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Visibility of building exposed surfaces for the potential application of solar panels: a photometric model

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Abstract

Urban areas are facing a growing deployment of solar technologies on the built exposed surfaces such as roofs and façades. This transformation often occurs without consideration of the needed architectural quality, which depends on the context sensitivity and on solar technologies visibility from public space. The definition of visibility is explored in this paper, and major assessment methods are described. Specifically, a Cumulative Viewshed Algorithm (CVS) is compared with a novel backward raytracing Illuminance Metric Approach (ILL). Results from a test-case in Geneva show how CVS better describes visibility from a remote perspective, while ILL is a promising and fast method for closer viewpoints, especially in urban canyon environments.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Rendering—Visibility

1. Introduction

Residential buildings are responsible for 29% of the total energy consumption in Switzerland [OFE14]. The "Energy Strategy 2050" is promoting the implementation of the "nearly zero energy building" concept (NZEB) by stating that by 2020 "all new buildings should be self-sufficient throughout one year in terms of thermal energy produced by renewable sources and partially by electricity produced on site" [Swi13], in line with the same objective expressed at European level [Eur10]. The achievement of an annual "nearly zero energy balance" for a building implies a combined effort in reducing the energy demand while increasing the local energy production: solar radiation, as a renewable source of both thermal and electrical energy, is a key factor to meet this goal. New technologies such as BIPV (Building Integrated Photovoltaics) and BIST (Building Integrated Solar Thermal) allow the exploitation of solar potential in a densely built environment [MR12]. When cities undertake massive solar refurbishment, the urgency of the renewable production goals should not exempt to preserve the quality of urban, landscape and cultural environments [Swi14]. Solar panels should not be considered as pure technical components for energy production but also as architectural elements.

2. Scope of the work

The LESO-QSV method [MR11], [MR15] has been developed to assist authorities on the decisional, educational and urban planning aspects of architectural integration of solar technologies: a successful architectural integration quality is desirable, but not always necessary. The acceptability of a technical installation with a given level of architectural quality depends on the surrounding urban environment: the discriminating parameters are the socio-cultural value of the urban context (sensitivity) and the visibility from the public space of the building envelope component that will host the solar plant (visibility). From an urban planning perspective, by focusing on existing districts, it is essential to estimate local sensitivity and visibility to envision which areas require which architectural integration quality, and combine this information with the computed solar irradiation. In fact higher quality requirements may translate into slightly higher investments to achieve suitable aesthetic standards or may require the reduction of the collectors surface to preserve the external appearance of buildings [FSS*15]. The evaluation of sensitivity is related to the site character and cannot be estimated without a deep knowledge of the territory: this definition is in charge of the municipality or the local authority, and encompassed in the land use policy. On the other hand, visibility is a perceptive phenomenon and can be independently assessed. The main aim of this work is to define and estimate a visibility index of any building enveloping surface that can potentially host a solar collectors' plant in an urban area, to be used as major input parameter in the LESO-QSV method and determine the needed architectural integration quality.

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3. Fundamentals and research framework

3.1. Visibility assessment models

Visibility is a complex variable to assess since it depends both on physical and perceptive phenomena. The physical part mainly deals with optics and photometry: in this sense, visibility is defined as the luminance contrast between the target and its immediate background [SP16]. The perceptive part is related with physiology, neurobiology and psychology, and it is determined through more stochastic processes. Visual acuity is a parameter that is frequently used to assess overall vision: it can be defined as the angle with which one can resolve two points as being separate, given that the image is shown with 100Under a purely geometrical consideration, two points are mutually visible whether they are joined by a visibility ray, an uninterrupted segment like a laser beam: if an obstacle stops the visibility ray, target point won't be visible (visibility = 0), otherwise it will (visibility = 1). The area enlighted by a visibility ray is commonly known in the geomatic field as the "viewshed", and applied to DTM/DEM (Digital Terrain Models / Digital Elevation Models) through GIS (Geographic Information System) to extract a visibility index [Llo03]. When considering a viewpoint in the space, the set of all visibility rays is called "isovist" [Ben79], which is the locus of all visible points from the source viewpoint. It has been largely employed in urban visibility studies [Bat01], usually by considering horizontal visibility rays in a planar environment, such as an urban plan, to obtain its characteristic polygonal form. Nevertheless, 3D isovists have been introduced more recently thanks to more performing calculation capabilities [MR09], [SJF11] (Fig. 1). Viewshed and isovists give binary output on visible/not visible points but most of visibility studies aim at investigating precise objects of interest with proper dimensions. In this case the problem becomes more complex: in fact, the visibility of a dimensionless feature such as a point can be described by a binary output, while a physical object can be seen from different angles of sight at different distances. In other words, a more comprehensive geometric visibility index is introduced. This depends on the location of the viewpoint in relation with the position and the size of the target object, and is called "visual magnitude" [CM13], [GRBB07]. Interesting applications in estimating visibility of solar plants are available [MMT*14]. Most of these indicators assume that a visibility ray can cover infinite distances in immaterial ether. In reality a visibility ray cannot go beyond a certain distance, mainly by effect of atmospheric suspensoids scattering the light. The atmospheric attenuation of a visibility ray, which is essentially a light ray, can be measured objectively and is represented by the meteorological optical range (MOR), as "the length of path in the atmosphere required to reduce the luminous flux in a collimated beam from an incandescent lamp, at a colour temperature of 2 700 K, to 5 per cent of its original value" [Wor]. Furthermore, when an object of interest with given dimensions rather than a single point is considered, other factors such as the contrast between the object and the background or the visual acuity of the observer intervene [SB00]. The material composition of the target object influences its visibility not only by means of its colour but also with more complex optical properties such as reflectivity, diffusivity, refractivity of light. In particular, the glazed coating of a solar collector can either refract incident radiation through the glazing to the cells, or reflect it according to the angle of incidence of the beam. Under clear sky conditions in certain periods of the year, direct solar radiation might even be reflected in direction of the observer occasioning glare [CFG09]. The fact that an object can be seen does not mean it captures the observer's attention. For every point in a certain human visual field, the probability of human paying attention to any particular spot can be calculated: this is done through "saliency" algorithms, with interesting applications to visibility of solar plants [XW15]. The evaluation of perception remains the most difficult part to include in a visibility assessment model, even though eye tracking or virtual immersive technologies are enhancing research in this field [Mav06], [DAV13].

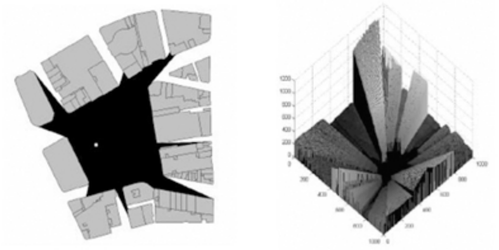

Figure 1: *a) a planar isovist [Ben79] ; b) a 3D isovist [MR09]*

3.2. Visibility indicators for urban environments

Visibility assessment becomes more complicated when it deals with multiple possible viewpoints and / or multiple possible targets. In this case the problem may be: a) identifying which viewpoints are more visually prominent over a given set of targets (hierarchy of viewpoints); b) which targets are prominently seen by a given set of viewpoints (classification of targets' visibility); c) how the mutual visibility changes when visual source and target sets overlap. One possible geometric indicator for GIS applications is the "cumulative viewshed" (also known as "times seen"), which counts the number of times each point in a target set is intercepted by a visibility ray coming from a point in a source set [Llo03]. Nevertheless, this is subject to the same limitations as single viewsheds. When physical target objects are considered, a unique method to accomplish all the goals listed at the beginning of this paragraph does not exist. Different indicators can quantify and qualify the visual prominence of a set of viewpoints in an urban environment [LC15], [BRKM10], some based on the sequential calculation of a sky-view factor [YPL07]. Fewer are available to identify target objects that are more prominently seen at urban dimension [AMH13], [LLH15]. An interesting proposal is to use a Virtual Geographic Environment (videogame renderer) or a realistic 3D reconstruction of the urban area, including vegetation and urban furniture, to easily compute the visual field of a set of viewpoints by exploiting the graphic processor [LLH13], then track their contribution back on target objects. Most of times, these methods are not taking into account visual attenuation over distance, even if some experiences on spot buildings and districts have been successfully conducted [GF15], [KTS13]. Material composition is rarely considered, despite its undeniable importance for the particular case of solar collectors in relation with the surrounding elements. In this case some remarkable indicators have been elaborated for large plants installations in countryside landscape [TSCBCBA09], but literature lacks of urban applications. Likely, perceptive models for visibility evaluation at urban scale are not comprehensive yet, despite some valuable research [PM15].

4. Physical methodology

The purpose of this work is to elaborate a visibility metric to identify the suitability of building exposed surfaces to the installation of solar collectors. This geometric index represents the visual size of a variable dimensions target in a visual field of different viewpoints. In this sense, some hypotheses can be formulated:

a) Visibility is intended as a property characterising the surface of a building envelope component, before any eventual installation. Since the aim is to respond to a planning need, the “objects of interest” included in the assessment are the building surfaces and not the solar collectors themselves, which are unknown at this stage and designed in a later phase;
b) Visibility depends on all the possible viewpoints located in the public space, either close or remote;
c) Visibility indicator should systematically include the visual attenuation over distance.

A good way to physically model visibility rays is to transform viewpoints into light sources. The comparison between photometry and visibility assessment has been already experimented in some archaeological sites [PWE11], and has been explored to be extended to large urban areas [SJF12]. Such a model has been adopted for the purpose of this work since it satisfies the hypotheses stated at the beginning of this paragraph:

a) A point light source, with a specific emitted luminous flux here compared to a flux of visibility rays, is placed at each viewpoint location. The luminous intensity per solid angle is proportional to the attention focus of the observer in a given direction. The quantity of flux reaching a particular surface of a target object is, by definition, the illuminance. Illuminance value is a property that characterises the surface by stating the quantity of incident light illuminating the surface. Target surface can also be split into smaller features, to refine measurements: when surface area is constant and unitary (A=1), illuminance is equal to the flux, and illuminance values on each feature can be added up. Then, the sum of illuminances related to many features can be averaged on their area to obtain a mean illuminance value. Hypothesis a) is verified.
b) All possible viewpoints in the public space are discretised on an evenly spaced grid and modelled as light sources, with their proper emitted luminous flux each. Illuminance being a linear function, the sum of all different luminous fluxes is equal to the total illuminance: in this way visual contributions by different viewpoints to a same target can be summed together. Hypothesis b) is verified.
c) Illuminance attenuates over distance according to Allard’s law [Int] (Equation 1). In fact, illuminance as visibility depends on the distance and on the solid angle the surface subtends (viewing angle). It comes with this statement and the definition of Meteorological Optical Range (see above), the expression of illuminance at the minimum visibility level (d = MOR), in Equation 2. Hypothesis c) is verified.

$$E = \frac{I(\omega)}{d^2} \times 0.05^{\frac{d}{\nu}} \tag{1}$$

$$E_{min} = \frac{I_0}{\nu^2} \times 0.05 \tag{2}$$

E	is the illuminance
$I(\omega)$	is the luminous intensity in the solid angle ω that the surface subtends
I_0	is the luminous intensity in the normal direction from the source to the surface
d	is the distance between the viewpoint and the barycentre of the surface
ν	is the Meteorological Optical Range (MOR)

5. Model set-up

5.1. Case-test description

For the case-test simulation, a neighbourhood in Geneva with well-known radiation data has been chosen [Mag11]. The building features are heterogeneous and the public space is characterised by different road sections, squares, bridges making it interesting as a visual landscape: it is a typical dense urban environment with isolated buildings, in-line blocks and courtyard blocks (Figure 2). Most of buildings being 4 or 5 storeys high, the “urban canyon” setting is prevalent especially in narrow streets (aspect ratio around 1).

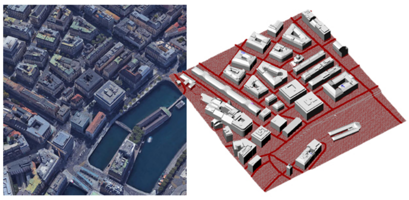

Figure 2: *a) aerial photo of the case-test taken from Google Earth ; b) the LOD2 3D model of the district*

5.2. Dataset and model implementation

Needed input data is the Digital Terrain Model (DTM) in raster format, the 3D vector of buildings and the roads polygons shapefile, eventually describing pedestrian occupation in its attributes (e.g. highway roads vs pedestrian areas). This is available for Geneva via the public geo-information platform SITG: 3D building vector is currently available at LOD2, that includes roof shapes and is the minimum requested to have reliable results [BLSV16]. For the purpose of this work, road axes are identified and viewpoints placed every 2.5 metres on the axis curve: an offset of 1.5 metres above the DTM z-coordinate is added to obtain a discretised grid of probable observers (Figure 2). Then a mesh of “view sensors” is overlaid on building 3D surfaces, arranged on a square grid of

1.5 by 1.5 metres. All the geometric model manipulations, the data flow through the calculation engines and the results visualisation is managed via Grasshopper, the algorithmic modelling interface for the 3D modelling software Rhino.

5.3. Visibility assessment

Two different visibility assessment methods are used for the case-test: first, a cumulative viewshed is calculated from the viewpoints to the target sensors. A dedicated algorithm of Honeybee environmental plugin for Grasshopper is employed for this specific need [MA13]. Secondly, the physical methodology based on illuminance (briefly, the illuminance model) is tested: to do so, a detailed backward raytracing simulation of the model is launched on Radiance "rtrace" calculation engine. The following assumptions are adopted:

a) All the viewpoints are replaced by omnidirectional light sources, emitting homogeneously at the intensity of 2000 cd in all directions. This hypothesis means that the attention of the observer is uniform in all directions and there is no particular landscape feature concentrating his visibility rays.
b) The sky illuminance is uniform and set to 0. Ambient bounces for indirect light reflections are set to 0 and materials assigned to buildings surfaces are perfect absorbers with 0 reflectance. In this way there is no environmental interference with the visibility rays.

Simulation time for the illuminance model is approx. 15 minutes with a 3.2 GHz CPU, which is fast and easily replicable.

6. Results

Results for both assessment methods are shown in Figure 3. At first sight, visible portions of buildings are more concentrated in the cumulative viewshed (CVS) than in the illuminance model (ILL). It is evident how CVS results show no variability along the façade height because of the absence of visual attenuation within the algorithm, while ILL model takes this attenuation into account and shows a drastic change in illuminance value from a façade point at the observer's height to a higher one. It has also to be noticed how ILL sensors are less sensitive to the contribution of far viewpoints and all façades in the district are characterised by a similar illuminance plot. This can be explained through the property of illuminance attenuation with the square of the distance from the source (see Equation 1), as well as with the calculation assumption a) concerning the omnidirectional light emission of modelled viewpoints. In particular, a spherical photometric solid resulting from an omnidirectional emission means that the observer's attention is uniform in all directions within his visual field and all the infinitesimal unit areas projected on the sphere have the same weight. In other words, there is no directionality of vision as the observer has the freedom to look in every direction with a constant interest (like it is usually done in touristic squares or panoramic spots). The advantage of using a vectorial model as input for calculations is the easier data manipulation, aggregation and filter. Since each output variable is stored in a data tree, result values can be queried according to display needs: average values per surface, per building or even per district can be extracted for a customised scale-adaptive data rendering. For instance, two possible data aggregation approaches are represented in Figure 4 for CVS and ILL. In plot a) and b), the sum of all visibility values linked with the set of target sensors on a given surface indicates the global visual prominence of that surface according to CVS or ILL models.

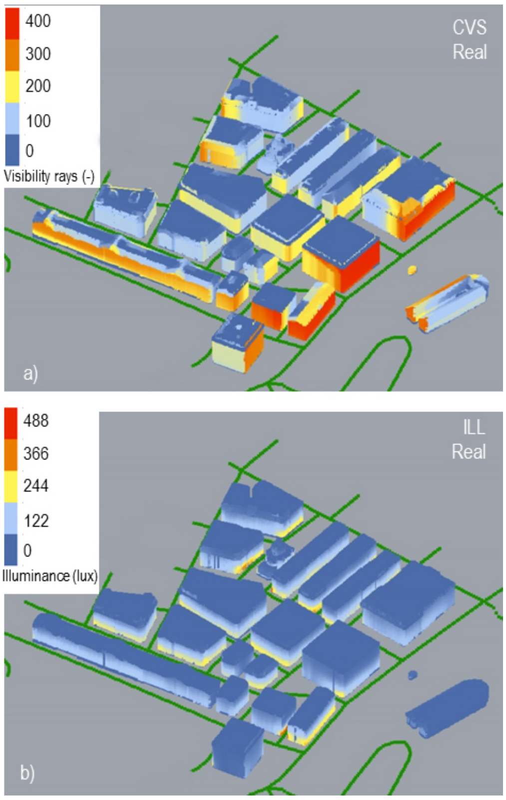

Figure 3: *results for visibility analysis through Cumulative Viewshed (CVS) (top) and Illuminance Model (ILL) (bottom), by target point*

7. Conclusion and further developments

The two methods mentioned above give complementary information about the visual perception of the analysed district. In particular, CVS qualifies the possibility of viewing a given feature from a set of viewpoints without describing its visual prominence (how much it is visible). ILL provides a better characterisation of the visibility variation in an urban canyon, including visual attenuation, as the influence of far viewpoints is less significant. It might be argued that CVS is more adapted to describe visibility from remote viewpoint locations, while ILL is more suitable for close viewpoints in the immediate surroundings of the target: this notion can be compared to the concept of close and remote visibility expressed in [MR15]. Nevertheless, the assumption of an omnidirectional uniform vision appears to be too much simplified and should be refined according to the prevalent direction of the observer's movement and perception. Another parameter to be included in the model is the viewpoints density as a function of their importance in the urban visual landscape. The more a place is considered to be

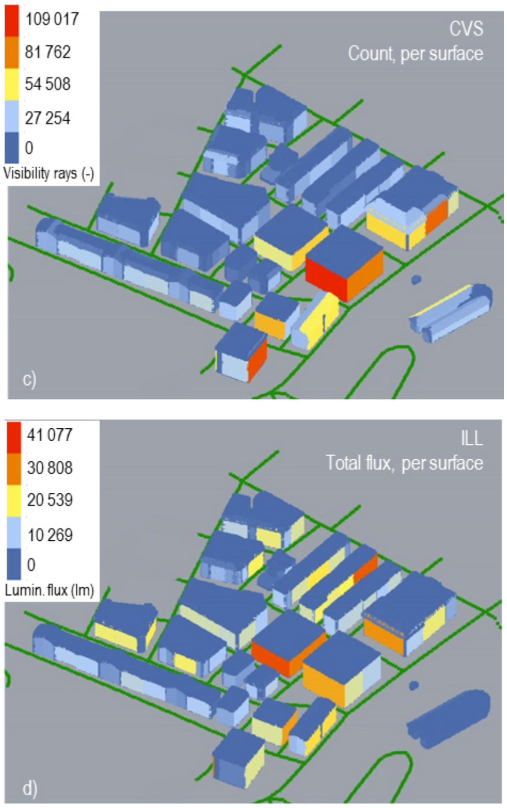

Figure 4: *results aggregation for visibility analysis through Cumulative Viewshed (CVS) (top) and Illuminance Model (ILL) (bottom), by target surface*

a nice view spot because it is located in an important square or in a sightseeing area, the denser the viewpoints in the model. Finally, a consideration about the study area: the case-test described in this paper is located in Geneva as it relies on a detailed 3D model and an exhaustive solar potential estimation. A benchmark of the algorithms via the application to other databases is foreseen.

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