Predictive model of solar potential on building façades with the sky view factor as shading indicator

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Abstract. Building façades represent a considerable part of the urban surface and the solar energy they receive can significantly contribute to the whole urban solar potential. Extending the use of building facades to produce more renewable energy can help address the challenges of climate change, promote energy independence, and create economic benefits.

A major challenge in harnessing solar energy from vertical surfaces is the variation of solar availability on urban facades, which can be affected by orientation, neighboring buildings or vegetation. An easy, reliable and robust method for evaluating the solar potential of facades since the strategical stage of the building development can assist experts in designing façades where building integrated photovoltaics (BIPV) can be efficiently implemented.

This study aims to identify a relationship between the variation of the sky view factor (SVF), a measure of the amount of sky that is visible from a given position, and the corresponding reduction of solar irradiation due to shading. This can then be used to predict the solar potential at each point on the façade on a monthly basis only depending on orientation, SVF value and geographical coordinates, drastically reducing the complexity of analysis and without requiring time-consuming tools.

1. Introduction

The integration of Photovoltaics (PV) in facades can transform each building surface into energy producer smothering the electricity production during the day [1] and contributing to the climate and energy transition. To achieve this goal it is necessary to estimate the solar irradiation potential so strategic decisions can be addressed since the early design stages of a new building or settlement. However, it is not efficient to adopt BIPV simulation tools at this stage since they are typical for the technical design stage and require several details to provide a reliable output. Nowadays, there are few tools that can be used for estimating the solar potential of building facades at the early design stage:

(i) solar cadasters [2, 3], which are urban maps based on 3D city models such that represent the solar irradiation potential over existing building surfaces, typically at LOD2 [4].

(ii) web-tools connected to radiation database for all locations around the world that allow evaluating the solar irradiation potential for a surface that is defined by the user in terms of orientation and azimuth [5].

(iii) software and/or plugins that implement ray-tracing methods to compute the solar irradiation over surfaces of 3D models, such as Grasshopper and Ladybug tools [6]

Even though different tools exist for the assessment of the solar potential of facades, stakeholders involved in the early design are looking for tools suitable for this process stage. Indeed, these tools should be capable to provide a preliminary assessment of the solar potential also for new building facades accounting for shadings due to neighboring buildings or vegetation with reasonable computation time and without investing too many resources in modeling urban context in new software or plugins.

Thanks to the increasing generation of 3D urban models, several web-tools or urban cadasters are arising. Therefore, a major challenge in assessing solar potential of these vertical surfaces is the development of a quick and reliable method to assess the variation of solar availability on new facades, which can be affected by orientation, neighboring buildings, or vegetation.

The goal of this study is to identify a method capable to profit of the existing 3D urban models to predict the solar potential of facades without simulation tools and with low computational efforts. Among the different variables influencing solar irradiation, the sky view factor (SVF) has been widely used to evaluate the potential for solar energy generation on building facades, showing a high correlation with the target variable, making it an excellent candidate to be used in a predictive model. Indeed, several studies investigated relationship between it and solar radiation on building facades [7, 8, 9]. However, the novelty of this study is represented by the adoption of SVF for the development of metamodel that can be combined with existing 3D urban models to quickly provide the solar irradiation potential of new facades without requiring the final user to carry out simulations.

2. Methodology

The approach adopted is based on the calibration of a metamodel to estimate the solar potential on building façades on the basis of some easily accessible inputs.

An Extreme Gradient Boosting (XGBoost) model [10] is trained over a dataset of almost 800’000 observations. XGBoost is a powerful tree-based algorithm that can handle large datasets and high-dimensional data. It performs well in various machine learning tasks and has built-in support for regularization and is widely used in industry and research.

2.1. Training dataset

The training dataset is built using the parametric Rhinoceros plugins Grasshopper and Ladybug, analysing:

- 127 locations worldwide (longitude & latitude)
- 8 façade azimuths
- 4 urban density scenarios
- 16 points per façade

Locations are selected worldwide through a grid searching approach with a denser grid for the European continent. The four urban scenarios (Figure 1) are randomly generated for each new location by associating a different seed with each one. The solar radiation values are simulated on a monthly basis so that the results can be used for more detailed analyses under self-consumption and self-sufficiency regimes. Each façade has been divided into a grid of 16 elements and the solar irradiation value refers to the central point of each element, the point on which the SVF was also calculated.

The number of observations used for the metamodel calibration is therefore 780’288, total obtained by multiplying the number of locations, façade azimuths, urban scenarios, grid elements and months of analysis. SVFs are calculated directly through Ladybug for the different points on the facade by summing the orthographic projected area of the sky dome patches that are visible from the analyzed point and dividing it by the total area of projected sky dome patches. In addition to the global SVF, for each grid point twelve partial SVFs were calculated on as many sections of the sky dome so that the final metamodel could weight differently an obstruction to the south rather than the north (Figure 2).

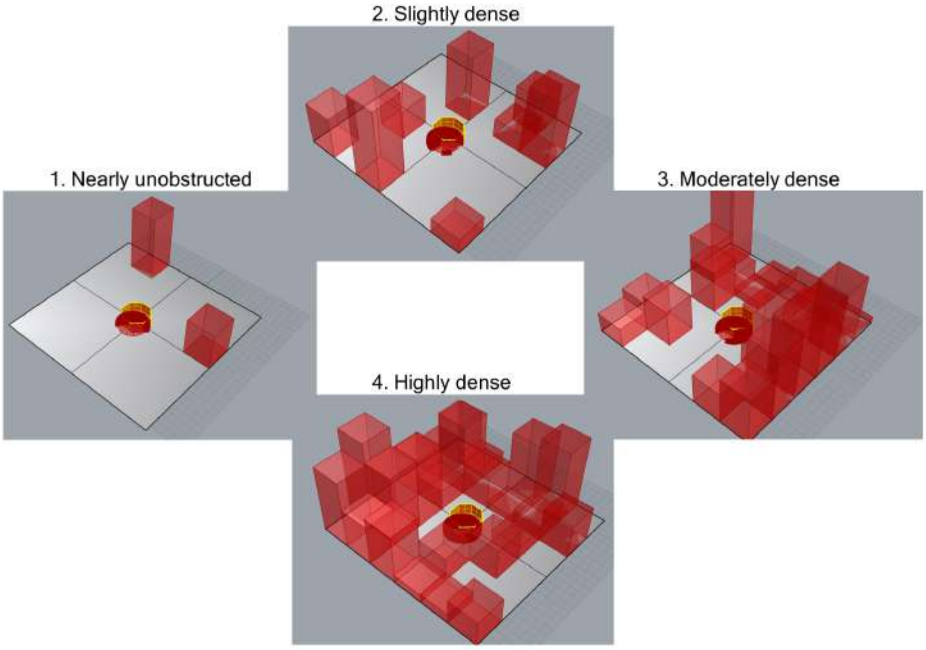


Figure 1. Urban scenarios considered for the training dataset definition

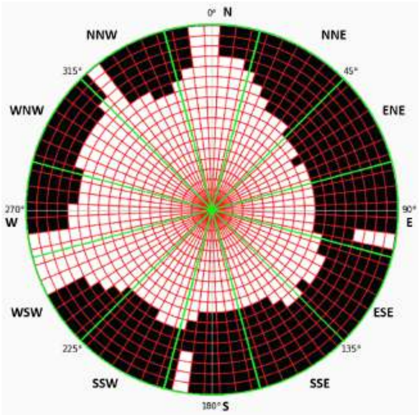


Figure 2. Sky dome division to compute 12 partial SVFs

2.2. Xgboost calibration

Cross validation is used in combination with an optimisation algorithm to calibrate the metamodel. In particular, after having defined the hyper-parameters to be optimised and their range of variation, these are processed as design variables and calibrated using Bayesian optimisation to minimise the error. In each iteration, cross validation was used to increase the robustness of the optimiser and improve the generalisation of the model.

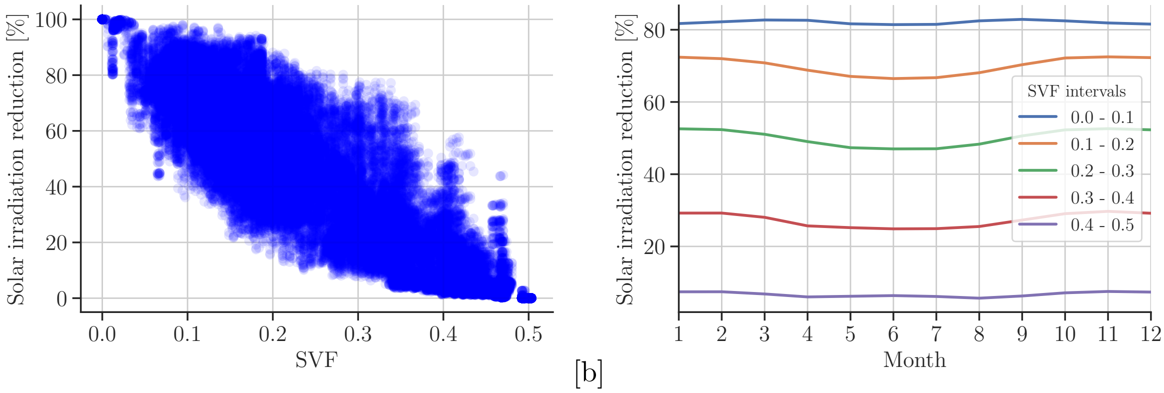
In conclusion, the calibrated metamodel accepts as input a vector of 16 features (latitude, longitude, façade azimuth, month, 12 partial SVFs) and returns as target the percentage reduction in solar irradiation due to shading.

3. Main results

3.1. Exploratory data analysis

An exploratory data analysis was conducted in order to validate the training dataset and extrapolate relevant information. Figure 3a shows the dispersion of the target variable as a function of SVF. This is maximum for intermediate values of the SVF until it reaches minimum values in the cases of complete shading (SVF=0) and completely free sky (SVF=0.5). The case of no shading provides an SVF of 0.5 (not 1) because half of the sky dome is obscured by the inner part of the façade. Figure 3b shows the median solar irradiation reduction for all months and SVF intervals. It can be seen that reductions are rightly slightly greater in the winter months when, as the sun is low, small shadows have a greater impact.

It is also possible to characterise the reduction in solar irradiation in probabilistic terms with respect to the SVF. Figure 4a for example shows the probability of exceeding multiple reduction values as the month changes (3 months in the example provided) by setting an SVF interval of interest. This analysis can be generalised to the whole dataset and Figure 4b provides the probability of exceedance over 5 SVF-intervals, considering the whole year. The curves are consistent with the phenomena under investigation and provide relevant information in the case of statistical analysis or uncertainty propagation processes.



[a]

[b]

Figure 3. [a] Scatter plot of a sample of SVF values with the corresponding solar irradiation reduction. [b] Median solar irradiation reduction per month and SVF interval

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3.2. XGboost performance

The calibrated metamodel shows a high accuracy with a mean absolute error and mean squared error of 1.4 and 5 respectively, and an R2 score of 0.994. Figure 5a shows an example of a comparison between target variable and metamodel prediction for a set of 50 observations, while Figure 5b provides the distribution of the absolute value of the residuals. The 95th percentile of the distribution of residuals is below 5%, confirming the goodness-of-fit of the model. In order to verify the importance and impact of the selected inputs, SHAP coefficients (Shapley additive explanations) [11] were also calculated for each of them (Figure 6), except for the various SVF

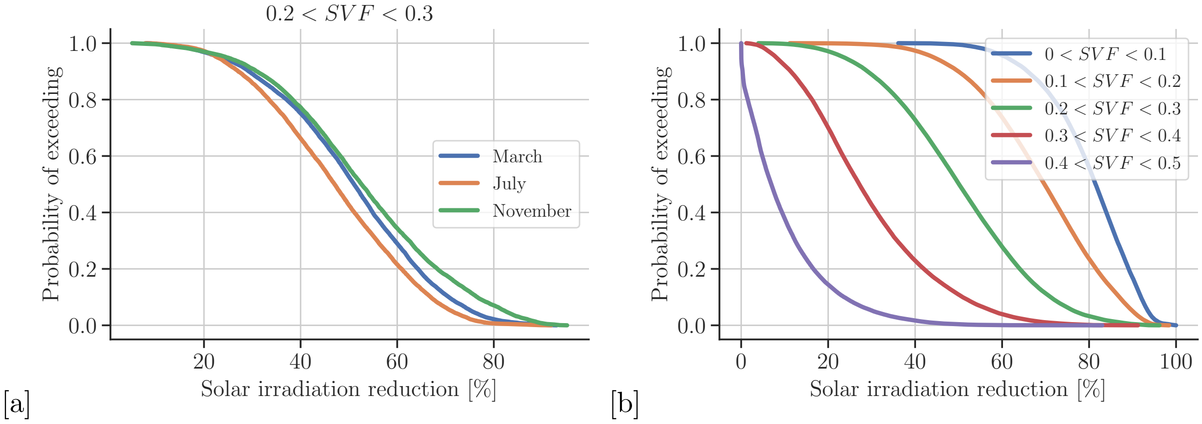

Figure 4. Complementary Cumulative Distribution Function (CCDF) for different solar irradiation reduction levels. Figure 3a refers to one SVF interval and 3 specific months, while Figure 3b reports a CCDF for 5 SVF intervals considering the entire year.

partitions.
SVF, as expected, proves to be extremely well correlated with the target variable, with the azimuth of the façade in second position, while in geographical terms, it is the latitude that plays a major role.

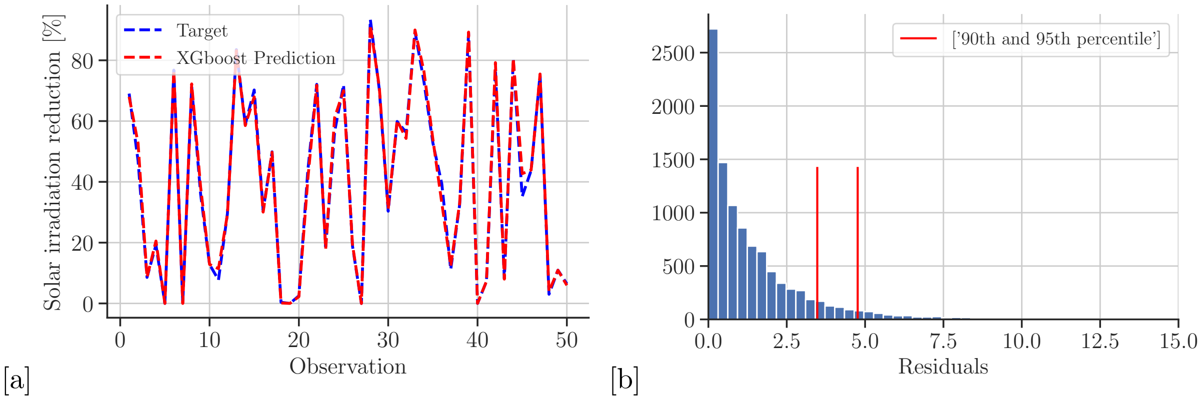

Figure 5. [a] Comparison between the target variable and the model prediction for 50 observations. [b] Histogram of the residuals absolute value with the 90th and 95th percentiles indicated.

4. Conclusions

In conclusion, the use of building facades to produce renewable energy through BIPV systems can have significant environmental and economic benefits. However, a major challenge is the development of methods to take into account the variation of solar availability on urban facades already in the early design stage with reduced efforts by a variety of users (eg. investors, building owners). For this reason, this study proves how a metamodel-based approach assuming the SVF as main predictor of solar irradiation on building façades succeeds in ensuring high accuracy with low compatutional costs.
The generated training dataset also provides additional relevant insights. A dedicated exploratory data analysis made it possible to highlight detailed aspects of the problem, with

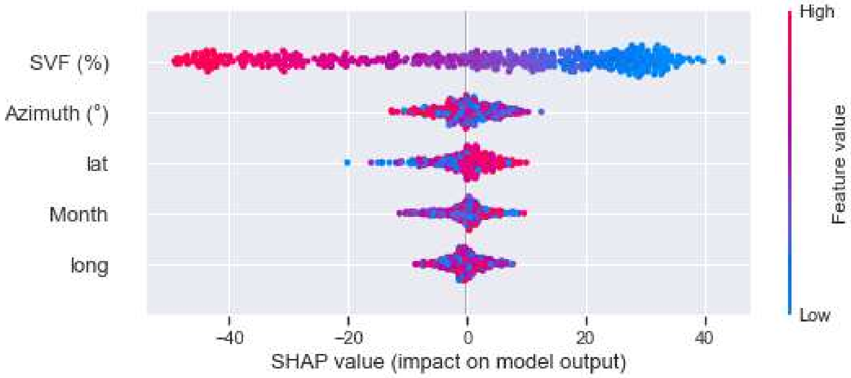

Figure 6. SHAP values for the model inputs

the possibility of extrapolating CCDF curves for probabilistic analysis.

The obtained results aim to fill a gap in the current literature, which provides SVF analyses on reduced datasets by defining mainly linear models. This is achieved by generalising the predictive model, extending its range of use thanks to an extremely large dataset and a significantly better performing regression algorithm.

Further efforts should aim to provide simplified non-linear regression equations to facilitate faster and more extensive usages, ensuring good accuracies.

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