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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

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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; while 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.

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 their microclimate and, in turn, their use (Littlefair, 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

* Corresponding author.
E-mail address: C.Chatzipoulka@kent.ac.uk (C. Chatzipoulka).

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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 and Sattrup, 2011) and, urban microclimate and outdoor thermal comfort (e.g. Ali-Toudert and 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 and Krainer, 2001; Lu and 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 and 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 and Shakespeare, 1998), including CBDM (Mardaljevic, 2010), DIVA (Jakubiec and 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., 2012). 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 and 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