal environment within cities with significant implications for human comfort and health, as well as buildings' energy demands. This research investigates the relationship between urban geometry, average sky view factor (SVF) and solar access at the ground level, which are both associated to the outdoor radiant environment, and thus, thermal conditions in open spaces.

Most research on the impact of urban geometry on outdoor thermal environment use the urban street canyon as the basic structural unit to focus on. Urban street canyon allows the effect of the two crucial parameters for solar access, urban geometry and orientation to be studied (Arnfield, 1990). For instance, height-to-width ratio (H/W) and street orientation have been considered as design parameters in several studies assessing shading levels in hot climates (Ali-Toudert & Mayer, 2006; Emmanuel et al., 2007; Johansson & Emmanuel, 2006).

In real street canyons, along with or instead of H/W, the sky view factor (SVF) is being used to describe the intensity of the surrounding built environment. SVF is a ratio whose value expresses the openness of a point to the sky, with 0 and 1 denoting a totally obstructed and unobstructed point, respectively. Its capability to express the built obstruction even in non-symmetrical configurations has established SVF as a major geometric parameter in a wide range of urban environmental studies. Its effect on daytime and nocturnal air temperatures has been extensively studied, in different climatic contexts (e.g. Eliasson, 1996; Giridharan et al., 2007, Yamashita et al., 1986). The relevant findings have not been clear about the existence of possible correlation, especially regarding daytime air temperatures, highlighting the dependence of the phenomena on larger urban scales. Compared to air temperatures, the correlation of SVF with on-site measurements of surface and mean radiant temperatures has been found statistically stronger (Bourbia & Boucheriba, 2010; Krüger et al., 2011; Wang & Akbari, 2014). Their negative relationship at night is justified by that the capacity of a surface to emit longwave radiation to the sky is proportional to its openness to it. Regarding the daytime though, several researchers acknowledge the limitation of the

SVF parameter to predict solar access at given points due to its failure to associate the urban geometry information to solar geometry (Krüger et al., 2011; Nouri et al. 2017).

SVF is also regarded as a performance indicator when assessing environmentally diverse urban typologies and forms (Project PREcis, 2000; Ratti et al., 2003; Zhang et al., 2012). In this case, average -rather than individual- SVF values are considered referring to entire urban surfaces, such as building façades -associated to illuminance levels-, or areas -associated to outdoor thermal conditions-. Especially, in urban climate research, average SVF (mSVF) is commonly used to evaluate annual mean or maximum UHI intensity ($\Delta T$) distribution within a city. Several studies have proposed analytical expressions, in the form of: $\Delta T$= a-b*mSVF, where a and b vary with city (Unger, 2004). Average SVF is also referred to as affecting the absorption of shortwave solar radiation, causing daytime heating (Ratti & Richens, 2004).

Considering the average SVF as a performance indicator with a wide range of applications in urban climate and environmental studies, it is important to understand how it is related to the urban geometry. Its negative relationship with the quantitative aspect of it is certain, in the sense that higher built densities tend to result in lower average SVF. Nonetheless, research indicated that average SVF is also affected by the urban layout. Cheng et al. (2006) found that increasing density by increasing site coverage (i.e. built-up area) has a greater influence on average SVF than increasing building height. Hu et al. (2016) showed that optimizing the density distribution layout by differentiating the building heights in an urban form may yield a decrease in average ground SVF up to 7%. Both studies are based on generic urban models and, thus, with no reference to specific cities. Chatzipoulka et al. (2016) examining real urban forms in London ascertained that the geometric parameters influencing average ground SVF differ from those affecting average façade SVF.

The present study examines the relationship between urban geometry, average SVF and insolation values in open spaces, analysing 132 real urban forms, of 500x500m area, in London and Paris. It belongs to a new era of urban analysis studies which make use of 3D digital models of cities, and powerful computer tools to investigate spatially-expressed (environmental) phenomena (Patino & Duque, 2013). The big sample size examined enables the statistical exploration of the relationships that combined with the spatial scale at which the topic is being investigated constitute two major features of the research

## Research considerations and objectives

Figure 1 illustrates the theoretical schema which summarises the methodological approach of the research. The overriding consideration is that solar radiation is strictly directional and as such, its interaction with the built form is highly predictable. Therefore, a shadow pattern is determined by solely two parameters, urban geometry and orientation of it in relation to the sun position. As the position of the sun in the sky changes in time, it is assumed that urban geometry and solar access are bound in a dynamic relationship of temporal characteristics which are to be explored.

In addition, the research distinguishes urban geometry into *built density* and *urban layout*. Built density measures the built volume in an area, and urban layout refers to how the built volume is allocated spatially, horizontally and vertically, within the area. This distinction is deemed necessary, and emerges from the admittance of two facts. First, it is urged by the opposite environmental connotations of built density at the city and neighbourhood scales, positive and negative respectively, which suggests a compromise between urban densification and environmental quality. Second, as the negative effect of built density on solar and daylight availability is a given, the methodological isolation of the density parameter allows the effect of urban layout to be investigated.

Special emphasis is put on average SVF which is employed both as an integrated geometric parameter and environmental performance indicator. Two successive investigations are conducted, focusing on: (i) the relationship between average ground SVF (dependent variable) and urban geometry, as expressed by a series of geometric measures, and (ii) the relationship between average SVF (independent variable) and solar access in open spaces, examined at different times. The objectives are:

- to examine to what degree average ground SVF can be estimated using geometric parameters and, whether it can be modified optimizing the urban layout,
- to explore to what extent urban geometry defines the solar access in open spaces and whether average SVF can be used as an indicator of it, in different times/periods.

As an early study provided evidence about the impact of solar geometry on the causal relation between urban geometry and solar access (Chatzipoulka et al., 2015), two cities at similar geographical latitudes, London and Paris, were selected to be analysed. Their differences in terms of urban geometry allows the sensitivity of the results to be tested.

It is worth highlighting that the orientation parameter is not considered in the analysis and thus, its impact on solar access remains a missing factor. Nonetheless, assuming the theoretical schema in Figure 1, it may be identifiable in the results indirectly. If urban geometry explains the insolation levels in open spaces, it would mean that the orientation effect is limited. The opposite is not necessarily true, as a weak relationship between urban geometry variables and solar access may also stem from their imperfection to capture the variations of urban geometry and specifically, urban layout.

**Methodology**

The research is based on the analysis of real urban forms, and features three methodological stages: (i) the geometric analysis of the urban forms, (ii) their solar access and SVF analysis, and (iii) the statistical analysis of the results of the two previous stages.

***Case studies***

London and Paris are located at similar geographical latitudes (London: 51°30’26’N, and Paris: 48°51’24’N). and within a similar climatic context, experiencing temperate climates. However, they present major differences in their urban geometry, which is tightly interwoven with their history and tradition in urban planning in the last centuries. Paris exemplifies the planned European cities with a high degree of order, compactness and uniformity (Benevolo, 1993; Evenson, 1979). On the other hand, London is considered a general exemption, “*the most resistant* [city] *to a general plan*” (Benevolo, 1993, pp. 204). Its urban area has been rather developed by an order of magnetism around its centre, and its urban fabric presents a high degree of incoherence and heterogeneity (Hall, 1989).

The 3D digital models of the two cities were downloaded from online database (Centre for Environmental Data Archive; Service de la Topographie et de la Documentation Foncière) in .shp format and converted into raster images, i.e. digital elevation models (DEMs), of 0.5m spatial resolution, using ArcMap in ESRI ArcGIS software. Each DEM was next divided into cells of 500x500m area which corresponds to the so-called neighbourhood scale. Similar spatial scales have been used by previous studies on relevant topics (Lau et al., 2015; Lindberg & Grimmond, 2011a).

The selection of the cells to be analysed, referred to hereinafter as urban forms, was made by observation and considering the results of a preliminary geometric analysis. The major criteria included: (i) continuity of urban fabric, (ii) acquisition of the wider range of built density values found in two cities, and (iii) inclusion of different urban layouts. The sample of London consists of 72 urban forms selected from three representative areas: in central, west and north London, which are of high, medium and low built density, respectively (Figure 2). Paris was represented by 60 urban forms across its major urban area enclosed by the city's peripheral road (Figure 3).

***Geometric analysis of studied urban forms***

Extensive geometric analysis of the studied urban forms was performed in MATLAB using image processing techniques. This involved the computation of 18 urban geometry variables, built density -referred to hereinafter as simply density- and 17 urban layout descriptors (Table 1). The purpose was the set of the variables used to capture as much as possible the variations of urban geometry. Their definitions are provided in the Appendix.

The outputs of the geometric analysis are next used in the statistical analysis where the relationship of urban geometry variables with average ground SVF is explored. Prior to this, they were examined comparatively for the two cities as to identify major differences in the two samples. The most significant ones for affecting the research findings are summarized below. Special emphasis is put on density, site coverage and mean building height which are major urban measures and strongly interrelated. Increasing building height and site coverage constitute the two ways to increase density, or otherwise, for a given density, the two parameters are inversely proportional.

A first observation is that the ranges and standard deviations of values of most variables are greater for London compared to Paris, and in some cases the difference is significantly big. Regarding density values, the range in London's sample is about 5 times greater than in Paris, from 2.8 to 33.1 and 5.2 to 11.4 [$m^3/m^2$], respectively. With respect to *mean building height* (MeH), the difference is even greater, with the values ranging from 11.8 to 50.1m in London's sample, and only 14.6 to 21.5m in that of Paris. In contrast, the ranges of *site coverage* (SCo) values in the two cities are relatively close, i.e. 20-69% for London and 32-67% for Paris. Regarding the remaining urban layout descriptors, those expressing characteristics of the horizontal urban layout, such as *mean outdoor distance* and *mean building footprint*, are found to vary equally in the two cities. On the other hand, there is an important number of variables, most of them related to height and volume metrics, for which the sample of London presents extremely high maximum values, increasing considerably the respective range.

Pearson Correlation analysis performed including all 18 geometric variables showed significant correlations ($p<0.01$) among most of them in both cities. This is to some degree expected as the calculation of some geometric parameters involve the same metrics. However, in London, their co-variation is much more profound, and partially related to that most of the urban layout descriptors correlate highly with density. It is worth mentioning that in London's urban forms, density correlates very well both with site coverage ($R^2=0.901$, $p<0.001$) and mean building height ($r=0.960$, $p<0.001$). Their statistically strong relationship with density should be considered as a special characteristic of London. In Paris, only the relationship of site coverage with density is significant ($r=0.826$, $p<0.000$), whereas, that of mean building height with density is relatively weak (r=0.288, p=0.026). The increased intercorrelation of the urban layout descriptors in London compared to Paris was also reflected in the results of the Principal Component Analysis (Figure 4).

It should be noted that there are identified differences between the two cities which concern qualitative characteristics of the urban layout and cannot be fully expressed by the numeric variables used. Such a difference is the geometric order characterising the greatest part of Paris, with aligned urban blocks defined by straight, long and wide streets, i.e. boulevards, as opposed to London's general "fragmentation". As discussed later, this should be acknowledged along with the outcomes of the geometric analysis in the interpretation of the results.

***Simulation tools and outputs***

Ground SVF and solar access simulations were performed in SOLWEIG 2013a (Lindberg et al., 2008). Simulation inputs were the 3D geometry of the urban forms in DEM format, and locations' geographical information. Simulation outputs were generated in matrices of the same size as the DEMs used. Figure 5 demonstrates the DEM of an urban form and the two types of maps derived from the analysis in SOLWEIG: (i) SVF maps, and (ii) shadow patterns. As seen, the original area of the urban forms was extended by 100m in all directions to consider the effect of the surrounding buildings. With respect to shadow patterns, these were generated for three representative days, 21 June (summer solstice), 21 March (equinox) and 21 December (winter solstice), from sunrise until sunset, at 10-minute intervals, as suggested for complex environments (Lindberg & Grimmond, 2011b). Apart from instantaneous shadow patterns, average daytime ones were also produced on the same days.

Next, average ground SVF (mSVF) and average ground insolation (mSOL) values were computed by processing the SVF and shadow pattern maps in MATLAB.

Their values range from 0 to 1. mSVF expresses the average openness of the considered open space to the sky. mSOL measures sunlit open space over total open space expressing average solar exposure at a given time. mSOL expressing mean insolation of open spaces at a given time are referred to as *instantaneous* mSOL, while those expressing mean insolation over the day as *daytime* mSOL.

## Results

### *Relationship of mean ground SVF with urban geometry variables*

The statistical analysis reveals a strong negative correlation between density and mSVF for both cities, with the correlation coefficient for London ($r=-0.940$, $p<0.001$) being considerably higher than for Paris ($r=-0.787$, $p<0.001$). This is partially attributed to the considerably wider range of density values in the sample of London which strengthens the statistical relationship. At the same time, in Paris, a great number of urban forms feature similar densities and, hence, the relatively reduced correlation confirms that urban layout influences significantly the mSVF. Furthermore, the curve estimation tests show that the relationship is better described by a logarithm model, with the $R^2$ obtained from linear regression though being equally high (Figure 6). The logarithmic relationship indicates that the effect of density on mSVF is more profound in low densities, and reduces gradually as density increases.

The relationship of mSVF and 17 urban layout descriptors was tested through different statistical tests. Pearson Correlation results (two-tailed) are presented in Table 2 (Column A). The r values demonstrate that mSVF correlates significantly with most of the independent variables, in both cities. For London, the strongest variable is *site coverage* (SCo) with r being -0.950; whereas, for Paris, it is *complexity* (Cex) with r value -0.936 (Figure 7). It is remarkable that, in Paris, the correlation between Cex and mSVF is significantly higher than that achieved by density.

Nonetheless, the results are apparently affected by the intercorrelation of the variables. Especially, in the case of London, it is the strong correlation of most of urban layout descriptors with density that causes the perceivably higher r values. This is confirmed when performing partial correlation with control for density, the r values of most of the descriptors reduce drastically (Table 2, Column B). On the other hand, in Paris, the effect of controlling density is less significant with the correlations for *compactness* (Com), *complexity* (Cex) and *façades-to-street ratio* (FaS) remaining significant strong ($r>0.8$), with all of three being associated to the area of building façades. Moreover, the significance of *mean outdoor distance* increases remarkably ($r=0.893$, $p<0.01$) for Paris with this becoming the most influential variable, while the strongest variable for London remains *site coverage* ($r=-0.698$, $p<0.01$). *Site coverage* and *mean outdoor distance* are two variables measuring in different ways the open space; thus, it can be argued that mSVF is primarily affected by the quantitative characteristics of the open space. This also explains why the effect of *mean building height* on mSVF is found to be positive as, for a given density, higher buildings mean larger open spaces.

Performing stepwise linear regression tests, considering all urban geometry variables, the models of three variables obtained include two common variables for London and Paris, and the $R^2$ achieved are particularly high, 0.984 and 0.956, respectively. Specifically, in London, mSVF is described as a function of *site coverage*, *complexity* and *mean outdoor distance* (mSVF= 0.847 -0.005*SCo -0.135*Cex +0.006*MeD); whereas, in Paris, mSVF is given as a function of *complexity*, *mean outdoor distance* and *mean building volume* (mSVF= 0.591 -0.120*Cex +0.19*MeD - $5.473e^{-7}$*MeV).

Acknowledging the strong collinearity of the urban geometry variables, and in order to examine to what extent their total variance can explain the variations of mSVF, multiple regression analysis was performed considering as independent variables, the factors derived from the Principal Component Analysis (PCA) test. These are three for London and five for Paris, explaining 87% of the variance of the urban geometry variables in the two cities. The $R^2$ values obtained are particularly high, 0.971 for London and 0.962 for Paris.

Overall, it can be argued that simple urban geometry measures can explain the mSVF variations, even in cases that the density parameter does not vary considerably. The findings also demonstrate that mSVF can be modified by considering the influential layout parameters in designing a new urban development. Beside *mean outdoor distance* and *site coverage*, there are other geometric parameters the significance of which was confirmed in both cities. Specifically, increasing buildings' façade area, as expressed by the Cex and FAS, was found to affect negatively the mSVF, whereas, varying building heights (StH) and increasing the directionality (Dir) of the urban form enhance it.

***Relationship of mean ground SVF with mean insolation of open spaces***

*Average instantaneous insolation of open spaces*

Regarding the relationship between mSVF and instantaneous mSOL, the analysis reveals some major findings. Statistically, the relationship is best described by linear or exponential curves depending on day and time, i.e. the position of the sun for which each mSOL value was computed. Specifically, for high solar altitudes such as occurring on 21 June and 21 March close to midday, the relationship is better described as linear. For low solar altitudes, such as on 21 December and in early morning/late afternoon hours, the best curve fit is achieved by exponential models. Therefore, when the sun is at lower positions, the negative effect of mSVF on the insolation of open spaces is more powerful in areas of increased built obstruction. More importantly, either considering linear or exponential regression results, the strength of the relationship is found to vary in the day in a specific way: $R^2$ values are at their lowest at sunrise and sunset, and increase gradually towards midday. For consistency, the paper focuses hereafter to the linear regression results.

Examining first London, Figure 8 demonstrates the mSOL values computed for 72 urban forms at indicative hours -from sunrise to midday- on 21 June plotted against their mSVF. Observing the $R^2$ values and trendlines, it appears that the strength of the relationship as well as the effect of mSVF on instantaneous mSOL increases in time. However, there are cases where this general rule does not apply. Specifically, the highest $R^2$ appears at 10 a.m. rather than noon, and the $R^2$ value at 11 a.m. is lower than at 9 a.m. Nonetheless, the differences are very small, with the relationship being particularly strong after 9 a.m. This may be interpreted as that the sensitivity of the mSVF-mSOL relationship to increasing solar altitude reduces once the relationship gets strong enough, i.e. once the sun gets high enough in the sky. Similar observations are made when examining the scatter plots on 21 March and 21 December.

The next step was to plot all $R^2$ values obtained from linear regression analysis against time, by day. As shown in Figure 9(a-c), the points outline curves of an inverse U shape, quite symmetrical to the vertical notional axis passing from the middle of the day. Moreover, moving from the winter solstice to the summer solstice, the relationship between mSVF and instantaneous mSOL becomes stronger and for longer time over the day. Indicatively, the $R^2$ is above 0.8 between 7.00 a.m. and 7.00 p.m. on 21 June, and between 9.00 a.m. and 15.00 p.m. on 21 March. On 21 December, maximum $R^2$ values are close to 0.6. For comparison, the same tests were repeated for density, and the $R^2$ obtained were plotted on the same graphs (i.e. Figure 9). As observed, mSVF explains better the variations of instantaneous mSOL than density, at most of the time on different days.

Since the variations of the strength of the relationship of mSVF and instantaneous mSOL in time is attributed to the varying solar altitude, all $R^2$ values obtained for all three days were combined and plotted against solar altitude angle. Precise solar altitude angles were derived from the online NOAA Solar Position Calculator. As seen in Figure 10, the points of different days outline a relatively smooth and well-defined curve, i.e. they present similar $R^2$ for any given altitude.

Although the analysis of Paris' urban forms confirms the major findings, the $R^2$ values -on average and regarding the maximum ones- are reduced, and the relationship appears less consistent and predictable. Plotting the $R^2$ values against time on each day the curves appeared are less smooth compared to those in Figure 9, and present a lower degree of symmetry. This is clearly illustrated in Figure 11 which combines the $R^2$ results derived from Paris' analysis on three days. As seen, the points outline a curve of similar logic as in Figure 10, but they are scattered over a greater area showing a greater discrepancy of $R^2$ for a given solar altitude.

To obtain a better insight about the relative limitation of mSVF to explain instantaneous mSOL in Paris, analysis focused on 21 March and mSOL values at 30-min intervals. Linear regression tests were repeated considering as independent variables the PCA factors explaining 87% of the variance of urban geometry variables in the two samples, three for London and five for Paris. Figure 12(a&b) allows the comparison of the $R^2$ results obtained when testing the PCA factors, mSVF and density as independent variables. Regarding London, the PCA factors and mSVF explain similar percentages of the variation of mSOL during that day, which are higher than those explained by density, at most of the times. Regarding Paris, the PCA factors and mSVF perform significantly better as predictors of mSOL than density. Moreover, the differences between the PCA factors and mSVF are more evident but without the former enhancing substantially the symmetry and smoothness of the curve. Therefore, it can be argued that it is not mSVF less capable to predict mean insolation of open spaces in Paris, but in general the urban geometry variables used. It may also indicate that the missing factor, i.e. the orientation effect, is much more significant for the insolation of open spaces in Paris than in London.

*Average daytime insolation of open spaces*

The relationship of mSVF with average daytime insolation of open spaces was also found to be affected by the solar altitude, referring to average solar altitudes on three representative days considered. mSVF can -almost- fully explain the variation of daytime mSOL on 21 June and 21 March, in both cities (Figure 13). This is in line with the findings of a past study in London which, testing the same relationship for dates of similar sun's altitudes, i.e. 25 September and 3 June, reported a perfect fit ($R^2$=0.99) on both days (Lindberg & Grimmond, 2011a). The consideration of a winter day however revealed an important reduction in the strength of correlation. The fact that the $R^2$ are slightly higher on 21 March compared to 21 June implies that the influence of increasing solar altitude may even inverse and become negative when this exceeds a certain value. It is also noted that, on 21 December, the relationship is better described as exponential (London: $R^2$=0.773, Paris: $R^2$=0.559).

Comparing the $R^2$ obtained for the two cities, although those for London remain higher compared to Paris, the differences are small, especially on the longer days. Therefore, it can be argued that the factor which interferes with the effect of urban geometry on instantaneous mSOL in Paris, and undermines their relationship is neutralised. Assuming that this factor is indeed the orientation, it is sensible that its impact on the average daytime insolation is eliminated due to multiple solar azimuths considered in the computation of the latter.

Finally, the trendlines in Figure 13(a&b) were adjusted by setting intercept to zero for the models to be usable for predicting average insolation of open spaces in the two cities. Comparing the multiplying factors for London and Paris, on the same day, it is observed that they are in a very good agreement as their numeric difference is in the order of $10^{-2}$. This suggests that the prediction models may be of relevance to other locations at similar geographical latitudes, as their sensitivity to different urban geometries is rather low.

**Discussion**

The comparative analysis of London and Paris confirms the major findings of this research, strengthening their validity. Numerical discrepancies emerged in the statistical results, if examined along with the results of the geometrical analysis of the cities, enhance the understanding of the subject matter. These numerical discrepancies can be summarised in that, the relationships between density and mSVF, and between mSVF and average insolation values were found to be stronger in London, compared to Paris. This is related to diverse factors as explained below.

Selecting urban forms across the whole range of densities found in the two cities was a deliberate methodological decision which resulted in different ranges of the density values in the two samples, but without the respective numbers of urban forms considered being proportional to them. The extremely wide range of densities in London strengthens the density-mSVF relationship, which was found to be almost perfectly linear. However, there is another influential factor, a special characteristic of

London. This is the strong correlation of density with most urban layout descriptors examined, which neutralises -statistically- the effect of urban layout of the urban forms on mSVF, especially evident in the case of Paris.

In particular, in London, built density increases equally vertically and horizontally as indicated by the strong correlation of density with site coverage and mean building height. In contrast, in Paris, density presents a strong linear relationship only with site coverage. Since site coverage and more generally, the quantitive characteristics of open space were found to have an increased impact on mSVF, a finding that is in line with previous studies (Chatzipoulka et al., 2016; Cheng et al., 2006), it becomes apparent that density has an increased effect on mSVF in Paris. Plotting density and mSVF values computed for the two cities on the same graph, it is observed that Paris' urban forms of high density present lower mSVF, compared to those of London of similar density (Figure 14). This is directly attributed to higher densities in Paris achieved mainly by increasing site coverage, reducing open space.

Regarding the relationship between mSVF and average insolation of open spaces, the inconsistency and reduced correlations in Paris are not related to the quantified geometric differences between the two cities, and can be hardly justified by the 1.7 times greater range of SVF values in London. The fact that the discrepancies concern mostly instantaneous mSOL, rather than daytime mSOL, suggests that the major factor affecting the relationship is eliminated when the average relationship is examined for the day. As implied by the schema in Figure 1, this factor can be identified as the orientation which is a logical inference considering that its effect on average daytime insolation is neutralised by multiple solar azimuths. The amplification of the orientation effect on instantaneous mSOL in Paris is associated with the existence of boulevards, i.e. long and wide, straight streets, which cut across the otherwise tight and compact urban fabric. The coincidence of the axis of such a continuous and linear open space with the sun azimuth increases dramatically the percentage of sunlit open spaces at the given moment (Figure 15).

The increasing correlation of mSVF with solar exposure of open spaces as the sun altitude increases can be perceived as when the sun rises higher in the sky vault, the openness of the outdoor space to the sky approaches its exposure to the sun. According to the quadratic curves in Figures 10&11, the $R^2$ presents theoretically a maximum value for a solar altitude angle beyond which the correlation starts to reduce. Solar altitude angles tested (i.e. 0° to 65°) did not allow the verification of the quadratic relationship. However, assuming the extreme case that the sun altitude happens to be 90°, then, all the open spaces would be sunlit independently of their mSVF, and thus the statistical relationship between mSVF and mSOL would be null. The example indicates that the strength of the mSVF-mSOL relationship must present a maximum value; however, it does not provide evidence for whether the relationship is quadratic (i.e. symmetric to the maximum value). Furthermore, the sun altitude angle for which the $R^2$ value is maximised must be unique for each urban form, and related to its mean height-to-width ratio.

## Conclusions

The research provides considerable insight on the impact of urban geometry on the urban radiant environment at the neighbourhood scale, associated with outdoor thermal conditions and the urban microclimate. The major findings are derived from the comparative analysis of urban forms in London and Paris.

The first investigation focused on the relationship of average ground SVF (mSVF) with a series of urban geometry variables, including built density and 17 urban layout descriptors. Regarding built density, its relationship with mean ground SVF is better described by logarithmic curves, and much stronger in London ($R^2$= 0.903) than in Paris ($R^2$=0.638). The case of Paris demonstrates that the mSVF in urban forms of similar density may differ considerably due to the variation of urban layout highlighting the significance of the latter for modifying mSVF. However, including in the statistical analysis the urban layout descriptors, it was ascertained that they can explain the variations of mean ground SVF equally well in London and Paris ($R^2$>0.9), and presumably in every city.

Controlling the effect of density, the most influential variable for mSVF in London is site coverage (r=-0.698), whereas, in Paris, mean outdoor distance, i.e. distance between buildings (r=0.893). As site coverage and mean outdoor distance are two metrics of the open space, it can be argued that mean ground SVF is primarily affected by the quantitative characteristics of the open space. Interpreting the above into urban design guidelines would suggest that the mSVF can be modified by adjusting the horizontality and verticality of an urban form, or development. In other words, one way to increase mSVF in densely built-up areas is to opt for higher buildings as to free more open space at the ground level. In addition, the differentiation of building heights may be also beneficial as the relevant variable was found to correlate significantly and positively with mSVF in both cities. When the above do not constitute an option, for instance, in compact urban areas of fixed building heights, architects should put emphasis on simple built forms, avoiding unnecessary facades' undulations, as well as their alignment as to enhance the directionality of the urban form.

The second part of the research examined the correlation between mSVF and average insolation of open spaces, on representative days in the year. The results revealed the temporal characteristics of the relationship as induced by the varying solar geometry. Its strength was found to vary with solar altitude, either referring to average instantaneous or daytime insolation values. In general, mSVF can explain and predict better the variations in the insolation of open spaces for periods that the sun is at/ passes through higher positions in the sky. However, the effect of increasing solar altitude diminishes gradually as the solar altitude continues to increase, and some findings imply that beyond a point the effect may even become negative.

The other parameter influencing the strength of the relationship of mSVF with solar access in open spaces is the time period over which the relationship is examined. Specifically, mSVF can explain much better average daytime rather than instantaneous insolation. This is not related to the solar altitude, but the various solar azimuths characterising a daily sun path which neutralise the orientation effect. The effect of orientation becomes particularly evident in Paris' urban forms regarding instantaneous solar access due to the existence of boulevards. As a result, mSVF is appreciably less capable to predict average insolation of open spaces in Paris at given moments, compared to London. In contrast, the results concerning daytime average insolation are numerically close for the two cities, especially on 21 June and 21 March. On both days, the relationship of mSVF and daytime average insolation was found to be almost perfectly linear ($R^2$>0.93). Therefore, it can be argued that mean ground SVF can accurately estimate average daytime insolation of spaces for at least half of the year, for locations of similar latitude.

Overall, the study demonstrates that mean ground SVF is a key parameter when studying the outdoor radiant environment, as it bridges urban geometry information with resulting radiation fluxes occurring in the open space, taking into account both longwave and short-wave radiation availability. The significance of urban layout for the openness of urban open spaces to the sky and, by extension, the radiant environment, indicates the potential of urban design to promote environmental sustainability in cities, without compromising the objective for densification of the built environment.

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**Appendix:** Definition of 18 urban geometry variables considered in the analysis.

***Built density***, total built volume within the site over site area, [$m^3/m^2$].

***Site coverage*** (SCo), total built-up area over site area, [%].

***Mean building height*** (MeH), mean building height weighted by building footprint area, [m].

***Standard deviation of building height*** (StH), standard deviation of building height weighted by footprint area, [m].

***Standard deviation of site height*** (StS), standard deviation of height of the entire urban form, including built forms and open spaces, weighted by footprint area [m].

***Maximum building height*** (MaH), height of the tallest building in the area, [m].

***Mean outdoor distance*** (MeD), mean distance between buildings, [m].

***Standard deviation of outdoor distance*** (StD), standard deviation of distance between buildings, [m].

***Max outdoor distance*** (MaD), maximum distance between buildings, [m].

***Compactness*** (Com), total building surface to building volume ratio, [$m^2/m^3$].

***Complexity*** (Cex), total façade surface area over site area, [$m^2/m^2$].

***Facades-to-street ratio*** (FaS), façade surface area to un-built area, [$m^2/m^2$].

***Number of building volumes*** (NoB), number of built volumes in an urban form [-].

***Mean building footprint*** (MeF), mean footprint area of built volumes lying entirely within the site, [$m^2$].

***Standard deviation of building footprint*** (StF), standard deviation of footprint area considering built volumes lying entirely within the site [$m^2$].

***Mean building volume*** (MeV), mean volume considering built volumes lying entirely within the site, [$m^3$].

***Standard deviation of building volume*** (StV), standard deviation of volume considering built volumes lying entirely within the site, [$m^3$].

***Directionality*** (Dir), standard deviation of ground's permeability in 36 directions weighted by site coverage, [-].

Urban geometry variables

| Name | Unit | Abbreviation |
|---|---|---|
| *Built density* | $m^3/m^2$ | |
| ***Layout descriptors*:** | | |
| *Site coverage* | % | SCo |
| *Mean building height* | m | MeH |
| *Standard deviation of building height* | m | StH |
| *Standard deviation of site building* | m | StS |
| *Maximum building height* | m | MaH |
| *Mean outdoor distance* | m | MeD |
| *Standard deviation of outdoor distance* | m | StD |
| *Max outdoor distance* | m | MaD |
| *Compactness* | $m^2/m^3$ | Com |
| *Complexity* | $m^2/m^2$ | Cex |
| *Facades-to-street ratio* | $m^2/m^2$ | FaS |
| *Number of building volumes* | - | NoB |
| *Mean building footprint* | $m^2$ | MeF |
| *Standard deviation of building footprint* | $m^2$ | StF |
| *Mean building volume* | $m^3$ | MeV |
| *Standard deviation of building volume* | $m^3$ | StV |
| *Directionality* | - | Dir |

Table 1. 18 urban geometry variables considered in the analysis.

110x133mm (300 x 300 DPI)

| | A. Correlation | | | | B. Part.Corr. Ctrl_Density | | | |
|---|---|---|---|---|---|---|---|---|
| | London | | Paris | | London | | Paris | |
| | r | p | r | p | r | p | r | p |
| Density | -0.940 | 0.000 | -0.787 | 0.000 | | | | |
| Sco | -0.950 | 0.000 | -0.871 | 0.000 | -0.698 | 0.000 | -0.634 | 0.000 |
| MeH | -0.869 | 0.000 | 0.137 | 0.298 | 0.347 | 0.003 | 0.615 | 0.000 |
| StH | -0.684 | 0.000 | 0.669 | 0.000 | 0.358 | 0.002 | 0.385 | 0.003 |
| StS | -0.858 | 0.000 | 0.393 | 0.002 | 0.331 | 0.005 | 0.522 | 0.000 |
| MaH | -0.663 | 0.000 | 0.530 | 0.000 | 0.117 | 0.330 | 0.238 | 0.069 |
| MeD | 0.458 | 0.000 | 0.869 | 0.000 | 0.526 | 0.000 | 0.893 | 0.000 |
| StD | 0.173 | 0.145 | 0.678 | 0.000 | 0.317 | 0.007 | 0.641 | 0.000 |
| MaD | 0.159 | 0.182 | 0.532 | 0.000 | 0.205 | 0.087 | 0.387 | 0.002 |
| Com | 0.856 | 0.000 | -0.190 | 0.145 | 0.301 | 0.011 | -0.842 | 0.000 |
| Cex | -0.940 | 0.000 | -0.936 | 0.000 | -0.468 | 0.000 | -0.829 | 0.000 |
| FaS | -0.943 | 0.000 | -0.929 | 0.000 | -0.425 | 0.000 | -0.800 | 0.000 |
| NOB | 0.777 | 0.000 | 0.413 | 0.001 | 0.291 | 0.014 | -0.216 | 0.100 |
| MeF | -0.835 | 0.000 | -0.546 | 0.000 | -0.621 | 0.000 | 0.157 | 0.237 |
| StF | -0.757 | 0.000 | -0.537 | 0.000 | -0.070 | 0.564 | -0.172 | 0.194 |
| MeV | -0.842 | 0.000 | -0.491 | 0.000 | 0.217 | 0.069 | 0.197 | 0.135 |
| StV | -0.584 | 0.000 | -0.373 | 0.003 | 0.372 | 0.001 | 0.067 | 0.612 |
| Dir | 0.705 | 0.000 | 0.409 | 0.001 | 0.454 | 0.000 | 0.434 | 0.001 |

Table 2. Pearson Correlation and partial correlation results for mSVF and urban geometry variables.

140x108mm (300 x 300 DPI)

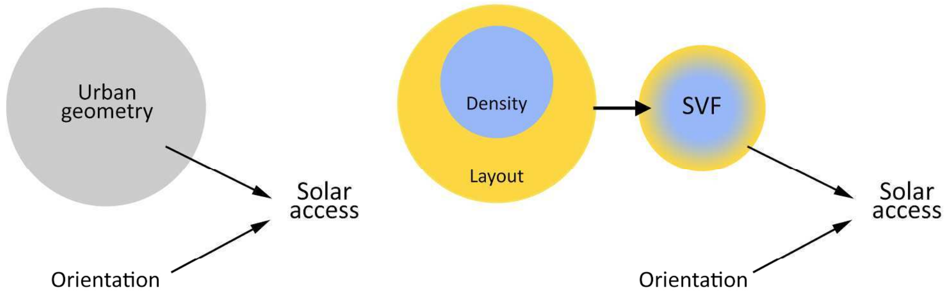



Figure 1. Theoretical schema depicting the methodological approach.

209x75mm (300 x 300 DPI)


Figure 2. DEMs of three areas in London, divided into cells of 500x500m; 72 urban forms included in the analysis (28 in central, 25 in west and 19 in north London) highlighted in red.

330x379mm (300 x 300 DPI)

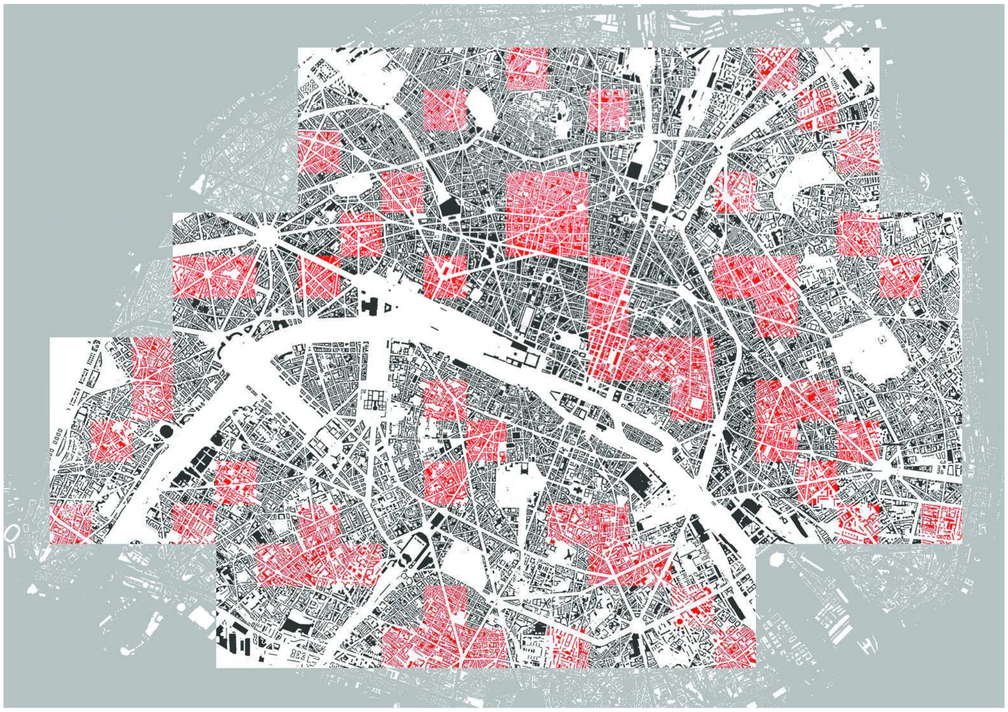
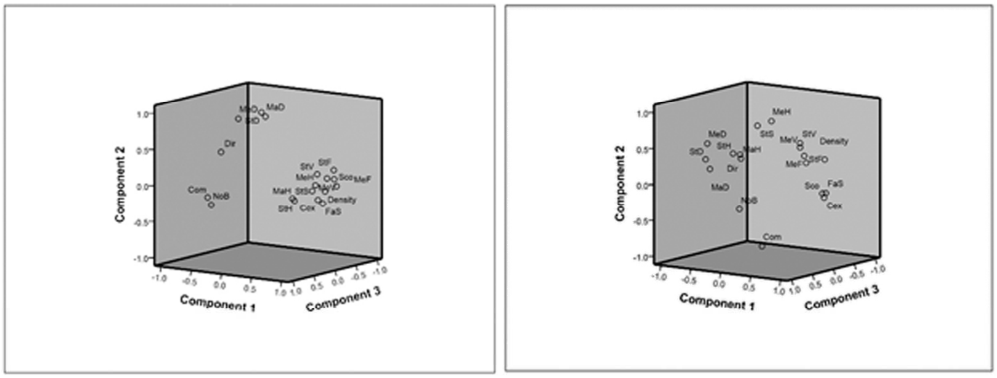


Figure 3. DEM of Paris: analysed area on white background, and 60 selected urban forms highlighted in red.

170x119mm (300 x 300 DPI)




(a) London (b) Paris

Figure 4. 3D plot of Principal Component Analysis results conducted for 18 urban geometry variables in the two cities.

158x65mm (300 x 300 DPI)

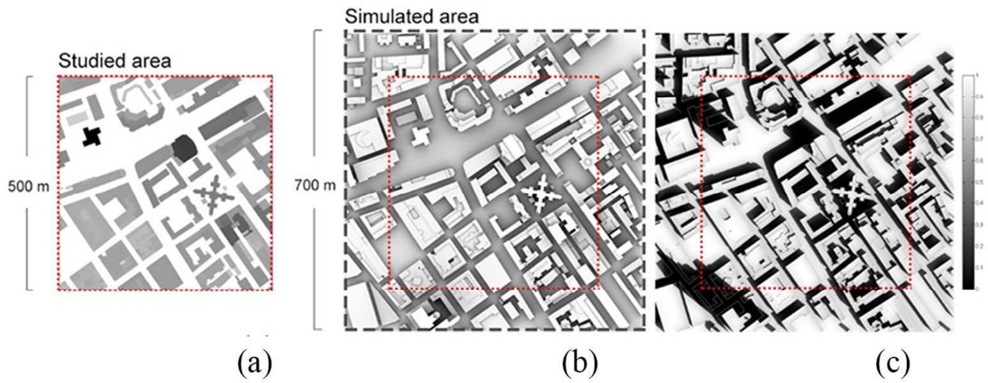
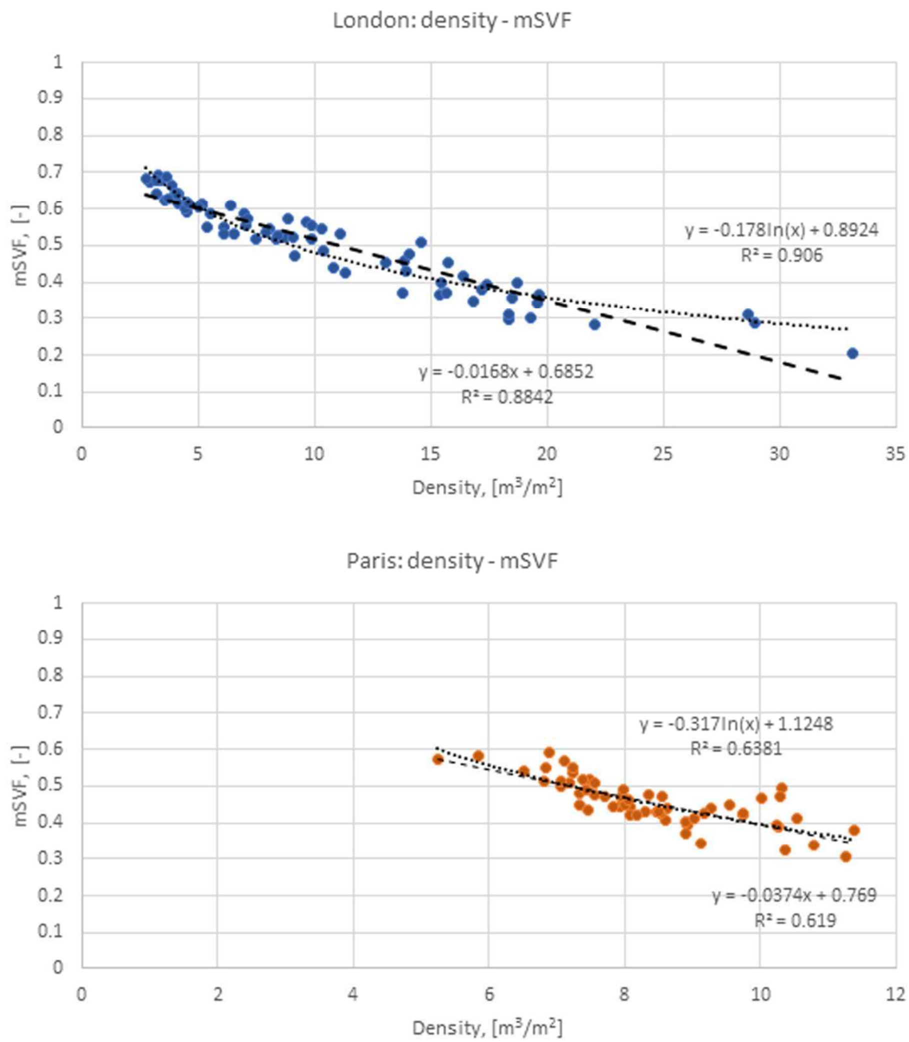



Figure 5. Example of an urban form in central London: a) DEM, b) SVF map, c) shadow pattern at 9 a.m. on 23 April.

129x50mm (300 x 300 DPI)




(a)

(b)

Figure 6. Scatter plots of mSVF against density values for London (a), and Paris (b).

125x134mm (300 x 300 DPI)

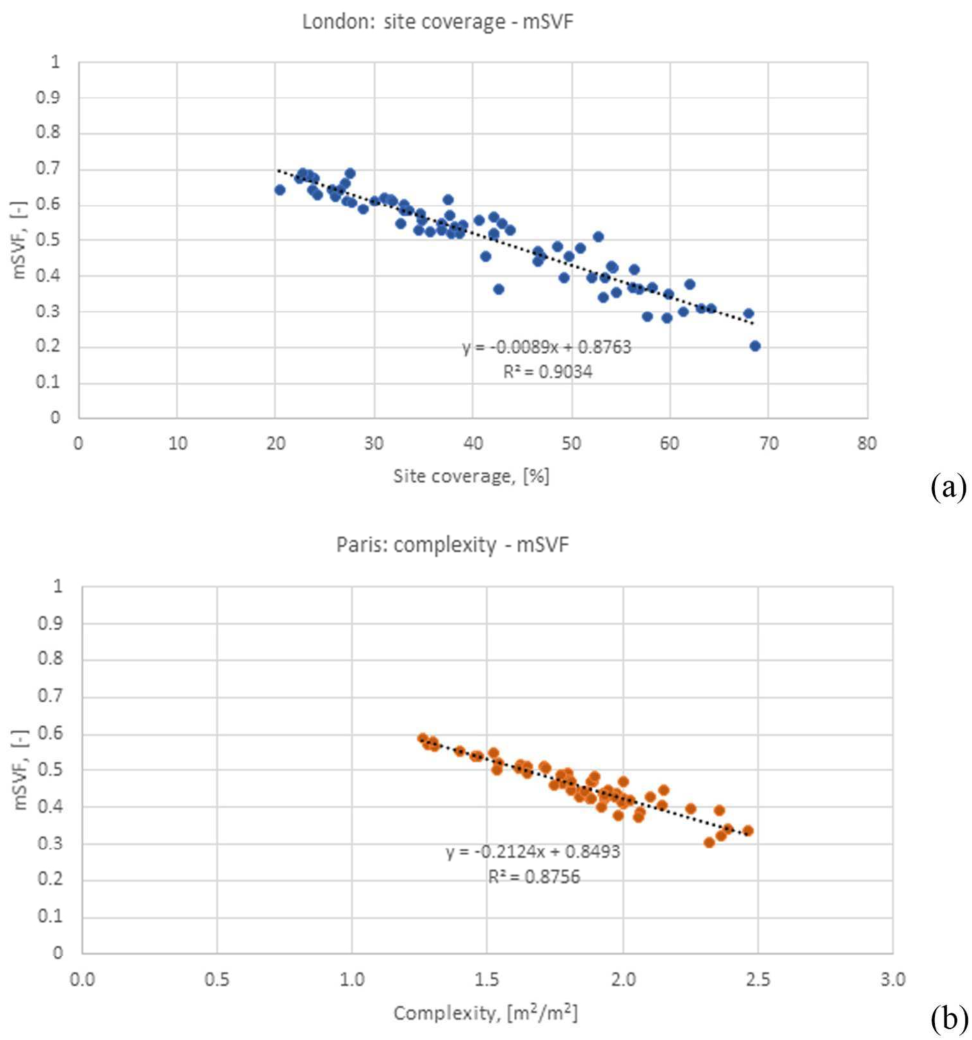



Figure 7. Correlation of mSVF with strongest urban geometry variables, *site coverage* for London (a) and *complexity* for Paris (b).

125x134mm (300 x 300 DPI)

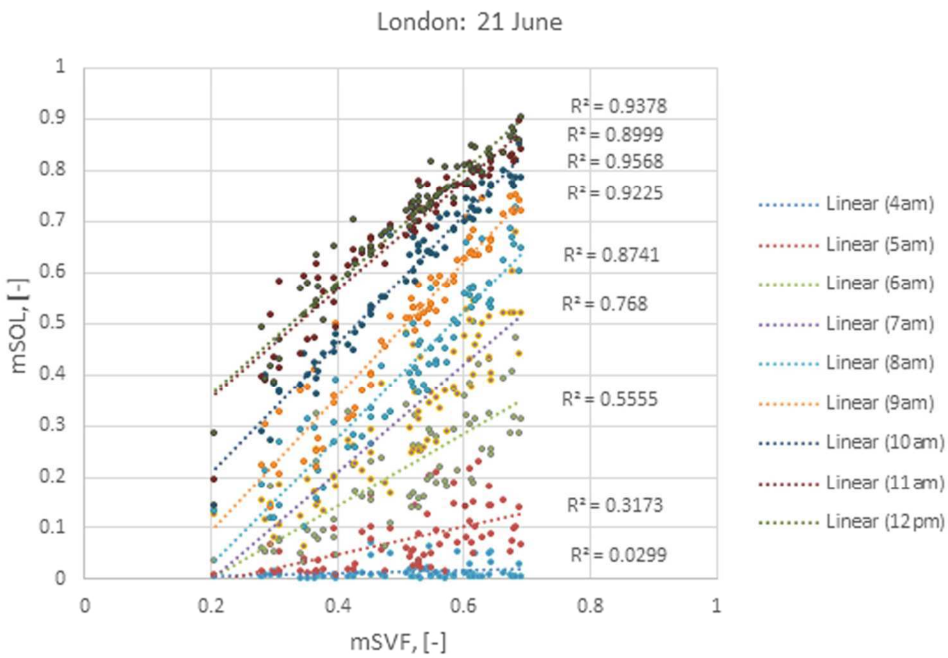



Figure 8. For London, instantaneous mSOL plotted against mSVF values for representative hours, from sunrise to midday, on 21 June; and $R^2$ derived by linear regression.

119x83mm (300 x 300 DPI)

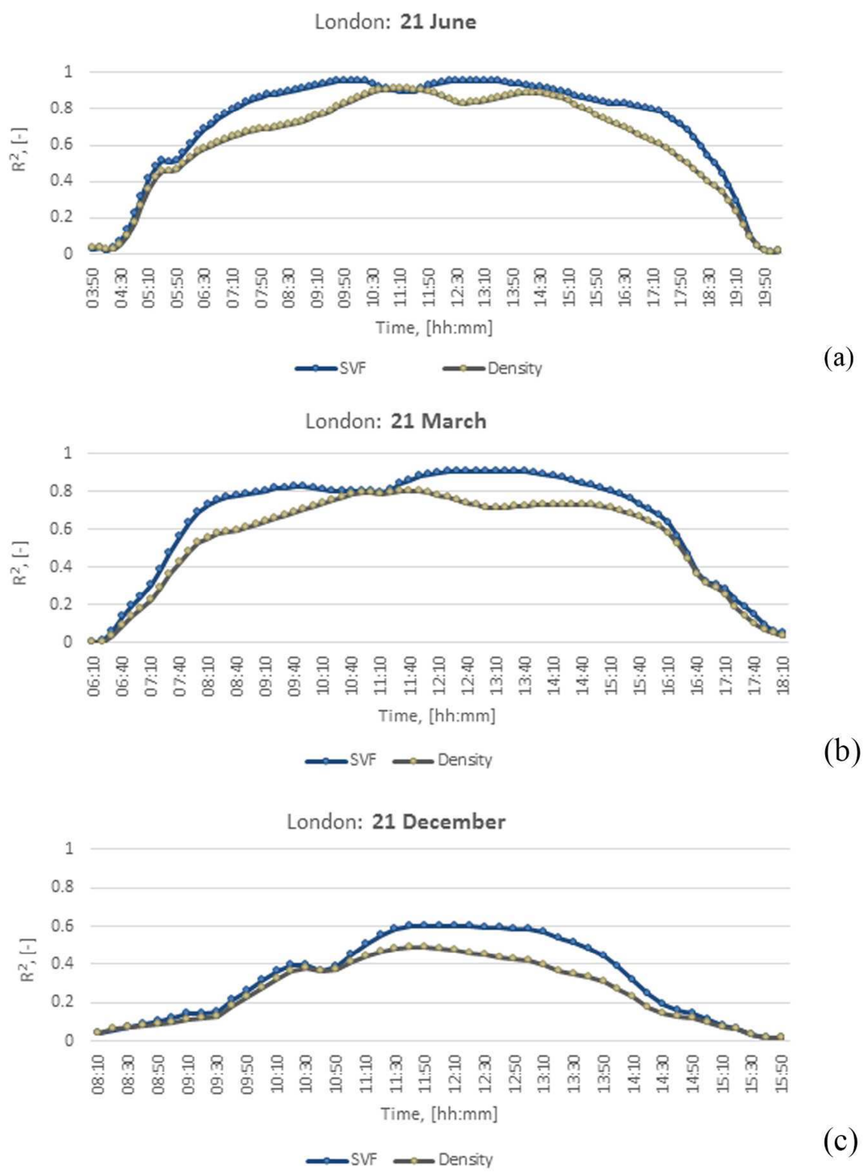



Figure 9. Variations of $R^2$ describing the strength of the linear relationship of instantaneous mSOL with mSVF and density, on three representative days, for London.

134x182mm (300 x 300 DPI)

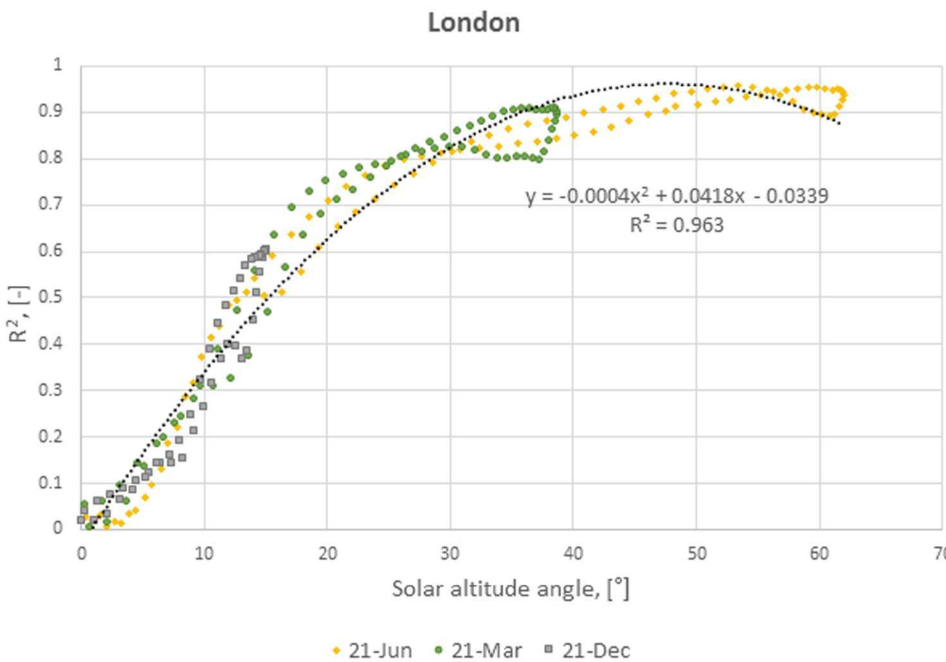



Figure 10. Combining all $R^2$ for the linear relationship of mSVF with instantaneous mSOL on three days, plotted against solar altitude angle, for London.

140x97mm (300 x 300 DPI)

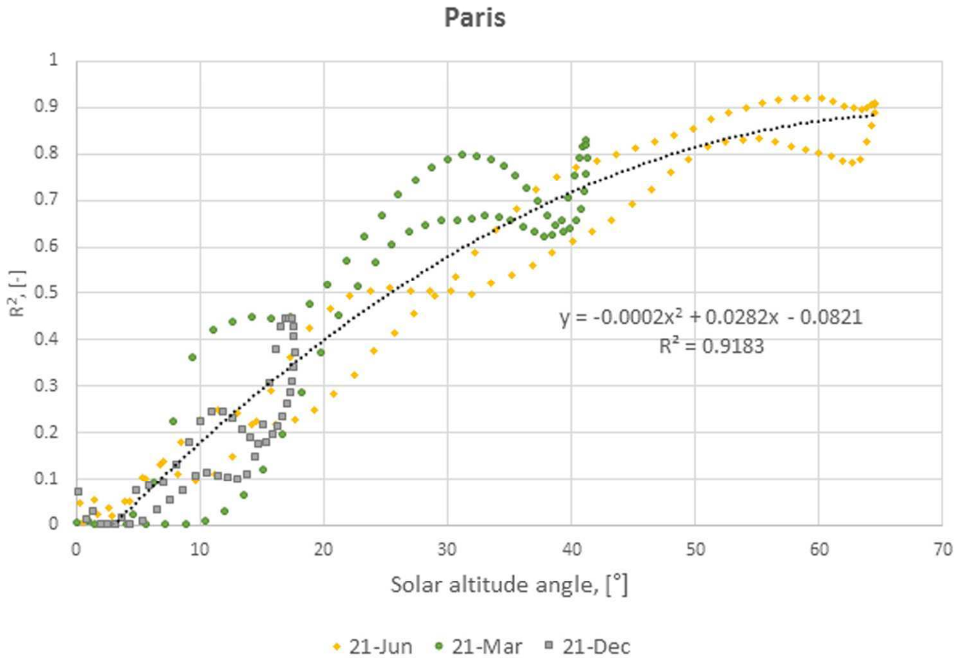



Figure 10. Combining all $R^2$ for the linear relationship of mSVF with instantaneous mSOL on three days, plotted against solar altitude angle, for Paris.

140x97mm (300 x 300 DPI)

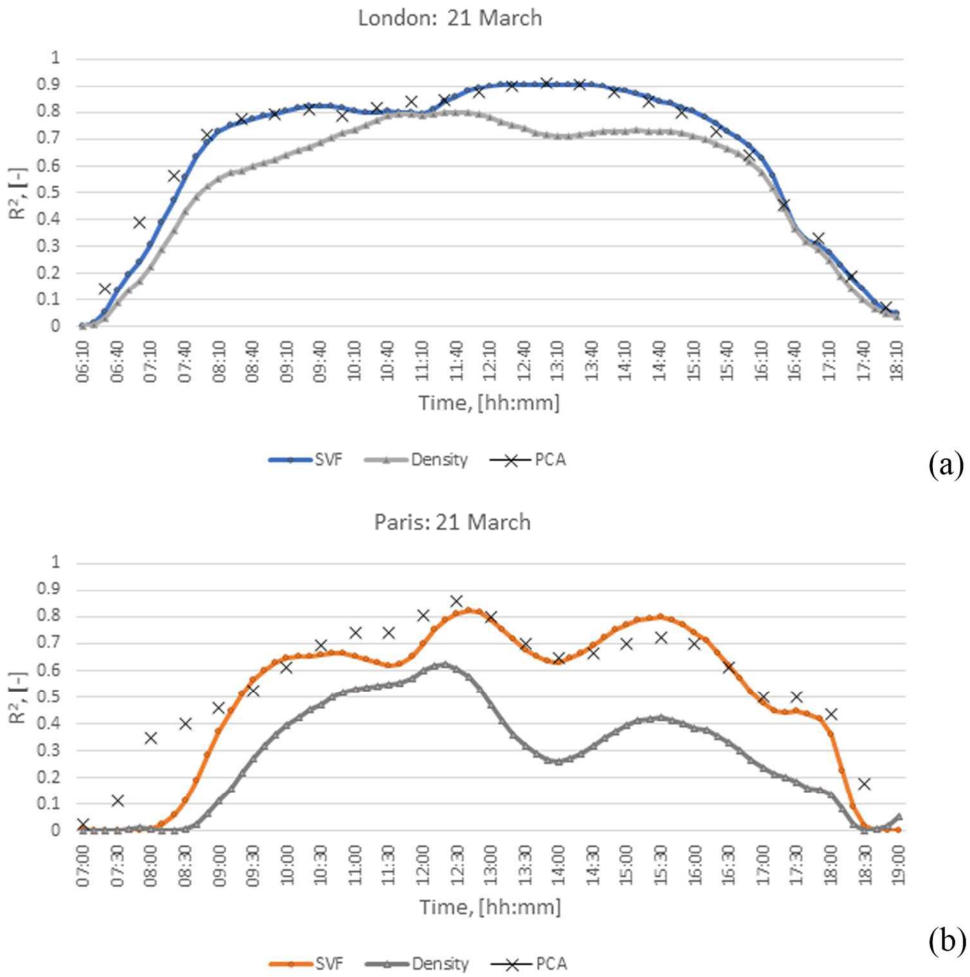



Figure 12. Variations of $R^2$ describing the strength of the linear relationship of instantaneous mSOL with mSVF, density and PCA factors, on 21 March, for London (a) and Paris (b).

126x127mm (300 x 300 DPI)

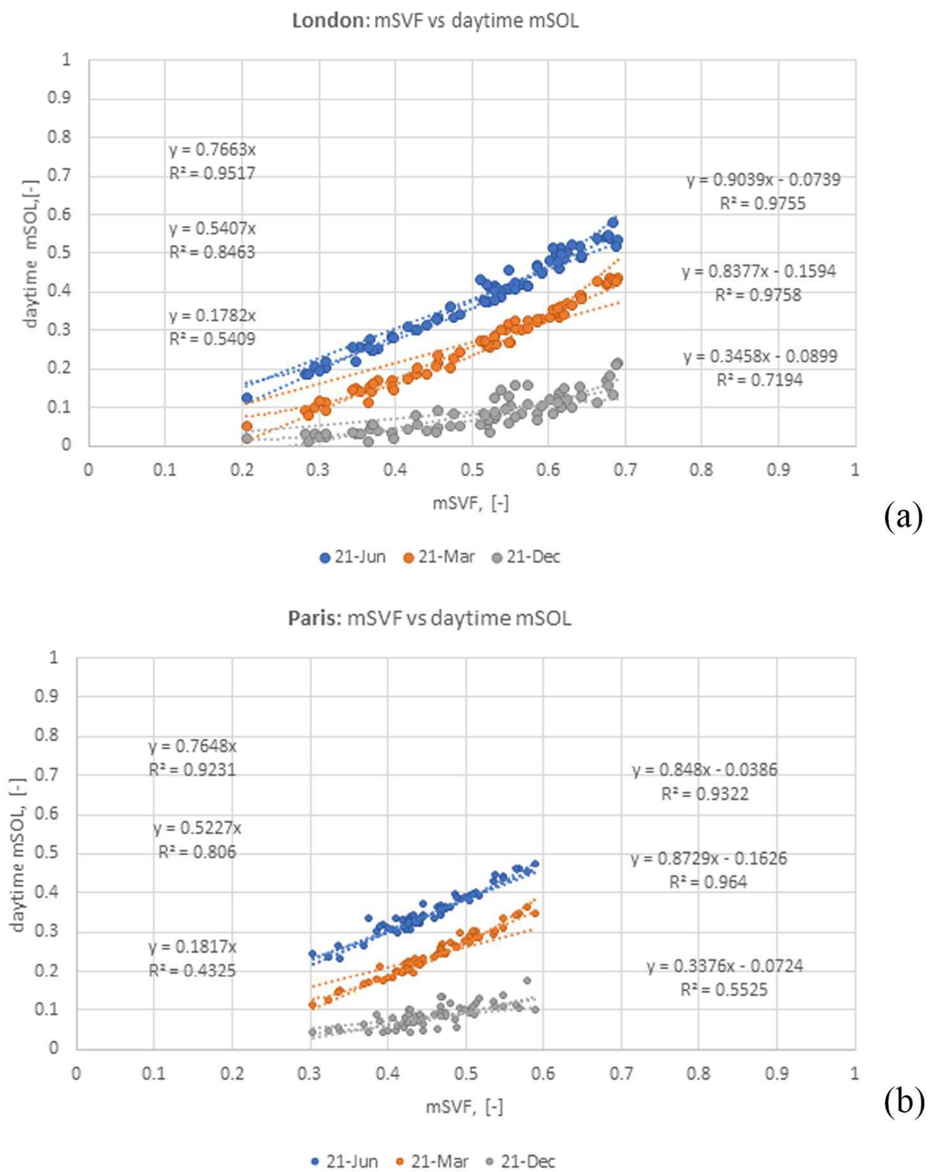



Figure 13: Daytime mSOL values for London (a) and Paris (b), on three representative days, plotted against mSVF. Linear models when intercept is free (right), and set to zero (left).

110x140mm (300 x 300 DPI)

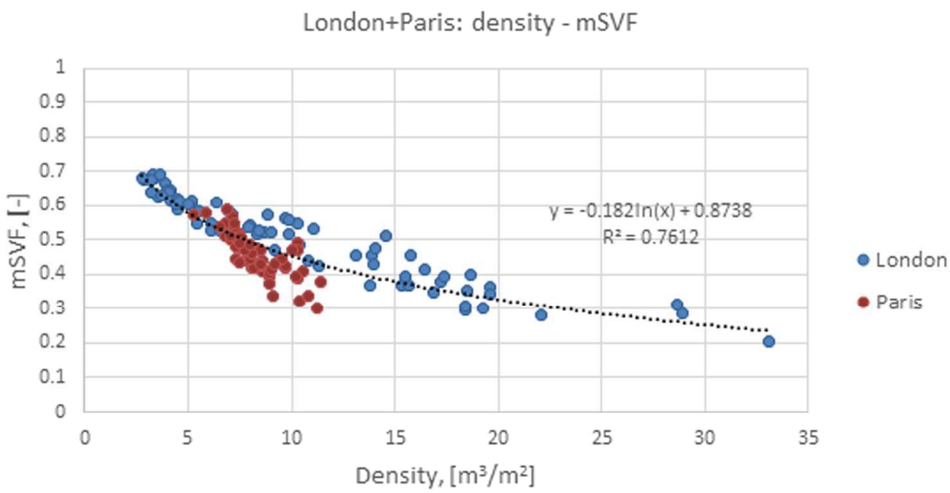



Figure 14. Scatter plots combining mSVF and density values in London and Paris.

119x63mm (300 x 300 DPI)

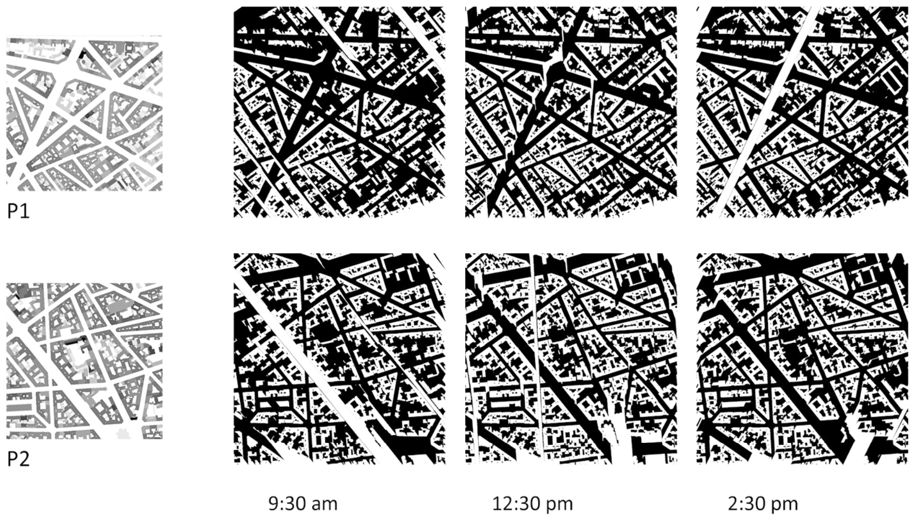



Figure 15. Two urban forms in Paris exemplifying the increased effect of orientation due to the presence of boulevards: shadow patterns on 21 December at different times.

165x94mm (300 x 300 DPI)