USING INTERPOLATION TO GENERATE HOURLY ANNUAL SOLAR POTENTIAL PROFILES FOR COMPLEX GEOMETRIES

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ABSTRACT
In order to evaluate the feasibility of roof and façade mounted or building integrated solar technologies such as photovoltaic and solar thermal panels, information on the solar potential availability under consideration of local conditions such as geometrical obstructions is required.

Future sustainable urban energy systems will be characterised by multi-carrier systems, where the design and operation of conversion and storage technologies exploits synergies between technologies. This requires fundamentally different design methodologies, such as the ‘energy hub’ approach.

In the architectural design process of buildings and cities, whether manual or with the aid of computational optimization techniques, it is typical to iterate and change designs many times. A fast but sufficiently accurate model to evaluate the solar potential is crucial in this process.

This paper presents the first version of a new model, where an annual hourly solar profile for arbitrary geometry is generated based on weather data, basic equations for beam and diffuse irradiation on tilted surfaces, and interpolation methods. The novelty of this method is that the interpolation is only applied to the obstruction calculations, hence maintaining the full hourly fluctuations of the weather data. It is highlighted in which design and optimization approaches such a solar model is of interest. Results show a good fit of the general trends and of the total annual irradiation when comparing with EnergyPlus and Daysim.

INTRODUCTION
Solar energy technologies such as photovoltaic (PV) and solar thermal (ST) play a major role in decarbonising the energy supply sector and hence reducing greenhouse gas emissions (GHG) (Mulugetta et al. 2014). Characteristics of solar energy include fluctuations and intermittency, making it challenging to integrate such technologies into a reliable and efficient system. In order to design and simulate systems which exploit synergies between different energy carriers, conversion technologies and storages, novel methodologies have to be applied such as the ‘energy hub’ approach (Geidl et al. 2007). Here, time series data on energy demand and potentials are formulated as constraints in a mathematical optimization problem to solve for optimal energy system designs and optimal operational schedules. In Mavromatidis, Orehoung, and Carmeliet (2015) the authors have employed the ‘energy hub’ approach to determine optimal installations of roof PV in a Swiss alpine village.

In a recent study by Waibel, Evins, and Carmeliet (2016) the authors have shown the sensitivity of urban design to district energy system choices, especially with stringent carbon reduction targets. These findings suggest that building demand modelling and optimization should be considered in reciprocity with the design of district energy systems.

Time resolved solar potential data, necessary for an ‘energy hub’ optimization, can be obtained with building energy software such as EnergyPlus, GIS software such as ArcGIS Solar Radiation Analyst, or with specialized lighting simulation tools such as Daysim. The disadvantage of Daysim is the high computing cost, albeit with the best accuracy. ArcGIS uses 2.5D geometry information and is therefore not able to compute radiation values on façades. EnergyPlus is computationally efficient and able to account for obstructed geometrical situations typical in cities. However, values are only calculated for the center of each external building surface, and it is not possible to consider curved surfaces. Computing times are still relatively high due to thermal calculations extraneous in this context.

Using façades for PV installation is of growing interest, especially with ambitious carbon reduction targets, but also because the electricity production is more evenly distributed throughout the day (Renken, Muntwyler, and Gfeller 2015). Other studies found significant contribution of facades to the total solar potential in urban areas due to the large areas available (Redweik, Catita, and Brito 2013) and that solar potentials can be improved by 45% on facades with optimised urban morphologies for the case of a neighbourhood in London (Sarralde et al. 2014). The latter study also highlighted the high computing cost for evaluating solar potentials on façades.

From the literature reviewed the benefits of façades for solar energy generation become evident.
However, there is a lack of a fast method of solar potential evaluation for complex geometries, especially needed in urban design and optimization. In (Kleindienst, Bodart, and Andersen 2008) annual daylight performance information was obtained by interpolating values between few simulated moments. The drawback is that temporal fluctuations are lost this way as values are averaged.

In this work a fast model based on interpolation is presented which maintains temporal fluctuations. It is entirely embedded within the 3D NURBS software Rhinoceros and its visual programming platform Grasshopper, using the Rhino.NET SDK. Other tools in Rhinoceros exist which calculate solar irradiation such as UMI, DIVA and Ladybug/Honeybee, using Daysim/Radiance and EnergyPlus as underlying engine. However, in the new model presented the focus is on obtaining hourly annual solar potential profiles with low computing times.

OVERVIEW

The presented solar model calculates annual hourly solar irradiation on meshed surfaces based on view factors for beam radiation, a custom shading mask for diffuse radiation and weather file data for direct normal irradiation (DNI) and diffuse horizontal irradiation (DHI). Since the computationally most expensive calculations are those for the view factors, trigonometric interpolation between three days of the year (summer and winter solstice and equinox) is applied to derive view factors for each hour of the year. Reflectance as well as long wave radiation emitted from the ground and adjacent objects are not considered.

Irregularly meshed geometries with quad faces of any density can be used as analysis surfaces. The advantage of this approach is that regions of high spatial detail can be meshed more densely and other regions more coarsely. Obstructions also have to be meshed but not necessarily consisting of quad faces. Rhinoceros offers extensive methods for meshing.

![Double-curved mesh](image1)

Irradiation values averaged over a specified period are visualized in false colours directly on the analysis surface (Figure 1). In conjunction with the fast calculation time this allows for a performance driven intuitive design workflow. The tool and the source code are available online.

SOLAR IRRADIATION MODEL

Total solar irradiation $G$ is commonly decomposed into its beam $B$ (or direct) and diffuse $D$ fraction.

$$G = B + D$$  \hspace{1cm} (1)

For both $B$ and $D$ there exist a range of different models of varying complexity. The ones applied in this work are presented below.

Diffuse Radiation

For every hour $t$ of the year the diffuse incident radiation component on a tilted surface assuming isotropic sky $D_{iso}(t)$ is calculated from hourly diffuse horizontal irradiation values $DHI(t)$ from a weather file multiplied by the view factor for diffuse radiation $F_d$ of an analysis surface’s shading mask. $F_d$ is a fraction from zero to one, where zero means fully obstructed view to sky and one means no obstruction. It is a constant for the year, since an isotropic sky diffuse model is assumed. Its calculation is presented in the next section.

$$D_{iso}(t) = DHI(t) \times F_d$$  \hspace{1cm} (2)

Beam (Direct) Radiation

For every hour $t$ of the year the beam incident radiation component on a tilted surface is calculated according to following equation (Honsberg and Bowden 2015) (Luque and Hegedus 2011):

$$B(t) = F_b(t) \times DNI(t) \times \left(\sin(\delta) \sin(\varphi) \cos(\beta) - \sin(\delta) \cos(\varphi) \sin(\beta) \cos(\psi) + \cos(\delta) \sin(\beta) \sin(\psi) \cos(\varphi) \cos(\beta) \cos(HRA) + \cos(\delta) \sin(\beta) \cos(\psi) \cos(HRA) + \cos(\delta) \sin(\psi) \sin(HRA) \sin(\beta)\right)$$  \hspace{1cm} (3)

$DNI(t)$ are hourly direct normal irradiation values from a weather file. $\delta$ is the latitude of the location, $\varphi$ is the azimuth of the analysis surface with the orientation measured from South to West. $HRA$ is the hour angle, which converts the local solar time into the number of degrees which the sun moves across the sky. $F_b(t)$ is the view factor for beam radiation from zero to one, zero meaning that no solar vectors can reach the surface and one meaning that no solar vectors are blocked by obstacles. The obstruction algorithm is presented in the next section.

The solar vector for any moment of the year is calculated according to the algorithm presented in (Blanco-Muriel et al. 2001).

OBSTRUCTION CALCULATION

The obstruction calculation in this work is conducted for $B$ and $D$ separately. For the diffuse radiation $D_{iso}(t)$ only one obstruction factor $F_d$ is used for all $t$, since the shading mask is identical throughout the year.
year. However, this is not sufficient for the obstruction factor $F_d(t)$ of the beam radiation, which has to be calculated based on many solar vectors.

**Shading Mask**

The view factor $F_d$ for diffuse radiation is identified with a custom shading mask. A sky dome is spanned over the analysis surface and all potential obstacles. The radius of the sky dome is automatically set to the perimeter of the furthest obstacle relative to the analysis surface. The sky dome is discretised into a mesh with $u$ faces using native Rhino.NET functions and for each of its face vertices rays are constructed to the analysis surface centroid and checked for collision with the obstacle geometries. If a ray is not blocked by an obstacle, then the obstruction factor for diffuse radiation $F_d^m$ between the analysis surface and mesh face $j$ of the sky dome will be increased by one. $F_d^m$ is divided by the number of vertices $k$ (four for quad faces and three for triangles) and multiplied by the mesh face area $a_{sk}$ to account for the different mesh face sizes of the sky dome. The total view factor of an analysis surface for diffuse radiation $F_d$ is obtained with following equation:

$$F_d = \frac{\sum_{j=1}^{u} F_d^m \cdot a_{sk}^m}{A_{sk}}$$

(4)

$A_{sk}$ is the total area of the sky dome. $F_d$ is a number of zero to one, where one indicates no obstruction and zero indicates no access to diffuse radiation.

Two settings in the tool are available; to adjust the resolution of the sky dome mesh, and to apply the obstruction calculation to each mesh face of the analysis surface (detailed mode), instead of only its mesh centroid (simple mode). The sky dome with overlayed shading mask can be visualized in Rhinoceros (Figure 2, left).

![Figure 2 DHI is reduced by the total view factor $F_d$.](image)

**Beam Shadow Factor**

Calculating the view factor for beam radiation $F_b$ is similar to the calculation of the view factor for diffuse radiation $F_d$. However, instead of using a sky dome, here rays are constructed for hourly solar vectors of a given day to each mesh face vertex of the analysis surface $m$. Again, the rays are checked for collision with obstacles. If a ray is not obstructed then $F_b^m$ (for mesh face $i$ of the analysis surface) is increased by one. If all four rays of a mesh face quad are not obstructed $F_b^m$ has a value of four. Again, to account for different mesh face sizes of the discretized analysis surface, $F_b^m$ is multiplied by the area $a_{sk}^m$ of this mesh face. The total beam radiation view factor $F_b(t)$ of an analysis surface for a specific hour of the year $t$ is hence given by:

$$F_b(t) = \frac{\sum_{m=1}^{n} F_b^m \cdot a_{sk}^m}{A_{sk}}$$

(5)

where $A_{sk}$ is the total area of the analysis surface. $F_b(t)$ varies from zero to one, where zero means that for the considered hour the analysis surface has no access to beam radiation at all and one means that there is full access to beam radiation. The factor is used to reduce the beam radiation component in equation (3) for each hour.

Averaging the view factors over the analysis surface can be omitted, hence generating $n$ solar potential profiles instead of one, where $n$ indicates the number of mesh faces of the surface.

![Figure 3 Reducing beam irradiation $B(t)$ of an analysis surface by view factors $F_b(t)$.](image)

**INTERPOLATION ALGORITHM**

In the previous sections the equations for calculating the total irradiation $G$ on an analysis surface were presented and the algorithms for the view factors for both diffuse and beam radiation components were introduced. The novelty of this work however is the interpolation algorithm for the beam view factors presented in this section. This allows a significant reduction in computing time while maintaining annual hourly fluctuations, characteristic of solar potential profiles.

**Using three simulated days for interpolation**

In contrast to $F_b$, which is valid throughout the year, the view factor $F_b(t)$ for beam radiation is only valid for the considered solar vector and hence only for a certain hour of the year. Since the view factor calculation is computationally expensive, especially with a large number of obstacles, finding approximations here yields in the greatest time savings.

In this work, instead of calculating view factors for beam radiation for all daylit hours of the year, we propose to calculate typical days of the year which capture the extreme and the average sun angles.
Hence, the view factors are only calculated for the summer solstice, when the sun angle is steepest, for winter solstice, when the sun angle is lowest and for an equinox day, which represents average sun angles (Figure 3). The equinox day can be used twice, for the spring and autumn equinoxes.

The hourly view factors for these three days are stored, and to obtain view factors for the remaining hours of the year, denoted as \( F'_b(h, d) \), the stored factors are interpolated trigonometrically (Figure 4):

\[
F'_b(h, d) = \begin{cases} 
F_{\text{day}1}(h) \times x(d) + F_{\text{day}2}(h) \times (1 - x(d)) & (6) 
\end{cases}
\]

\( F_{\text{day}1}(h) \) and \( F_{\text{day}2}(h) \) are a pair of the previously calculated view factors for winter solstice, equinox and summer solstice, used for interpolation. \( h \in [1, 365] \) represents the hour of the day. \( x(d) \) denotes the trigonometric weighting factor and depends on the day of the year \( d \in [1, 365] \):

\[
x(d) = \begin{cases} 
\cos(0,5\pi(1 - x'(d))), & \text{if } d \in 1^{\text{st}} \text{ or } 3^{\text{rd}} \text{ quarter} \quad (7) \\
\sin(0,5\pi x'(d)), & \text{if } d \in 2^{\text{nd}} \text{ or } 4^{\text{th}} \text{ quarter} 
\end{cases}
\]

\[
x'(d) = \left( \frac{(d_{\text{day}2} - d_{\text{day}1}) - (d_{\text{day}1} - d)}{(d_{\text{day}2} - d_{\text{day}1})} \right) 
\]

Quarters in this context are counted between the winter solstice, vernal equinox, summer solstice and autumnal equinox.

**VALIDATION**

A case study in the city center of Zurich is used for validation of the new model developed here (Figure 5). The urban context is shown in green and the building which is analysed for its annual solar potential is shown in red. The building is located on the South-West corner of the site. A TMY weather file from Meteonorm for the city of Zurich was used. Topography has not been included, but could easily be as geometrical obstacles. The new model is compared with the Daysim daylight coefficient method and with EnergyPlus, both executed via the Rhinoceros Grasshopper Plug-In Ladybug/Honeybee (Mostapha Sadeghipour Roudsari and Adrian Smith + Gordon Gill Architecture, Chicago 2013). Five different analysis surfaces are compared in total, for each building façade and the flat roof.

For Daysim, sensor point grids of 10x10 for the South and North facades, and 14x7 for the East and West facades and the roof, with an offset of 0.1m to the base surfaces were set. The following parameters were set with the ‘Honeybee RADParameters’-component in Grasshopper: high quality, 5 ambient bounces, 1000 ambient divisions, 20 ambient super samples, an ambient resolution of 300 and an ambient accuracy of 0.1. For the analysis of the results, the values of all sensor points are averaged per surface.

For the shading calculation in EnergyPlus the ‘Sutherland Hodgman’ algorithm for polygon clipping, detailed sky diffuse modelling and a calculation frequency of every 30 days (12 calculated days per year, EPlus12d) or every 120 days (3 calculated days per year, EPlus3d) were set. One thermal zone describes the whole building volume, with one calculation surface for every façade and roof.

For the new model, a mesh resolution of 10x10 for every building surface and a detailed shading mask calculation with a skydome consisting of 576 patches were set. The model was tested with three calculated days for \( F_b(t) \), as described in the sections before (Interp.3d) and with 12 days for \( F_b(t) \) (Interp.12d) which results in having the same 65 vectors as used in the daylight coefficient method in Daysim (Figure 3).

The calculation time with Daysim was 150 seconds and with EnergyPlus it was 18 to 23 seconds, whereas with the custom model it was 5.5 to 7.5 seconds on an i7-4800MQ 2.70GHz CPU with 16G RAM (Figure 6).
Time-series

Figure 8 shows the simulation results of one week in winter for the roof and one week in summer for the South façade for all studied models. It can be seen, that the new model has a generally good fit to Daysim and EnergyPlus. However, in the time series shown the new model tends to overestimate. There is no clear difference between Interp.3d and Interp.12d. EnergyPlus3d shows similar errors as the new model, indicating that using obstruction coefficients of only three days in EnergyPlus leads to significantly higher errors even with the detailed calculation models used in the software.

Heat maps

In Figure 7 heat maps show solar radiation for each model and the absolute error for the cases Interp.3d vs Daysim, Interp.3d vs EPlus12d and EPlus12d vs Daysim for each hour of the year for each of the five analysis surfaces. In general the patterns of the annual hourly solar radiation of all three models are in good agreement with each other. However, there are certain mismatches visible especially for the new model. The heat maps with the absolute errors show in red when the new model overestimates radiation, and in blue when the new model underestimates. Underestimation occurs especially on the roof in summer mornings, and on the West façade in the evenings. Overestimation occurs especially on the roof in winter evenings, on the South façade in summer evenings and on the East façade in the mornings. The error of EnergyPlus against Daysim is relatively low.

Statistics

In Figure 9 the results of the models are compared for each façade for the cases Interp.3d vs Daysim, Interp.3d vs EPlus12d and EPlus12d vs Daysim. Furthermore, histograms with the absolute errors in Wh/m² are shown. Only data for daylight hours is
included, which for this location is 4559 hours per year. Hence, a misleading bias to high correlation values due to hours of zero radiation is avoided.

It can be observed that the new model performs differently depending on the façade direction. Generally, a good fit can be recognized, which however becomes less clear with high irradiation values. The highest discrepancies of the new model are produced on the West façade. The comparison of EnergyPlus against Daysim shows significantly better match than the new model, however on the North façade a mismatch can be seen with higher irradiation values. For all comparison cases, the histograms show that the majority of the results have a small absolute error, with EnergyPlus against Daysim having a smaller spread than the new model against Daysim.

Figure 10 shows the total annual solar irradiation for all models and surfaces. With Daysim as the reference, the new model performs worse than EnergyPlus for the roof and the West façade. However, for the South façade the values of the new model are slightly better than those of EnergyPlus. For the North and East façade, both EnergyPlus and the new model have similar deviations to Daysim.

Table 1 summarises correlation coefficients (R), coefficients of determination (R²), maximum underestimated value (Max−) in Wh/m², maximum overestimated value (Max+) in Wh/m² and root mean squared errors (RMSE) in Wh/m² for all directions. While high correlation coefficients are achieved with the new model, the RMSE can be very high depending on the direction. Comparing all cases shows that absolute errors in the new model are up to four times higher than with EnergyPlus against Daysim.
Daysim. It is striking that the errors in EnergyPlus almost double when reducing the obstruction calculation frequency from 12 days to 3 days, while in the new model this reduction has a negligible effect.

Table 1

<table>
<thead>
<tr>
<th>South</th>
<th>West</th>
<th>North</th>
<th>East</th>
<th>Roof</th>
<th>R</th>
<th>R^2</th>
<th>Int3d</th>
<th>Max.</th>
<th>E+3d</th>
<th>RMSE</th>
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<td>0.86</td>
<td>0.95</td>
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<td>-</td>
<td></td>
<td></td>
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<tr>
<td>0.88</td>
<td>0.82</td>
<td>0.75</td>
<td>0.96</td>
<td>0.88</td>
<td>R^2</td>
<td>-</td>
<td></td>
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<td>-280</td>
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<td>-107</td>
<td>-82</td>
<td>-408</td>
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<tr>
<td>367</td>
<td>62</td>
<td>76</td>
<td>271</td>
<td>313</td>
<td>E+3d</td>
<td>Max.</td>
<td>Daysim</td>
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<tr>
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<td>55</td>
<td>23</td>
<td>45</td>
<td>85</td>
<td>RMSE</td>
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APPLYING

The main purpose of the tool is to have a fast and reasonably accurate solar potential model for the urban context, which allows the generation of spatially and temporally resolved solar irradiation profiles for complex geometries. This is important especially for intuitive urban building and energy systems design processes and computational optimization methodologies.

Time-resolved data is required for energy systems design using the ‘energy hub’ approach. A fast solar model becomes crucial if solar potential profiles on roofs and building facades change during an optimization or design process. One such work was conducted by Waibel et al. (2016), where the geometry of a neighbourhood consisting of four buildings was optimized for the profit generated by the rent using Simulated Annealing while reaching carbon reduction targets with an optimized district energy system using the energy hub approach (Figure 1, right). With every change in geometry, the solar potentials and consequently the optimal district energy system also changed. As the optimization process involved many design evaluations (several thousands, including multiple runs), reducing the computational cost of the evaluation model was a necessity in making the study feasible.

CONCLUSION

This work has presented the first version of a solar irradiation tool embedded entirely within the 3D NURBS software Rhinoceros and its visual programming platform Grasshopper. The purpose of the tool is to have a fast and approximate model to generate spatially and temporally resolved solar potential profiles for complex building geometries and building configurations. Such solar potential profiles are required in an ‘energy hub’ design approach, where synergies between different storage and conversion technologies can be exploited and matched with demands.

Other tools exist but their computing cost is too high for real-time feedback necessary in an intuitive design process or for a computational optimization methodology.

The tool presented here achieves its low computing cost mainly by omitting reflectance and with the trigonometric interpolation of view factors for beam radiation from three distinct days: summer solstice, winter solstice and equinox. From these days, the view factors for the rest of the year are deduced. Therefore, the main contribution of this tool was to show that as an approximation, the computationally expensive calculation of view factors does not necessarily need to be performed for as many days.

Comparing the custom tool with results from Daysim and EnergyPlus showed good agreement on general trends. The correlation graphs showed a reasonable fit for most of the façade directions. The main reason for the errors is suspected to be in the use of an isotropic sky for diffuse radiation. The poor performance of isotropic models for tilted surfaces is well studied (Reindl, Beckman, and Duffie 1990) and for this tool this issue should be tackled in the future by implementing other sky diffuse models.

Introducing error functions to the equations, which depend on orientation, tilt angle and cloud factors, could further improve the model fidelity without increasing calculation times. Error functions could be trained with supervised learning algorithms, using validated data sets from Daysim or Radiance.

With the known errors in the current implementation of the tool, the question arises as to the sensitivity of optimization and design outcomes. Further work is required here. Generally, using an approximate model as a first stage in a sequential optimization can speed up the entire process without necessarily compromising on the solutions found as long as the approximate model guides the search in the same direction as the more sophisticated model (Waibel et al. 2015). This would be a potential application of this tool.

When generating solar potential profiles of building facades, large surfaces should generally be avoided. There is a risk that the profiles are not representative anymore if the solar exposure is too diverse. This is
often the case in urban areas, where complex obstructions are present. Therefore, subdividing a façade into smaller patches should be considered.

**NOMENCLATURE**

G, Global solar irradiation; 
B, Beam (direct) solar irradiation; 
D, Diffuse solar irradiation; 
t, t, Hour of the year / day; 
d, Day of the year; 
D_{iso}(t), Hourly diffuse solar irradiation using an isotropic sky model; 
DHI(t), Hourly diffuse horizontal irradiation; 
DNI(t), Hourly direct normal irradiation; 
δ, Earth declination angle; 
φ, Latitude of location; 
β, Analysis surface tilt; 
ψ, Analysis surface azimuth; 
HRA, Hour Angle; 
F_d, View factor for diffuse irradiation; 
F_d^j Face of mesh face j of the sky dome; 
F_b(t), Hourly view factor for beam irradiation; 
F_b^i, Hourly view factor for beam irradiation via interpolation; 
F_b^i, Beam radiation view factor for mesh face i of the analysis surface; 
F_d^i, Hourly view factors of day d used for interpolation; 
a_{sky}, Area of mesh face j of the sky dome; 
A_{sky}, Total area of the meshed sky dome; 
a_{m}, Area of mesh face i of the analysis surface; 
A_{m}, Total area of the meshed analysis surface; 
xml, Weighting factor for interpolation;

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**REFERENCES**


