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To cite this article: Ahmed Hazem Mahmoud Eldesoky *et al* 2019 *J. Phys.: Conf. Ser.* **1343** 012015

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An integrated, agile approach for estimating solar radiation on building facades in complex urban environments

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Abstract. Urban solar radiation is a primary factor affecting indoor and outdoor thermal and lighting comfort. However, although 3D solar radiation models are achieving remarkable advances in urban climate planning support and decision making, they are time-consuming and cost-intensive. We aim at compensating for such limitations by providing an agile approach to estimate shadows and solar radiation on building facades, using elevation models (2.5D) and image processing techniques. This is achieved by making the best use of the new visibility toolset for raster processing, provided in ArcGIS, and GRASS GIS solar radiation 2D model. Results give a clear and detailed picture of the radiation condition in the study area, which offers promising opportunities for urban solar planning and assessment in complex urban areas.

1. Introduction

In urban areas, solar radiation is a key factor affecting indoor and outdoor human thermal and lighting comfort. This depends mainly on urban geometry and the building envelope design and its materials in terms of thermal properties. On the one hand, one of the major energy gains in buildings is the solar radiation leaking through the building opaque and transparent parts, increasing the indoor temperature [1]. On the other hand, the low albedo of envelope materials causes the release of a considerable amount of heat back into the atmosphere during the night, which contributes to a nocturnal urban heat island effect (UHI) and causes pedestrian discomfort [2]. The question then arises: Can architects and planners be better informed about urban materials implications (as major determinants for the nocturnal UHI as well as the overheating in buildings)?

Over the last two decades solar radiation and shadow models, incorporated into geographical information systems (GIS), have achieved remarkable advances in processing large urban areas with complex morphology [3,4]. In 2015, Freitas *et al.* published a full and comprehensive review for the literature of solar radiation tools and models that simulate the solar potential either at the micro-scale of architecture or at the local and macro-scale of urban areas [5].

In general, one can distinguish between two main groups of 3D (raster-based) solar radiation and shadow models based on their output quality and precision. In the first group, which we refer to as 'intermediate models', it is possible to determine the shadows and the solar potential on a whole facade vertical section for any time frame. For example, to calculate the solar radiation on building facades at a specific time, Carneiro *et al.* used astronomical formulae and a subroutine to slice a Digital Surface Model (DSM) at different floor levels (every 3 meters) and identify at which height vertical pixels are



sunlit (Figure 1a) [6]. Similarly, Redweik *et al.* have applied solar formulae [7] and developed an algorithm to determine facade shadows based on the shadow line projected on the horizontal plane behind an obstacle (Figure 1b) [8]. The second group encompasses those models that provide very detailed, but cost-intensive and time-consuming, 3D solar simulations, mainly for assessing the local photovoltaic (PV) potential or solar energy systems on buildings. In particular, the rise of these models has followed the introduction of the concept of facade “hyperpoints” (Figure 1d) [9], where every point at any facade could be better analyzed in terms of solar potential at different time periods. Since then, the approach has been widely employed and developed in further studies to improve the overall capacity and efficiency of the solar radiation model [10,11].

In fact, while it seems like a typical time, cost, and quality trade-off issue, it is worth highlighting that in some cases, based on the phenomenon under investigation, it may be desirable to go for less sophisticated models. For instance, although intermediate models are relatively less detailed compared to the more sophisticated ones, their outputs are adequate and satisfying; they can still provide holistic understandings about the overall energetic performance and environmental quality of urban fabrics.

In this paper, we present an integrated, agile GIS-based approach to improve the efficacy of 3D intermediate solar radiation models, to work in very dense and complex urban areas. In particular, we use visibility analysis (in this case meant as the visibility to an emulated sun source; Figure 1c) to estimate the solar radiation on building facades using 2.5D models (i.e. with height information assigned to the 2D surface) and image processing techniques.

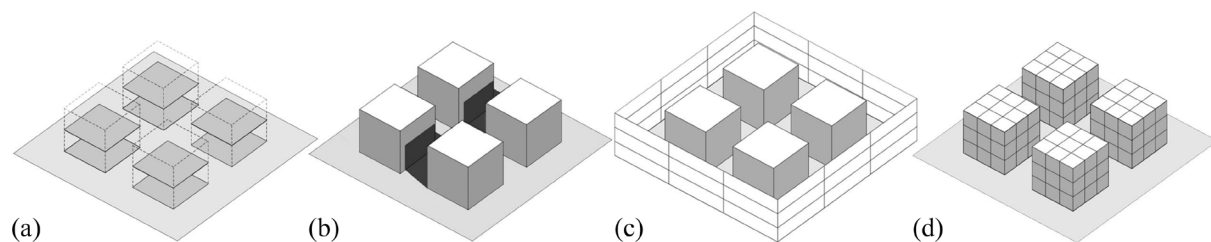


Figure 1. Approaches in urban solar radiation modelling. Intermediate models: (a) Slicing the 2.5D model, (b) Maximum shadow length, (c) Emulated sunspot; and (d): Facade *hyperpoints*.

The main goal is to support urban climate planning and policy making at the local scale, especially in cities that are still limited to the use of a 2D digital topographic database (DTDB) or where recent meteorological information is not available. It is also worth mentioning that it is not our main objective at this level of investigation to develop a subroutine nor a software plugin. Rather, we aim at introducing a theoretical framework that could be incorporated into a GIS platform in future work.

2. Test dataset

Since the aim of this paper is to introduce an intermediate effective assessment for the solar radiation on building facades at the micro and local scale, using 2.5D models and image processing techniques, we tested this approach in a compact squared area of 450 meters wide in central Milan, Italy, where a 1m Digital Elevation Model (DEM) was retrieved from the vector database of building footprints.

3. Method

Global solar irradiance/irradiation (measured in Wm^{-2} or Whm^{-2}) falling on the earth surface relies on three main components [4], i.e. the beam (direct from the sun), the diffuse (from the sky), and the reflected (from the ground). However, considering the reflected component is only a small part [4], in this paper, we address the calculation of the beam radiation in particular, because it is considered the most problematic, time-consuming, and complex procedure in urban solar radiation modelling [5], while we adopt a simplified method to approximately calculate the diffuse component.

Two pieces of information are essential to calculate the global (beam and diffuse) solar radiation (measured in W or Wh) on facade vertical sections at a given time and a certain geographical location; these are the height [m] or the area [m^2] of the sunlit surface (the surface exposed to the sun) and the

solar instantaneous energy [Wm^{-2}] (on the facade top and ground points). In order to estimate the global solar radiation on building facades, an effective model that takes advantage of the visibility toolset in ArcGIS, GRASS GIS *r.sun* model, and other image processing tools was designed (Figure 2).

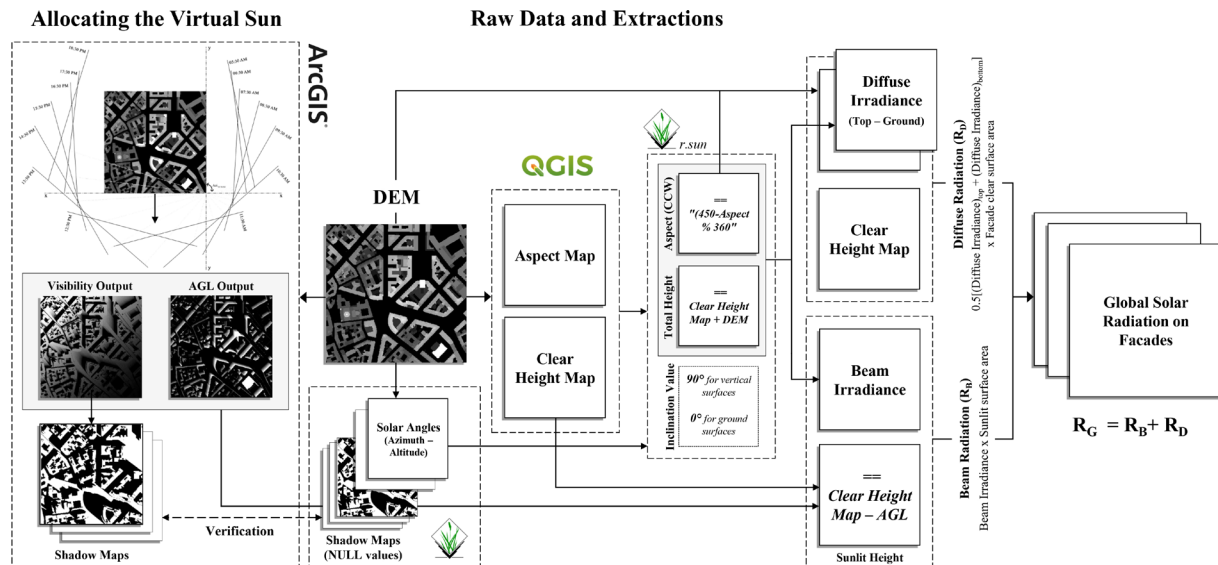


Figure 2. Model workflow for the calculation of the global solar radiation on building facades.

3.1. Calculating facades sunlit height using the visibility toolset (ArcGIS)

In the visibility toolset (ArcGIS 10.3), it is possible to determine the visible pixels, belonging to a 2.5D model, from a given set of observers. Additionally, the optional output ‘above-ground-level’ (AGL) raster gives the extra height required to make invisible pixels visible to at least one observer. Hence, the hypothesis (graphically displayed in Figure 3a) is that at the micro/local scale (A), within the extents (E) of the study area, a virtual sun (as a source of beam and diffuse radiations) could be simulated as a vertical plane surface (S) that composes vertical observer lines (L), allocated along evenly distributed distances (d), and where observer points or voxels (v), representing the sun light source (where θ is the sun altitude angle), are deployed along each of these observer lines at equal distances (z) until reaching the ground level of the DEM. Accordingly, by employing these sun voxels as ‘input observer point features’ in a visibility analysis, where the DEM is the ‘input surface raster’, we can ensure the additional height that makes invisible pixels visible to at least one voxel. The height of the sunlit surface at each facade pixel in the DEM is then calculated by subtracting the obtained AGL values, at facade ground points, from the facade clear height (from the neighboring surfaces) as shown in Figure 3b.

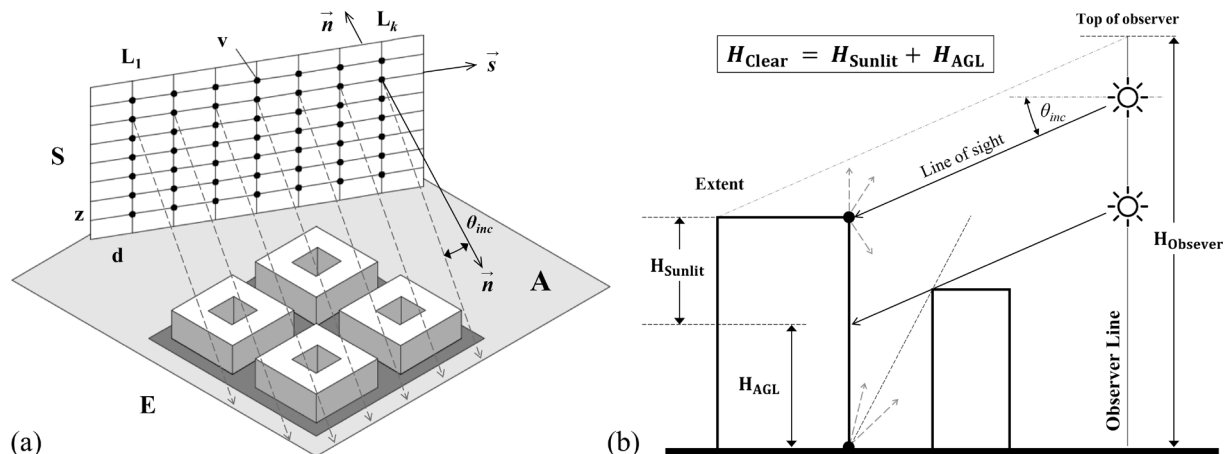


Figure 3. (a) The virtual sun hypothesis and parameters; (b) The determination of the sunlit height.

Besides, the new Viewshed 2 tool (visibility toolset) utilizes the graphics processing unit (GPU), which further speeds up the computation process. The GPU is efficient in performing parallel computations [12], which makes the process of determining facade shadows much faster than a standard shadow algorithm, where for each pixel (or hyperpoint) of the DSM, the algorithm applies an iterative search for an obstacle in the direction of the sun using a *matrix approach* [13]. In a study to estimate solar energy potentials on building roofs using a GPU-accelerated solar radiation model, it was demonstrated that the GPU can reduce the computation time up to 46% [14].

Two steps were required before and after running the visibility analysis. First, a pre-processing to create an emulated sunspot is undertaken, then, a post-processing step is provided to calculate the clear height [m] or the area [m²] of the sunlit surface(s) of the built environment at a given day and time.

3.1.1. Creating an emulated sunspot. Sun position at a specific time and a certain geographical location can be defined by knowing two parameters, described as azimuth and altitude angles. However, there are several methods to calculate the solar angles. In this approach, the solar position information used in the solar irradiance and irradiation model *r.sun* (GRASS GIS) was retrieved for each sunshine hour of August 4, 2017 (the warmest day of the year as recorded by the weather station in central Milan). Afterwards, to create the virtual position of the sun, further geoprocessing in ArcGIS was required to locate (horizontally and vertically) each of the voxels (v) along the sun virtual plane surface (S), referred to above in Figure 3a. At the end, for each sunshine hour, a line shapefile (along which vertices were deployed equally at 1m) was created within the horizontal extents of the DEM and replicated a number of times (n). The number of times is equal to the height at which the line of sight, at the top of each observer line, is within the vertical extents of the DEM (see Figure 3b). A progressive value (0-n) was assigned to each of the replicated lines resembling its progressive elevation from the ground of the DEM.

3.1.2. Running the visibility analysis. After having created the emulated sunspot, we customized the parameters that control the visibility analysis in the Viewshed 2 tool so as to integrate the emulated sun line-shapefiles as ‘input observer line features’ (where every vertex along a line-shapefile works as an observer point feature) and the DEM as the ‘input surface raster’. The analysis was repeated for the sunshine duration over the whole day (on an hourly basis), and the results are shown in Figure 4.

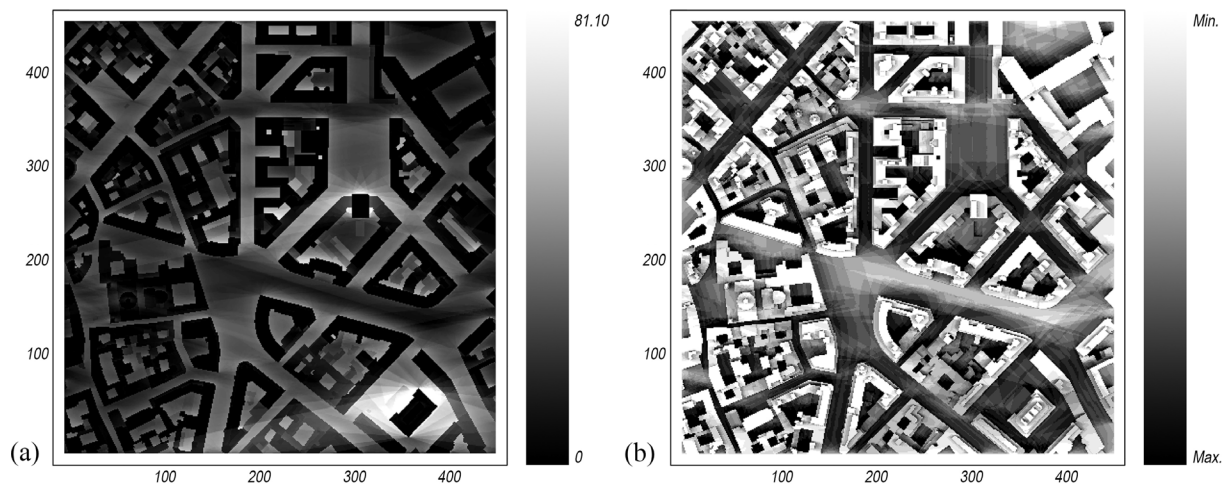


Figure 4. The output of the visibility analysis in ArcGIS. (a) The mean AGL values [m]; (b) The mean shadow intensity on August 4, 2017.

To verify the effectiveness of the proposed methodology in creating an emulated sunspot, the covariance and correlation matrices, in ArcGIS, were computed twice for several shadow raster maps (generated automatically in GRASS GIS *r.sun* model and through the output of the visibility analysis in ArcGIS) to check their level of similarity. The results demonstrated a very strong correlation (0.965 – 0.979).

Finally, a filter (Wall Height and Aspect) [11] in QGIS was applied to the DEM to identify the facade pixels and their clear height (from the neighboring surfaces), and the height of the sunlit surface at each facade pixel of the DEM was calculated as follows:

$$H_S = H_C - H_{AGL} \quad (1)$$

where H_S is the height [m] of the sunlit surface, H_C is the clear height [m] of each facade pixel, and H_{AGL} is the additional above ground level height [m] at the facade ground point/pixel. The facade was considered completely shadowed if ($H_{AGL} \geq H_C$).

3.2. Estimating the beam and the diffuse solar irradiances using the *r.sun* model (GRASS GIS)

Estimating the beam and the diffuse irradiances [Wm^{-2}] on inclined planes (slope = 90°) is the secondary component in calculating the global solar radiation on facade vertical sections. In this regard, the *r.sun* open source model in GRASS GIS was chosen among others for its flexibility and effectiveness for processing large urban areas with complex morphology, under clear and overcast sky conditions [4]. Accordingly, the beam irradiance [Wm^{-2}] on the top of each facade and the mean diffuse irradiance [Wm^{-2}] (on the bottom and the top of the facade) were calculated using, as input parameters, the facade total height from ground raster map and both the DEM and the facade total height map respectively.

3.3. Estimating the global solar radiation on building facades

As discussed earlier, global solar radiation could be estimated as the sum of its beam and diffuse components (considering that the reflected component is negligible). Therefore, the beam and diffuse solar radiations on each facade vertical section (1m wide) of the study area were calculated for each sunshine hour based on equations (2) and (3):

$$R_B = B_T * A_S \quad (2)$$

where R_B is the beam solar radiation [W], B_T is beam irradiance [Wm^{-2}] on the top of the facade, and A_S is the area [m^2] of the sunlit surface.

$$R_D = \left(\frac{D_T + D_G}{2} \right) A_C \quad (3)$$

where R_D is the diffuse solar radiation [W], D_T and D_G are the diffuse irradiances [Wm^{-2}] on the facade top and ground points respectively, and A_C is the facade clear surface area [m^2].

Finally, the total (daily accumulated) global solar radiation on each facade vertical section (1m wide) of the study area was calculated for August 4, 2017 (at a one-hour interval) using the following formula:

$$R_G = \sum_k^n (R_B + R_D)_k \quad (4)$$

where R_G is the total global solar radiation [Wh], k is the sun rise hour, and n is the number of sunshine hours. The output results are shown and discussed in the next section.

4. Results and discussion

The main outputs of this approach are several raster maps showing the solar radiation, on each facade pixel, for any instant or period of time. Looking more closely, Figure 5a shows that the site undergoes a significant variation of the total daily accumulated solar radiation. In particular, there is a necessity to reconsider the glazing ratio of some facades (that have accumulated considerable amount of heat during the day), to better optimize the energy gains in the indoor space, as well as to improve the outdoor thermal comfort at street level. Also, other information could be retrieved to understand the overall energetic and environmental performance of the whole site. For example, the diffuse radiation was found to share almost half of the total global solar radiation received by all the facades of the study area (around 47%). This gives rise to the notion of the possibility of building more compact urban fabrics without affecting the environmental quality (e.g. indoor natural light), especially in hot climates.

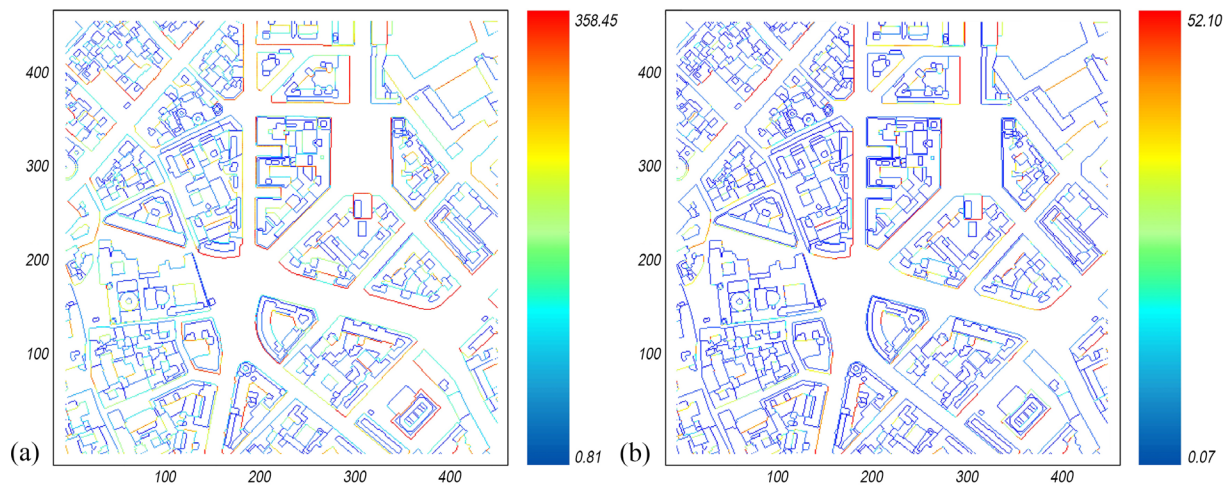


Figure 5. (a) The total (daily accumulated) global solar radiation [kWh] on August 4, 2017; (b) The global solar radiation [kW] on August 4, 2017 10:30 AM, on each facade vertical section (1m wide).

The accuracy of the results depends mainly on the quality of the input database. Thus, considering that the input DEM was retrieved from a vector database, it has been assumed that the built environment is in a simple form, where exterior landscape shading elements do not exist (e.g. trees), and building outlines in the DTDB resemble the roof edges (no balconies or canopies, overhangs or vertical fins, etc.).

5. Conclusions

In this paper we have discussed the development of an agile theoretical approach to estimate solar radiation on building facades using 2.5D models and GIS techniques. The effectiveness of this approach is twofold: making it possible to process dense urban areas with complex morphology efficiently, using parallelized computations, while at the same time maintaining a fewer, constant number of sightlines to determine facade shadows. Moreover, the level of detail of the output maps gives a clear and detailed picture of the radiation condition of the whole study area, which makes the approach very promising for urban solar planning and assessment in very compact urban environments. It would be of interest, in further similar-scale work, to consider the reflected component of the solar radiation and better model the diffuse one. Also, observed hourly meteorological data and higher quality 2.5D models (e.g. LIDAR-derived-DSM) could be utilized to improve the overall accuracy of the output results.

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