Implementation of a solar model and shadow plotting in the context of a 2D GIS: challenges and applications for the cooling effect of tree-covered based greening solutions in urban public spaces

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[ISBN : 978-2-910545-12-1]

Implementation of a solar model and shadow plotting in the context of a 2D GIS: challenges and applications for the cooling effect of tree-covered based greening solutions in urban public spaces

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RESUME. L'adaptation des espaces publics aux épisodes de chaleur intense est désormais un défi majeur pour la ville. Dans cette optique, cet article présente une contribution qui vise à délimiter et à traiter l'ombre au sol, qu'elle provienne des bâtiments ou du couvert arboré. Après une comparaison aux tracés des ombres obtenues via deux outils de référence, nous présentons un site urbain qui mélange des ombres d'origines différentes ainsi que divers indicateurs. L'objectif est ici d'aider les concepteurs urbains à trouver des solutions permettant de distinguer les contributions respectives des ombres, leur évolution annuelle et les éventuelles continuités d'ombres spatiales ou temporelles.

ABSTRACT. The adaptation of public spaces to episodes of intense heat is now a major challenge for the city. With this in mind, this article presents a contribution aimed at delineating and handling the ground shadow, whether it comes from buildings or from the tree canopy. After a comparison with shadows obtained via two reference tools, we present a real urban site that mixes shadows of different origins and, in addition, different indicators. The aim of these indicators is to assist urban designers with solutions that make it possible to distinguish the respective shadow contributions, their annual evolution and potential spatial or temporal continuities.

MOTS-CLES : carte des ombres, ombre urbaine, ombre du couvert arboré, microclimat urbain, conception basée sur l'ombre

KEYWORDS: shade map, urban shade, tree canopy shade, urban microclimate, shade-based design

1. Introduction

The urban heat island (UHI)[1] phenomenon (Sobstyl et al., 2018) is a bioclimatic response specific to compact high-rise urban districts, amplifies these overheating, exposes populations to high health risks, and significantly alters living conditions in the built environment (Davis and Gertler, 2015). Both climate and demographic pressures constraint decision-makers to organise urban lifestyles according to mitigation and adaptation strategies, which nowadays focus on how to cool down the urban space in short and mid-term.

(Aram et al., 2019) consider four groups of urban cooling strategies: i) vegetative cover, ii) stack night ventilation, iii) water bodies and iv) modification of surface albedos. (Ruefenacht and Acero, 2017) highlight the relevance of shading as a "key measure to improve Outdoor Thermal Comfort (OTC) and mitigate UHI because it leads to the reduction of air and surface temperature and can therefore result in cooling benefits". In this regard, (Middel et al., 2016) enhance "the importance of solar access active management". Considering outdoor air temperature difficult to control, (Aleksandrowicz et al., 2020) observe that sunlight exposure in streets is easier to regulate since it is directly linked to design decisions; therefore, they consider "outdoor shade as a primary comfort indicator".

We argue that a tool developed in the context of a standard GIS (based on shade index, tree canopy cover, etc.) can help in quantifying the microclimatic qualities of urban spaces revealing, for instance, sunlighted areas requiring shade intensification or, conversely, strategic shaded areas that deserve to be protected. The strictly geometric aspects of shading is essential in answering simple questions like: where are located the "shadow fences"[2] generated by the urban environment at a given date and time? What is the fraction of space, for a predefined study area - which is in shadow for a given date and time? What is the tree canopy contribution to the total shade cover? What is the evolution of this contribution over the summer period, the crown remaining unchanged? What areas are shaded for at least 3 hours on a hot summer day? Or even, to satisfy a constraint of temporal continuity, what areas are shaded for at least 3 consecutive hours on a hot summer day? Or even, do these areas guarantee spatial continuity in order to allow comfortable pedestrian mobility?

Simulation softwares such as Solene (Miguet and Groleau, 2002), Ladybug (Roudsari and Pak, 2013), UMEP-SOLWEIG (Lindberg et al., 2018) or ENVI-met[3], already allow shadow studies. Some of them (Solene and Ladybug) run as plugins of computer-aided design programs that do not offer the functionalities of GIS (power of synthesis of 2D maps, capacity to process large geographic areas, etc.) and require

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[1] As (Ruefenacht and Acero, 2017) summarizes: UHI "occurs because cities consume huge amounts of energy in electricity and fuel, have less vegetation to provide shade and cooling, and are built of materials that absorb and store energy from the sun".

[2] We borrow this expression from (Knowles, 2003) to underline the fact that shadowing can also, in itself, generate constraints useful to the urban planner during a design phase (in reference to the solar envelope concept).

[3] ENVI-met is a German trademark (No. 304 73 896), https://www.envi-met.com/

a particular expertise in architectural design. Therefore, their implementation by the geographic information departments of municipalities is difficult. In the contrary, UMEP-SOLWEIG has been embedded into a GIS. Nevertheless, they require digital surface and terrain models. In addition, the raster-based processes do not allow the shadow fences to be handled as simply as standard vector entities.

This article aims to highlight the interest of a specific vectorial development in a standard GIS to answer the questions mentioned above. After a presentation of the solar model and the treatment of mineral and vegetal shadows that we have implemented, we will present the mechanism for calculating multiple shadow overlaps. In the next section, we will highlight the interest of these developments in one case study of the Coolscapes research program. Finally, we will discuss the contributions of our tool to a microclimate sensitive urban space design.

2. Method

Two main principles guide our methodological development: replicability and transportability on the one hand, and ease of implementation on the other. To guarantee these two principles, we use standard topographic data sets such as the ones provided by the IGN BD TOPO® database (June 2020 edition) and a widely distributed free and open source software (QGIS Development Team, 2020). It is noteworthy that the presented method of shadow simulation and mapping is potentially applicable at larger scales, e.g. district or city scale.

2.1. 3D processing in the context of 2D GIS

The sun path geometry and the delineation of the cast shadow generated by buildings and tree canopies are intrinsically three-dimensional urban issues. Our aim is to identify shaded areas that allow the city dweller to cool down; therefore, we simply delimit these areas on a horizontal plane at a pedestrian level (in this case, we choose the ground plane). This simplifying hypothesis allows us, at the end of a 3D processing presented later on, to produce a classical 2D cartography in the context of a standard GIS.

2.2. Implementation of the sun path model

Pysolar and PyEphem are Python implementations of ephemerides that allow estimating the trajectories and positions of the sun over time. To ensure consistency with the laboratory's simulation tools, we have implemented the ephemeris model of the Solene software in the context of our GIS simulation. A systematic comparison of the positions returned by Pysolar with those of our simulation shows that the respective solar heights differ by less than 1% on annual average.

2.3. Shadow cast from a collection of right prisms

The topographic data sets employed here provide a 3D metric and vector description (structured in objects) of the elements of the territory and its infrastructures, usable on scales from 1:5,000 to 1:50,000. More precisely, this description consists in a set of polygons (sort of flat roof footprints) completed with an attribute equal to the height of the corresponding building. This twofold information allows us to generate a collection of right prisms each one representing a building in the urban model. The direction of the sun's beams being predetermined, it is then possible to i) calculate the ground shadow of each right prism, ii) and to proceed to a geometric union of all shadows.

2.4. Shadow cast from the tree canopies

Nantes Metropole's geographic information services provided us with a database of 75,156 trees in the conurbation. In addition to the point position of each trunk, this data includes various attributes such as the height of the tree, the circumference of the trunk, the species of the tree, etc. In the first version of tree modelling, we developed three different crown models: the first is spherical, the second cylindrical and the third conical. Based on the tree attributes and positions as well as the crown model and the sunbeam direction, we have then implemented a ground shadow model (the projection of a sphere being an ellipse for example). As in the case of the building shadows, at the end of the process we proceed to the geometric union of all tree shadows in order to deal with possible overlaps.

2.5. Management of shadow overlaps over several (consecutive) hours

To identify areas in the shade for several hours (possibly consecutively), we need to make multiple geometric intersections, the combinatory of which are potentially substantial (for example, being in the shade for 2 hours can be translated multiply: 10 am-11 am and 3 pm-4 pm, 1 pm-3 pm, etc.). To deal efficiently with this issue and bypass these numerous intersections, we proceed in three steps: i) geometric union (via the *unary_union* operator) of the shadow contours, ii) *polygonization* of the network of polylines thus produced, iii) for each polygon resulting from the *polygonization*, calculation of the number of enclosing shadow zones.

3. Case study and experimental setup

3.1. Case study: Graslin district in Nantes (France)

The study site is located in the centre of Nantes (France), including parts of the Graslin district. This area consists of 13.6 ha, 293 building footprints representing a total floor area of about 6.4 ha, and 98 trees. Its altimetry varies from 6 to 30 meters and the average height of the buildings is about 15.7 meters (with a standard deviation set at 5.8 meters). The explained method is applied to this site with a special interest in the urban garden called "Cours Cambronne". This classic French garden, lined with buildings and trees, covers about 0.9 ha and presents various shaded areas (from both surrounding buildings and 64 trees) that modify comfort indexes and citizens practices (i.e., sitting places and trajectories). It is roughly 180 metres long and 50 metres wide. It also has the advantage of crossing shadows from the tree cover (rows of trees) and the building environment, all on a relatively flat ground.

3.2. Experimental setup

In order to test our methodological proposal and respond to the research questions, we have defined several parameters as follows. Regarding the choice of representative dates and times for the annual sunshine simulation, we have chosen the 1st, 11th and 21st of each month. For each of these days, we have made a calculation with a hourly time step from 10 am to 4 pm. Regarding the choice of a representative summer day, we opted for July 21st. Regarding the tree modelling in this area, after empirical evaluation on site, we chose a cylindrical crown model with two distinct parameterizations. Eight trees in the Courtyard have a total height of 15 metres, a crown height of 10 metres and a crown radius equal to 5 metres. The rest of the trees are modelled with a total height of 9 metres, a crown height of 6 metres and a crown radius of 3 metres. It is noteworthy that although the trees in the area are deciduous, we do not consider the change in the crown due to seasonality.

4. Experimental verification

4.1. Comparison of shadows in the context of a CAAD software

The objective of this section is to use the solar model and the shadow engine implemented natively in the SketchUp software, to compare the shadows computed by the t4gpd plugin in the context of a GIS with those of a tool widely used by architectural practitioners. For that, we first import the building footprints and tree positions to build the corresponding 3D model using the SketchUp *pushpull* mechanism. We then import the shadow polygons produced by our simulations (through the SHP file format) and compare them visually to the shadows produced by the SketchUp shadow engine. Fig. 1 shows that these two shadow features match satisfactorily.

FIGURE *1. Comparison of the native SketchUp shadow features (in grey) with those from the t4gpd plugin (red polylines), on July 21 at 10 am UTC.*

4.2. Comparison with the Urban Multi-scale Environmental Predictor (UMEP)

As the verification proposed in the previous section is purely visual, we suggest comparing our simulation results with those of the UMEP reference tool. Indeed, the latter embeds the shadow generator plugin capable of generating shadow plots from building, ground or even vegetation digital surface models, in the QGIS context. In order to use UMEP's "Daily Shadow Pattern" functionality, we first had to generate a digital terrain model, a digital model of the built-up surfaces, and a raster model of the tree canopy. We used a metric precision raster model such as the one proposed by the IGN's RGE Alti® to stick as closely as possible to the building layouts. Fig. 2 shows the relatively good correlation of the raster shadows produced by UMEP with the vector traces from our simulations.

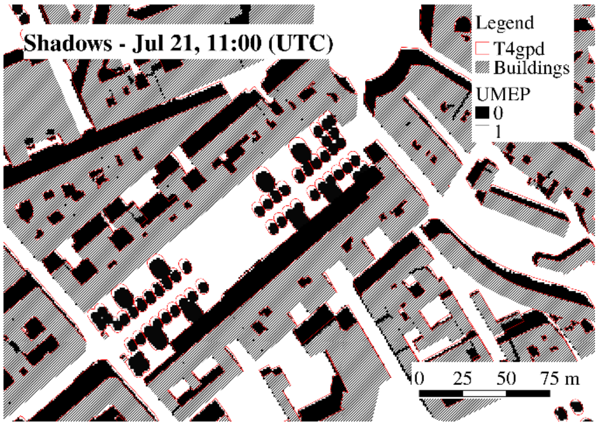

FIGURE 2. Comparison of the shadows from the UMEP Shadow generator (black pixels) with those from the t4gpd plugin (red polylines).

To go beyond this visual comparison, we measured the shadow-covered areas respectively produced by UMEP and our simulation tool at different times on 21st July. Table 1 shows variations ranging from 0.1% to 5.2%. Although this comparative analysis does not formally validate our simulation tool, it reinforces our ability to produce consistent results with the UMEP reference tool.

TABLE *1. Comparison of shadow-covered area measurements (in m²) assessed via the UMEP software vs. via the t4gpd plugin, on July 21st.*

	10 am	11 am	12 am	1 pm	2 pm	3 pm
UMEP	35,498.6	29,062.9	27,838.8	27,677.2	28,900.2	36,852.8
T4gpd	33,694.2	29,093.6	28,036.8	27,533.8	28,560.2	36,161.6
Deviation	5.2 %	0.1 %	0.7 %	5.2 %	1.2 %	1.9 %

5. Application to the French study site: Cours Cambronne (Nantes)

5.1. Shade ratios

5.1.1. Shade ratio at a given date and time

The first very simple application consists, in delineating the ground shadow due to the tree canopy and the built environment for a given territory, date and time. On 21 July at 12 am (UTC), the 293 buildings and 98 trees in the study site thus produce a ground shade of approximately 2.8 ha, i.e. approximately 20% of the total area. Furthermore, as shown in Fig. 3 (left), few streets oriented almost orthogonal to the sun's beams benefit from shade.

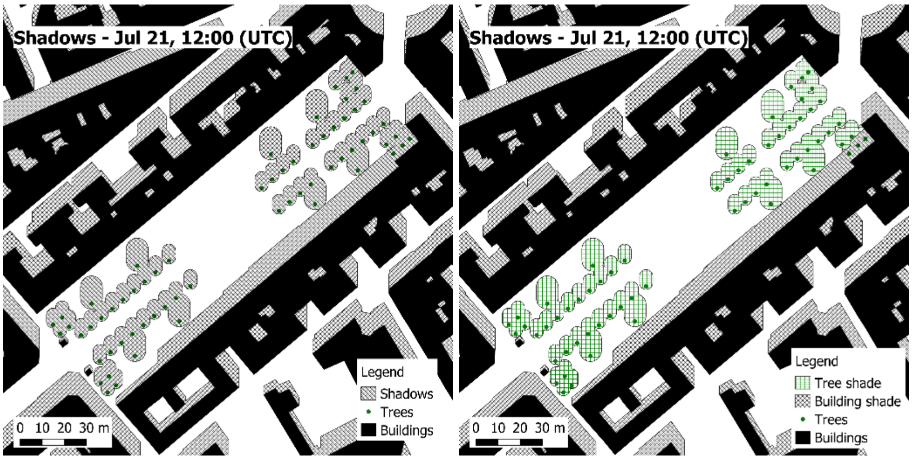

FIGURE 3. (left) The plugin allows evaluating both shadows of buildings and trees on a horizontal plane according to the date and time chosen. The result is a multi-polygon geometry (light grey area). (right) The plugin is able to distinguish, in the shadow cast on the ground, the contribution of trees (light green polygons) from that of buildings (light grey polygons).

5.1.2. Shade contribution of the tree canopy

In the context of urban greening policies, it is essential to distinguish the shadows generated by the built environment (i.e. the buildings) from those produced by the tree canopy. For the configuration shown in Fig. 3 (right), the shade produced by the tree canopy represents about 16% of the total shade on the ground. This contribution is naturally conditioned by the tree crown geometries as well as by their spatial distribution within the urban space (they may indeed be hidden by possible taller buildings).

5.1.3. Shade ratio evolution over the summer period

In this section, the yearly evolution of the shadow ratio for different times a day (between 10 am and 4 pm) is studied (Fig. 4). The considered period is chosen during summertime, when the sun is at its highest path in the sky and, consequently, the solar energy input is the greatest. Considering the results, for the period between spring equinox and autumn equinox, it can be seen that, the shade provided by the tree canopy is significant. In fact, the tree shades cover on average one third of the courtyard. This contribution is almost systematically higher than the one of the surrounding buildings. At its peak (at 2 pm UTC), it is even around 6 times higher than the shade provided by the buildings.

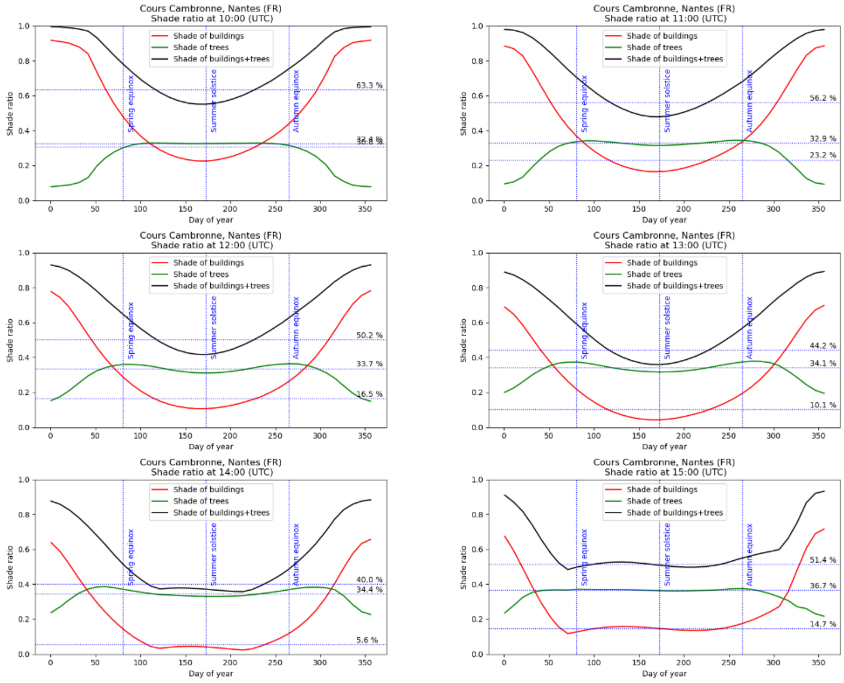

FIGURE 4. Evolution of shade ratios over the year for a few predetermined hours of daylight. The fall of foliage in autumn and winter is likely to modify the geometry of the crown and reduce the amount of shade.

5.2. Shadowing permanence

5.2.1. Delineation of shaded areas over several hours

The annual evolution of the ground shade presented in the previous section can also be studied for a given day. This allows distinguishing potential cool spots, during a heat wave event. Thus, the shade zones are cut out according to the number of hours of shade. With the special case of 21st July, Fig. 5 (left) shows the excessively fragmented nature of this cut within the shadow zone. It can be seen, however, that although the central strip situated halfway between the two rows of trees (longitudinal centre line of the courtyard) is finally fairly exposed, the tree roots are very well protected.

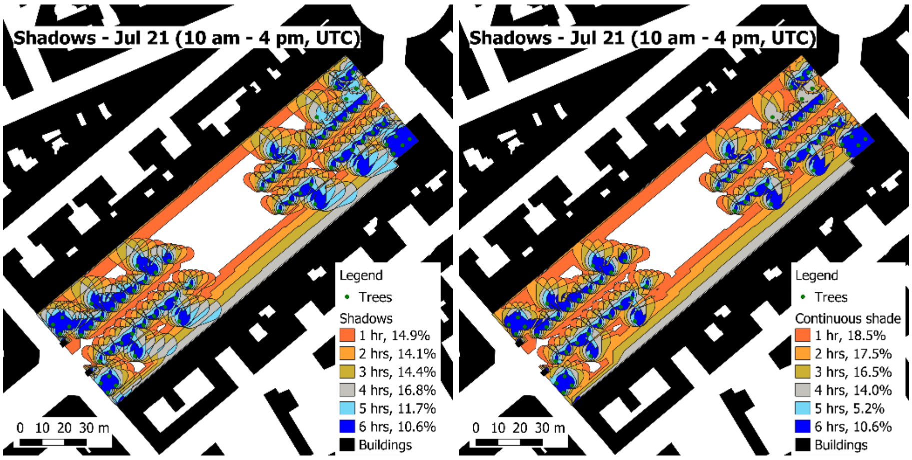

FIGURE 5. (left) Non-uniform distribution of shade in the courtyard during the hours when the sun is at its highest in summer. (right) Representation of areas in shade over several consecutive hours.

5.2.2. Delineation of shaded areas over several consecutive hours

The accumulation of shadow hours shown in Fig. 5 (left) does not include any notion of temporal continuity. However, it could be interesting to detect areas that are permanently in the shade (in order, for example, to design and deploy appropriate street furniture). Fig. 5 (right) shows a revised version of the indicator incorporating this dimension of continuity. The idea here is to represent areas as a function of their exposure to shade for several consecutive hours. As one can note, the overall fragmentation is much less, and patterns emerge that guarantee a certain spatial continuity.

6. Discussion

6.1. Pros: beyond descriptive analysis, shadow as a design object

While it is possible to vectorise the raster shadows obtained via UMEP, the underlying pixelisation is nevertheless problematic when seeking to use shadows for the design of urban spaces as given, for example, in the solar envelope concept (Knowles, 2003). From this point of view, our proposal is innovative in the specific context of geomatics as these vector shadows enable to delineate potential cool-paths and urban oases or cools spots in the urban fabric… all useful features for citizens during heat waves.

6.2. Contras: need for an energy-based approach

It should be noted, however, that the current method is not based on Digital Elevation Models (DEMs); thus, the interactions between the topography and the sun path model are not considered. This is a potential application limit especially for cities with significant elevation changes. Furthermore, the simplified and strictly geometric approach is not sufficient to properly inform the complex notion of pedestrian thermal comfort in heterogeneous urban spaces. On the one hand, particular building geometries (e.g., walkways, porches, steep rooftops) are not considered. On the other hand, thermal comfort simulation tools such as ENVI-met allow studying the spatial distribution of thermal comfort indexes by integrating an energy-based approach. Supplementing our tool with a more representative geometric approach, based on 3D city models (ex. CityGML (Biljecki et al., 2018)) and a thermo-radiative (or even aeraulic) model would make it possible to transform this prototype into a more relevant tool for city designers. Such an assessment will require considering the radiative models of the facades in a full 3D approach.

7. Conclusion

Our work contributes to an estimation, in the geomatics context, of tree-shaded zones to building ones, which is crucial for summer thermal comfort. It also makes it possible to go beyond the calculation and descriptive analysis of the shadows cast in the urban space and to use them as standard polygonal shapes. Continuing its development by integrating a comprehensive energy and a more realistic geometric model will make it operational for urban planners.

Acknowledgment

This study is supported by the French National Research Agency (ANR) under reference ANR-18-CE22-0003 (COOLSCAPES project).

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