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Solar potential on facades at urban scale: an integrated approach combining solar and digital building modelling

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Solar potential on facades at urban scale: an integrated approach combining solar and digital building modelling

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Abstract. The paper presents an integrated approach to improve the solar radiation modelling on facades in large-scale built-up areas. The modelling of the built environment must first be improved in terms of level of detail. Thus, from aerial oblique images, a digital twin of the urban scene is created, allowing to process the facades as textured objects and to detect windows using an artificial intelligence image processing. Reflected radiation is significant on vertical surfaces, but complex to model on large areas. The developed model is based on a simplified radiosity approach, which reduces the volume of analysis, storage and thus the computation time, while producing reliable results. A demonstration of the integrated tool is presented for an urban area in Geneva (1 km^2), including a solar energy balance assessment for one of the buildings using the results from the solar modelling. The perspective is to generalise the approach to a larger scale and to complete the solar cadastre of the roofs of the Greater Geneva area with the facades.

1. Introduction

In the context of the energy transition and the expected intensification of solar production in urban areas, building facades are becoming increasingly important for achieving transition goals, as roofs do not offer sufficiently large available surfaces for energy transition strategies.

Interactions between urban morphology and solar energy have been increasingly acknowledged [1]. Solar cadastres have proliferated over the past decade in many cities [2]. They are very useful tools to develop solar strategies, to raise awareness among property owners and to help triggering solar installations. However, they generally focus on roofs and still few consider facades [3]. Most of the current tools and approaches to model the solar potential on facades are generally limited to the level of specific buildings or a group of buildings, but few consider the scale of city [4].This is explained by a methodological and technical approach that is complex to implement, in particular due to two aspects: (1) the reliable modelling of the reflected component, which is significant on vertical surfaces but also complex to process in a reasonable calculation time [5]; (2) the increased level of detail and more accurate characterisation of the texture of the facades, which enables the identification of the parts that can be valorised by solar panels (excluding the glazed surfaces or the balconies for example).

Concerning aspect (1), a tool to process the solar potential of roofs over large areas has been developed [6] [7]. The solar cadastre of the Greater Geneva, available online on https://apps.sitg-lab.ch/solaire/), has been calculated using this tool, as well as the solar potential of the facades of urban districts. This tool is however incomplete, since it is based on an approach that is not adapted to the reliable modelling of the reflected component, moreover it does not consider the texture of the facades.

With respect to the second aspect, an increasing number of 3D urban models at the city level are available, in LOD 1 (Level Of Detail) in Europe, or in LOD 2 in Switzerland. These large datasets almost never include details of façade elements, as manually entering these elements would be both too time consuming and too expensive. However, in recent years automatic algorithms based on deep learning have been developed to automate this step, and thus creating new possible applications [8].

Therefore, the objective of this article is to propose an integrated tool and approach for modelling the solar potential on vertical facades adapted to the scale of urban centres (> 1 km^2) with reasonable computation time, paying particular attention to the reflected radiation which is the most complex component to model, and to the adapted level of detail to represent the facade texture.

2. Workflow

Figure 1 below gives an overview of the implemented method, the flow of data and tools used. Two main concepts have been integrated: photogrammetry and solar modelling.

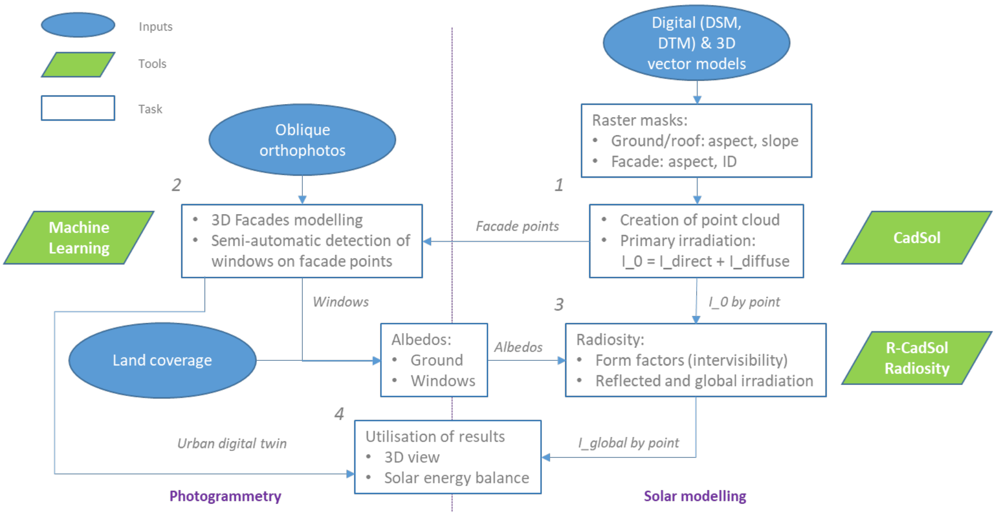


Figure 1. Workflow of the integrated tool and approach for solar modelling on facades. All the spatial input data comes from the geoportal SITG (Information system of the Geneva territory).

The steps are as follows: (1) From the 3D building vector model (used for facade line detection and calculation of the orientation of each segment) and digital models (DTM, DSM) raster layers are created. They serve as input for the calculation of the primary solar irradiation on the roof and facade considering shading related to the urban environment. The primary irradiation is divided into the direct (beam) and diffuse components. The urban scene is modelled as a cloud of points. (2) In parallel, oblique aerial images are projected on the 3D building model, allowing to texture facades and to detect facade elements such as windows using machine learning in a semi-automatic way. The point cloud is projected on the facade model and for each point we determine if it belongs to a window or not. (3) Reflected irradiation is calculated using the radiosity approach, considering the reflection factor (albedo) of the urban environment which varies according to the surface properties: ground and buildings. Finally, the global irradiation is calculated as the sum of the three components (direct, diffuse, reflection). (4) The last step concerns the exploitation of the results: 3D representations (windows, solar irradiation on the facades), solar energy balance at the scale of the buildings and the district.

3. Solar modelling

The solar modelling is performed in two steps: (1) modelling of the primary irradiation - direct and diffuse - according to the CadSol tool [3] [4], and (2) modelling of the reflected irradiation from the primary irradiation. Reflection is calculated using the R-CadSol tool presented in detail in [4], which is based on the radiosity approach as summarized hereafter. Radiosity considers that radiation is reflected on a given surface in a diffuse way from the nearby environment (ground, neighbouring buildings). The conventional radiosity method [9] is not suitable for analysing radiation at urban scale, since it involves computing inter-visibilities and form factors between all points (or meshes) in a scene, which is very storage and computationally time consuming. Thus, we propose to implement a simplified approach of radiosity, which consists in evaluating the inter-visibilities not between scene points, but from scene points to the meshes of a fictitious sphere (sky), and to identify the obstacles to these inter-visibilities. This considerably reduces the processing volume, the storage and the computation time (figure 2). A comparison was made on a fictitious urban canyon between the traditional radiosity and the simplified methods, and the differences are considerably small overall, which validates the method [4].

Figure 2 presents a comparative view of the two radiosity approaches (conventional and simplified), illustrated on a 300 x 300 m urban scene. The computation times are obtained with a prototype implemented with MatLab. This prototype has been later transferred to a C++ environment, which allows reducing the computation time (<1 minute on the example urban scene).

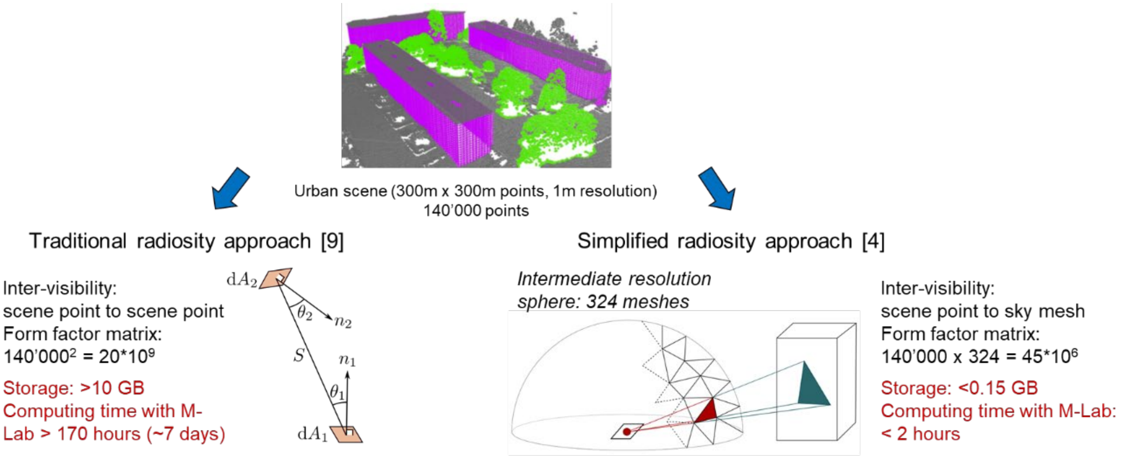


Figure 2. Comparative view of the two radiosity approaches: conventional and simplified and illustration on an urban scene.

4. Application to Geneva

The demonstration area is located in the peripherical area of Geneva (commune of Meyrin) and is made up of blocks of collective housings built during the 1960s (figure 5). This area is interesting because it presents relatively well-spaced and regular buildings with blind gable walls which could be equipped with photovoltaic modules (figure 7). The longest facades also offer many opaque surfaces which can be used for PV installations. The buildings being old and not energy efficient, solar installations could be considered on roofs and facades in a future retrofit.

4.1. Window extraction from facade images

First, the facades of the existing 3D urban model have to be textured (figure 3). To achieve this, a set of aerial images has been precisely georeferenced with the same system as the 3D urban model by bundle adjustment. Once the images are oriented, they can be used to calculate the ortho-image of each facade, allowing to make georeferenced measurements on those elements. In the figure 3, the result of the textured facades is shown (right image). The vegetation could also be modelled in 3D by photogrammetry (dense correlation). Secondly, the windows are extracted from the facade orthoimages using deep-learning. For this purpose, a pre-train Mask-RCNN [10] neural network has been used and trained on terrestrial images of buildings to detect windows (figure 4). Despite using terrestrial images, the network is relatively successful in detecting windows on aerial images. However, on some buildings, especially with balconies, the algorithm fails more often. In the future it could be useful to re-train the neuronal network on images of the area of interest.

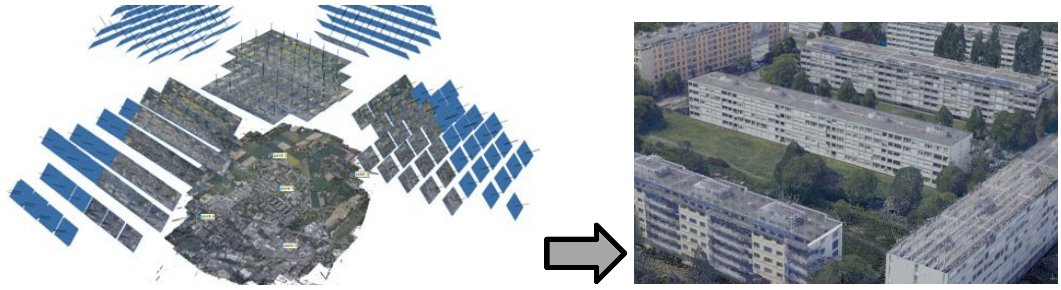


Figure 3. Digital twin construction process from the oblique photos: (left) computation of the orientation of oblique images over the area of interest with bundle-adjustment, and (right) the resulting digital twin.

Figure 4. Overview of the window detection performed on the facade ortho-images and reprojected on the 3D model of the buildings of the demonstration area.

4.2. Solar radiation processing on facades at large urban area

The aim is to demonstrate the ability of processing solar irradiation on facades at large urban scale in a reasonable computing time and storage. The illustration is made on a tile of 1 km^2 (1m of resolution) corresponding to a middle urban scale. We assume that the whole city can be processed tile by tile, using parallelized algorithms, in order to complete the solar cadastre of facades. The prototype of solar reflexion modelling based on the simplified approach encoded in C++ is used and gives a very satisfying computing time of 10 minutes. The primary irradiance – beam and diffuse – calculation on facades has already used performant computing solutions as introduced in [7] and takes some minutes for this area. Figure 6 below represents the yearly global irradiation output on facades.

Figure 5. Demonstration area (black square) and the example building (white) for the solar energy balance (section 4.3).

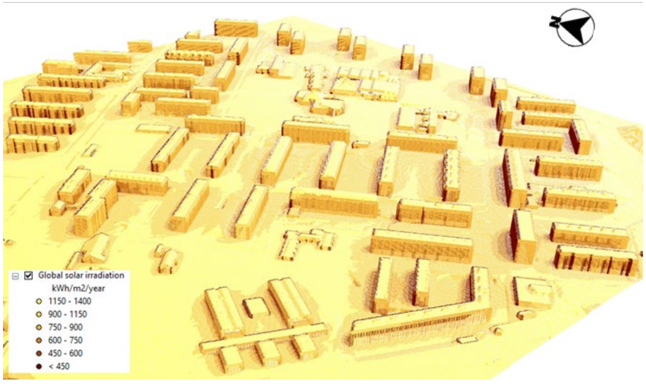


Figure 6. 3D view of the point cloud with global solar irradiation values in the demonstration area.

Figure 8 illustrates the whole process used to compute the solar irradiance on each point (ground, roof, facade). (1) Albedo factors are assigned to each type of coverage (from the land coverage map available from SITG, and a typical concrete building). (2) Form factors are processed according to the simplified approach of radiosity introduced in Chapter 3. (3) The primary irradiation – direct and diffuse – is computed. (4) From the steps 1, 2 and 3, reflected irradiation of 2 orders is computed. (5) Finally, the global irradiation is calculated as the sum of the reflected and the primary irradiations.

Figure 7. 3D picture with the example building in the bottom (Google map).

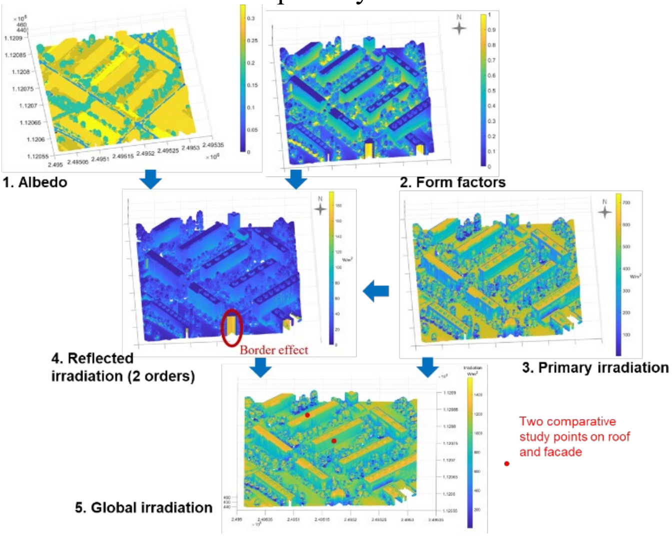
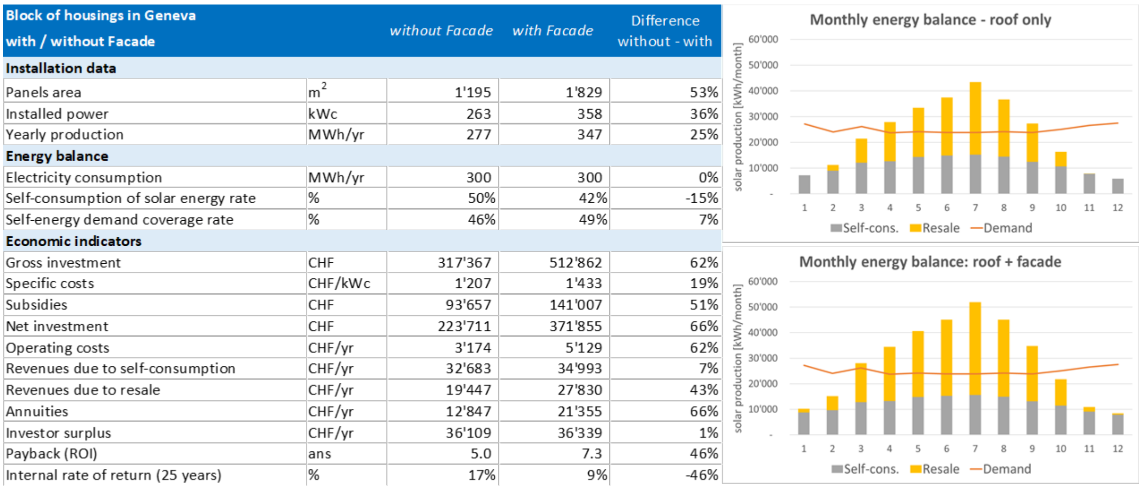


Figure 8. Irradiation process illustrated on a part of the demonstration area. Adapted from [4].

4.3. *Solar energy balance assessment*

The results from the photogrammetry (4.1) and the irradiation (4.2) processing make it possible to quite precisely determine the parts of the buildings that can be equipped with solar panels. We assume to install solar panels on opaque elements which are the roof and the unglazed parts of the walls identified using the windows detection. Moreover, the suitable surfaces should have a minimum irradiation of 750 kWh/m^2/yr according to the irradiation outputs. Urban scene points are selected according to these two criteria and corresponding suitable areas for solar panels are calculated.



Block of housings in Geneva with / without Facade		*without Facade*	*with Facade*	Difference without - with
Installation data				
Panels area	m^2	1'195	1'829	53%
Installed power	kWc	263	358	36%
Yearly production	MWh/yr	277	347	25%
Energy balance				
Electricity consumption	MWh/yr	300	300	0%
Self-consumption of solar energy rate	%	50%	42%	-15%
Self-energy demand coverage rate	%	46%	49%	7%
Economic indicators				
Gross investment	CHF	317'367	512'862	62%
Specific costs	CHF/kWc	1'207	1'433	19%
Subsidies	CHF	93'657	141'007	51%
Net investment	CHF	223'711	371'855	66%
Operating costs	CHF/yr	3'174	5'129	62%
Revenues due to self-consumption	CHF/yr	32'683	34'993	7%
Revenues due to resale	CHF/yr	19'447	27'830	43%
Annuities	CHF/yr	12'847	21'355	66%
Investor surplus	CHF/yr	36'109	36'339	1%
Payback (ROI)	ans	5.0	7.3	46%
Internal rate of return (25 years)	%	17%	9%	-46%

Energy and economic KPIs

Monthly energy balance (kWh/month)

Figure 9. Energy and economic KPIs for the example building and monthly energy balance.

On this basis, potential solar energy production is estimated and energy balance can be performed, as illustrated for the building highlighted in figures 5 and 7. The solar cadastre of the Greater Geneva includes a solar energy building database made up of energy and economic key performance indicators (KPIs). They are obtained from the hourly-based assessment of self-consumption of the solar energy and on the local electricity market feeds. Thanks to the integrated approach presented in the paper, the solar cadastre and its building database can be completed with data and information from the facade solar potential. Figure 9 provides those KPIs for the example building with and without considering the facades. It also gives, in both cases, the monthly evolution of the self-consumed solar energy, the one resold to the grid, in regards with electricity demand of the building. In this example, the economic balance only considers adding panels on facades, and not the retrofit costs. From these KPIs we can conclude the following: good economic profitability even with facades, facades add 25 % in the solar energy production, the energy demand coverage ratio in winter (December to February) is 28% with roof only and increases to 33% thanks to facades.

5. Conclusion and perspectives

This paper proposes an integrated approach and tools to process solar radiation at large urban scale not only on ground and roofs but also on facades, whose level of detail is improved thanks to image texturing using photogrammetry and deep learning algorithms. A demonstration and an application were given on an urban area of 1 km^2 in Geneva, including an example that uses the results for the solar energy balance assessment for a specific building. In particular, thanks to the adapted radiosity approach and to the proposed computing solutions, the reflected component, which normally is very complex and time consuming, is processed at this scale in just a few minutes. The image texturing of facades can also easily be automatically processed at large scale in a short time. This application shows that everything is ready now to generalise the approach and process the whole city or region working tile by tile (1 km^2 or larger) and to complete the solar cadastre of the Greater Geneva with the facade component. However, the automatic process does not allow to consider some particularities of the built fabric (irregular shapes of the facades for example). The machine learning algorithm should also be trained to include other facades features than windows, such as balconies. Moreover, while most of the roofs are suitable for solar panel installations, this is less the case for facades. Additional information and data should be considered to select suitable facades by taking into account heritage constraints, the type of materials, the perspective of retrofitting the building, etc. It shows that cities should implement integrated urban and solar energy planning strategies, and solar cadastre on roofs and facades can provide support to this.

Acknowledgements

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