École Polytechnique Fédérale de Lausanne

Interdisciplinary Laboratory of
Performance-Integrated Design (LIPID)

Semester Project Report - Master Semester 1

The influence of the Level of Detail (LOD) on the assessment of the photovoltaic (PV) potential in urban environments

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Contents

[1]This section has been written in collaboration with Stéphane Bonjour

1 Introduction

It is widely agreed that the climate is changing and has a disastrous effect on the diversity of animals and plants, the increase of natural disasters and the higher damages they are causing, and so on. Solutions are beeing searched to fight this change, as we saw it recently in Paris with the 2015 United Nations Climate Change Conference. One of the solutions proposed is to use renewable energies, as for example solar panels. That is why it is so important to know the potential of this kind of energy, especially in an urban environment. Indeed the roofs and façades of the buildings offer big unused surfaces and this would be a good way to use them. Another advantage is that there is no terrain to buy as it would be for a solar farm, what means less costs.

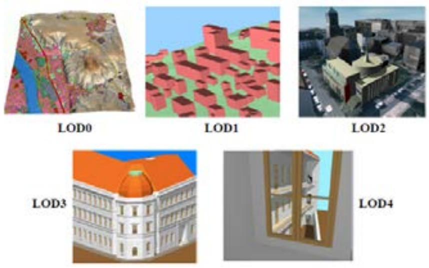


Figure 1: Description of the LODs as explained by Gesquière *et al.* [3]

Some studies already exist on the effect of the level of detail (LOD) for example about shadows as done by Biljecky *et al.* [5] or heat demand forecasts studied by Strzalka *et al.* [6]. The idea of this paper is to do a similar study, but on another important topic: the assessment of the photovoltaic potential (PV potential). One point will be particularly observed: the effects of the partial shading. Indeed, as some studies show it (see for example Khaing *et al.* [4]), the partial shading has an enormous influence on the electricity production of a PV panel. That is why it is so important to know how significant the difference of shaded areas is between the LODs.

In the 3D-modelling universe, the LOD has a crucial role, as it is the case to assess the PV potential in urban environment using this kind of models. According to the CityGML standards, there are five levels of detail (see Fig.1), going from the footprint (LOD0) to a precise model with inside and outside details (LOD4) as stairs and chimneys.

For the subject we are studying, meaning the assessment of the PV potential, the inside details are totally superfluous. That is why we are going to consider the LOD3 model as a perfect model. But an LOD3 model costs a lot more to do than an LOD1 or LOD2. This brings us to the main question we will try to answer in this paper: Is it useful to do an LOD3 model, or are LOD1 and LOD2 models precise enough to assess the PV potential of a building, or even of a city? The second part of the paper will handle the theme of the shading effects. Indeed, the production of electricity of PV cells is affected when a part of the cell is shaded. Therefore, what would be the consequences on the PV potential if all the zones unregularly lit by the sun would be considered as unusable for PV cells? This is the second question to be answered in this paper.

2 Methodology

First of all, some buildings have to be selected following some criteria. The objective was to choose buildings as different as possible in their location and their geometry. For the location, there are buildings from the old town as well

(a) B1

(b) B2

(c) B3

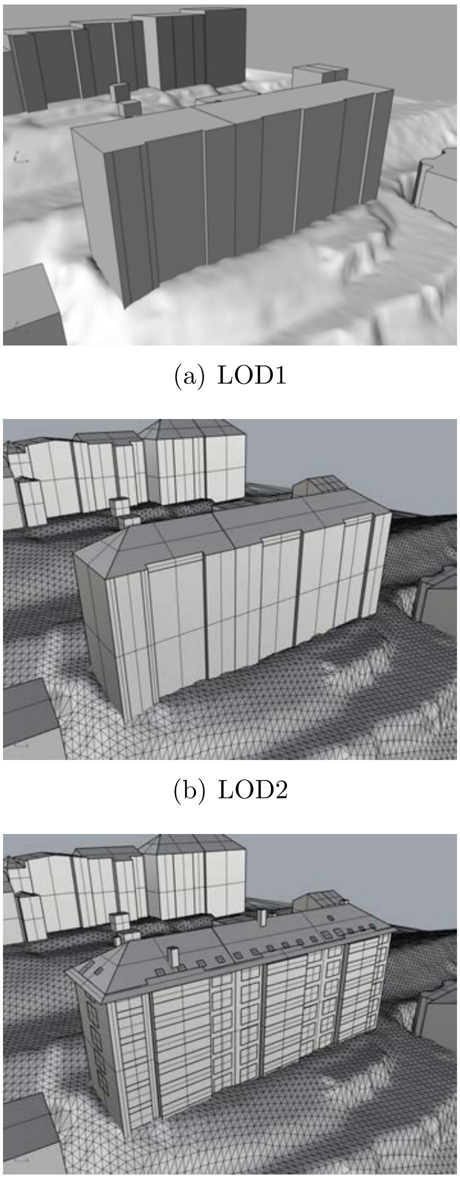
(d) B4

Figure 2: Four buildings chosen for the study

as the new center and the suburban area. Going from hip roof to flat roof, with dormers, chimneys, windows or balconies, a wide range of buildings is covered with the chosen buildings presented in the figure 2. The buildings 1 and 2 were studied more specifically by Stéphane Bonjour, and the 3 and 4 by myself.

The common part for the next subsections is the 3D modeling. All this part is done using the software *Rhinoceros*. The LOD1 and LOD2 models are created using a plane measuring the altitude of the terrain and the one of the buildings with a horizontal distance of one meter between the points, respectively fifty centimeters. With those points, the buildings are created automatically using the software *BuildingReconstuction*(Peronato *et al.* [7] section *3.1 Modeling* for more details). For LOD3, the LOD2 model is used as a basis and the only modifications are done on the studied building. This means that the environment is still modelled in LOD2 and the only part in LOD3 is this building (see Fig.3). For modelling it, online sources were used, as for example *Google Maps* [1] or the official web page of the canton Neuchâtel *Système d'Information du Territoire Neuchâtelois* [2].

All those models are then used for different kind of simulations using the software *DIVA for Rhino*, as it is explained in the subsections 2.1 and 2.2. But before doing the simulations, it is important to assign a weather file corresponding to the studied city (Neuchâtel in this case) created in Meteonorm, explained by Remund [8] and using datas from 1991 to 2010. The other important point is to assign materials to all the surfaces of the buildings and the terrain. As the effects of the choice of materials is not a focus in this paper, the standard characteristics are chosen for the materials. This means a reflectivity of thirty percent for the buildings (roofs and façades) and ten percent for the terrain.



(a) LOD1

(b) LOD2

(c) LOD3

Figure 3: Models for the different levels of detail of the building 4

2.1 Estimation of the error due to the LOD

In this part, the focus is put on the error committed using an LOD1 or LOD2 model considering the LOD3 one as the reality. The distance between the points of the grid calculating the irradiation is chosen as one meter to avoid too long simulations. The other important parameter is the number of reflections considered. In addition to the direct sun rays and the sky luminosity, one reflection is considered. This is done putting the ambient bounces parameter *ab-2*. With more reflections, the simulations would be too long and furthermore the effects of those second order reflections are negligible, as they are unlikely to occur and also due to the low reflection coefficients. This parameter has to be chosen for the simulation called *daysim-based hourly method*. For this part, the four buildings presented in the figure 3 are used. The relative error graphs are plotted considering the LOD3 model as the reality. The formula used to calculate the relative error (R.E.) is then

$$\text{R.E.} = \frac{\text{Irrad}_{\text{LOD1,2}} - \text{Irrad}_{\text{LOD3}}}{\text{Irrad}_{\text{LOD3}}} \quad (1)$$

This error is calculated separately for each building and threshold, for the whole building, the roof and the façades and for LOD1 and LOD2 (as the error of LOD3 in constantly zero).

2.2 Partial shading effects

This part is looking deeper into the effects of the partial shading on the PV potential. The three differences between the simulations done for this section of the work and the ones for the section 2.1 are the distance between the points of the grid, the number of reflections considered and the surface studied. Indeed, the only surface considered in this part is the roof.

To know if a point is shaded inconstantly on the surface he is representing, a distance two times shorter is chosen for the grid. Doing this, there are nine points (the nine nearest forming a square) of this new grid corresponding to one of the old grid used in the subsection 2.1. Both grids are represented in the figure 4.

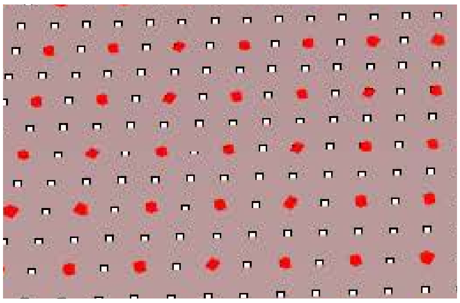


Figure 4: Representation of the old grid (red points) and the new grid (white and red points)

To have a look on the shading effects, the reflections do not have to be taken into account, as well as the sky luminosity. Only the direct sun rays are useful for this part, and this is done by putting the parameter *ab-0*. The simulation used is the same as in the section 2.1, namely the *daysim-based hourly method*. A sunlit hour is defined as an hour receiving at least one $\mathrm{Wh/m^2}$, what permits to calculate the yearly sunlit hours of each sensor of the new grid. To decide if an area is shaded or not, the following parameters have to be described:

mean sunlit hours (MeanSH) : to each old grid point, a mean value of sunlit hours is calculated using the nine points of the new grid corresponding to this point. The memorized value corresponds to the sunlit hours of the point of the new grid with the nearest value.

annual irradiation (AnnI) : corresponds to the annual irradiation of the old grid point

maximal irradiation (MaxI) : is the maximal irradiation on the roof, taking all old grid points into account

maximal sunlit hours (MaxSH) : this value is calculated using the LOD2 model and is the highest value of all the new grid points

permitted δ of sunlit hours (δ_{SH}) : is determined for each sensor of the old grid using the equation 2 and represents the highest difference in absolute value permitted between the mean sunlit hours (described just before in the text) and the sunlit hours of the nine new grid points corresponding

The equation to calculate the permitted δ of sunlit hours is the following:

$$\delta_{\mathrm{SH}} = \frac{\mathrm{AnnI} - \mathrm{threshold}}{2 * \mathrm{MaxI}/\mathrm{MaxSH}} \qquad (2)$$

This formula takes into account that with a higher difference between the annual irradiation and the threshold the shading effects can be more important without having an electrical production under the fixed limit. The ratio between the maximal irradiation and the maximal sunlit hours is used to convert a difference of irradiation into a difference of sunlit hours, and the factor 2 to compensate that the annual irradiation for a point with 0 sunlit hours is non zero due to the sky luminosity. An old grid point is considered as shaded, and therefore unusable for PV panels, if the sunlit hours of a certain number of its corresponding new grid points is too far away from the mean sunlit hours. This "certain number" will be varying from one to eight to have an analysis as complete as possible. The PV potential has to be recalculated for each one of those alternatives, putting an irradiation of 0kWh/m^2 for the shaded points.

3 Results

The results obtained are given in kWh/m^2 for each point of the grid and hour of the year. Those results have to be summed for the whole year for each point separately, because the interesting value is the yearly irradiation on the building. Using *Grasshopper3D*, the results can be represented visually, as it is shown in the figure 5.

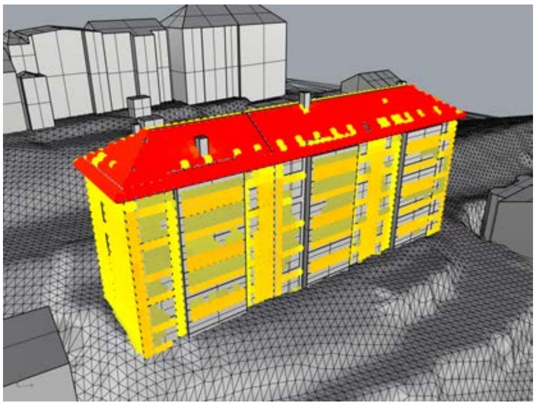


Figure 5: Irradiation on the building 4

To be able to compare the PV potential of buildings which are completely different, the results will be shown as the total irradiation of the building, calculated by multiplying the mean irradiation of each surface by its area, and divided by its footprint, meaning

$$\frac{\text{Irrad}}{\text{m}^2_{\text{footprint}}} = \frac{\sum_{\text{surfaces}} \overline{\text{irrad}} * \text{area}}{\text{footprint}_{\text{building}}} \quad (3)$$

As it is currently unprofitable to install PV panels on the parts of the building where there is an irradiation of 500kWh/m^2, the analysis will be done for different thresholds varying between 0 and 1200 kWh/m^2. This means that for a threshold of 500kWh/m^2, all the points of the grid with a lower irradiation than this value are considered as unusable for PV panels. The kind of graphs obtained doing this is presented in the figure 6.

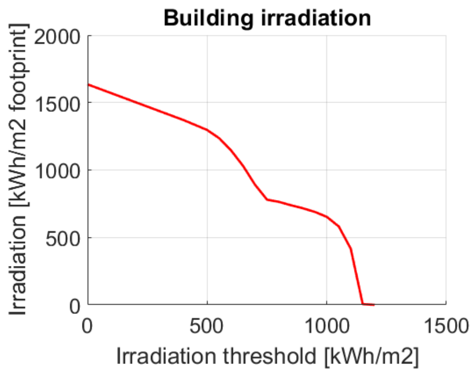
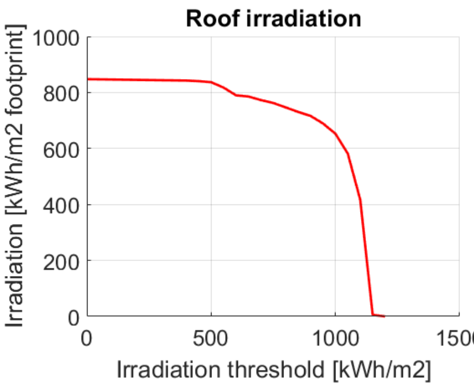


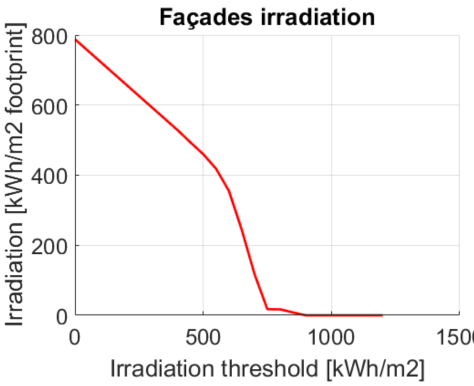
Figure 6: Irradiation on the building 4 in LOD3

As the irradiation is much higher on the roof than on the façades, it can be interesting to separate them for the analysis (see Fig. 7).

The complete results of the irradiation for the buildings 3 and 4 are presented in the figure 8. Due to the flat roof of the building 3 (see Fig.2(c)) and the flat roof in LOD1 for every building, there are three superimposed curves in the graph for the roof irradiation (3LOD1, 3LOD2 and 4LOD1). For the flat roof building, the LOD3 curve for the roof is lower than the LOD2 one. This is due to the chimneys



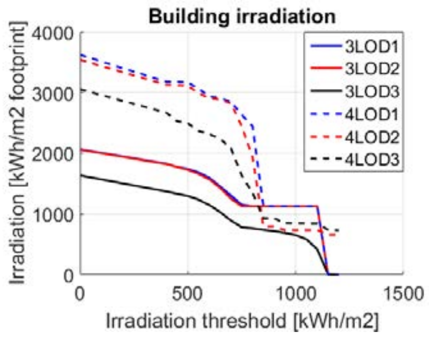
(a) On the roof



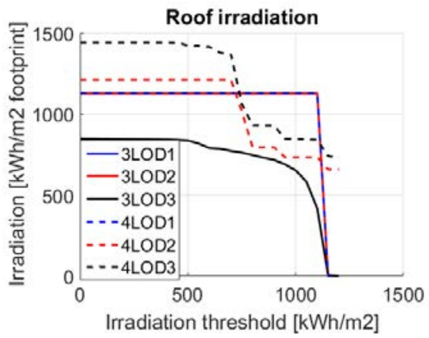
(b) On the façades

Figure 7: Irradiation on the building 4 in LOD3

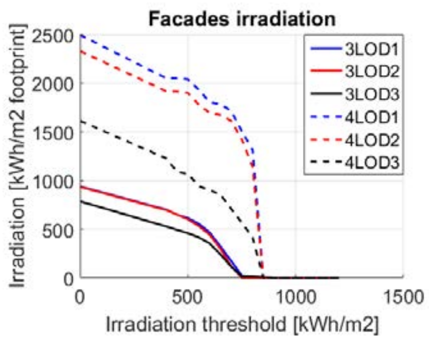
and other boxes added in the LOD3 model which involve losses of surface and shading effects. For the fourth building, the big overhangs which are present in LOD3 and not in LOD2 counteract those losses and that is what explains the higher curve for LOD3 than for LOD2. On those last curves, we observe three major falls (see Fig. 8(b)). The first one at a threshold of more or less 700kWh/m^2 is due to the side facing north northwest, the second one at 900kWh/m^2 due to the one facing east northeast and the third due to the one facing west southwest. In the other four curves, there is only one main fall, because of the flat roof of those models.



(a) For the whole building



(b) On the roof



(c) On the façades

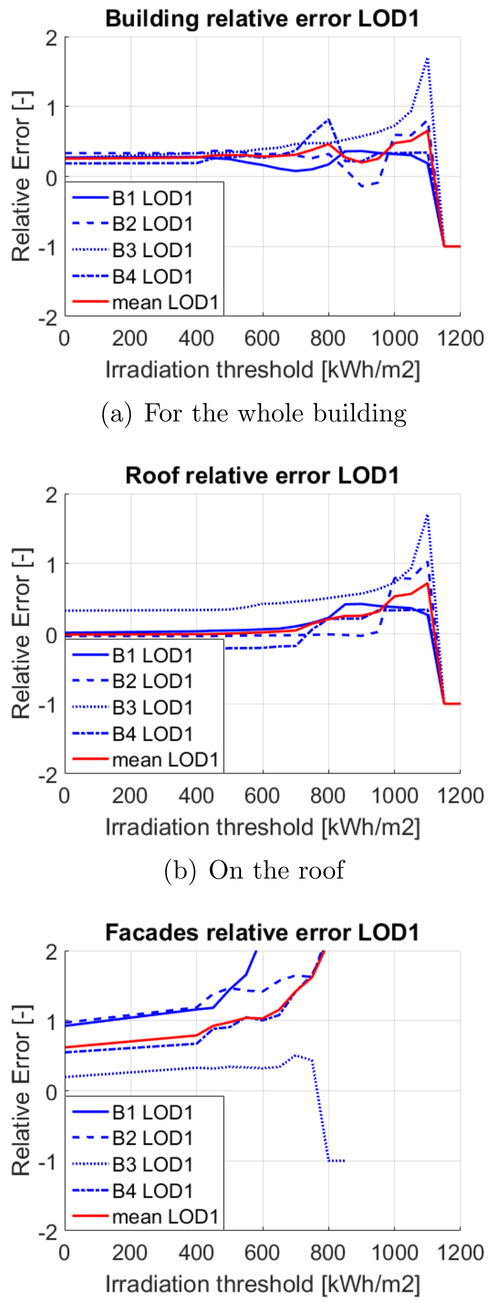
Figure 8: Irradiation on the buildings 3 and 4

The façades are decreasing more regularly, but reach a zero value much earlier than the roof at a threshold of 800kWh/m^2. With the prices and efficiency of the PV panels in 2015, it is not economically viable. That is why the section 2.2 will be done only regarding the roof. The LOD3 curves are lower than their corresponding LOD2 due to the windows and balconies added which induce losses in the PV potential.

The graph concerning the whole building is just the superposition of the roof and façades curves. The errors done for thresholds lower than 800kWh/m^2 are mostly due to the façades errors because of their much larger area then the roof and this can be well observed with the building 4. Indeed, the roof irradiation in this part of the graph is higher in LOD3 than LOD2, but it is the opposite for the façades. For the whole building, it is the same then for the façades and that means that they weigh more then the roof. But after this threshold, the façades are not more irradiated and the effects on the whole building are only due to the roof.

3.1 Estimation of the error due to the LOD [2]

The graphs obtained by plotting the curves described in the section 2.1, as well as a mean relative error, are presented in the figures 9 (LOD1) and 10 (LOD2). In the figure for the roof in LOD1 (see Fig. 9(b)), we can see that the error committed on the roof can be highly positive (building 3), almost zero (buildings 1 and 2) or even negative (building 4) for thresholds under 700kWh/m^2. Those differences are mainly due to the overhangs, absent in the building 3 (flat roof) in contrary to the three others, with a bigger one for the building 4 than for the first and second one. On the façades (see Fig. 9(c)), this error is almost always positive, due to all the area losses caused by addition of balconies and windows, which represent a big proportion of this surfaces. And in contrary to the roof with the overhangs, there are no added surfaces to compensate those losses.



(a) For the whole building

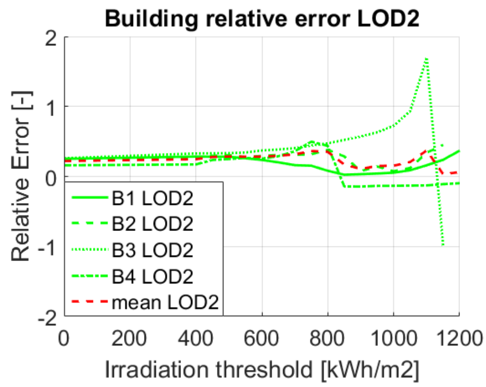
(b) On the roof

(c) On the façades

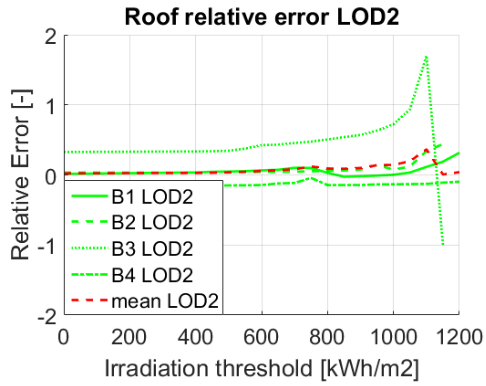
Figure 9: Relative errors of the four buildings and the mean relative error in LOD1

Looking at the building results in LOD1, we can see that the PV potential of a building is almost always overestimated for all different kinds of build-

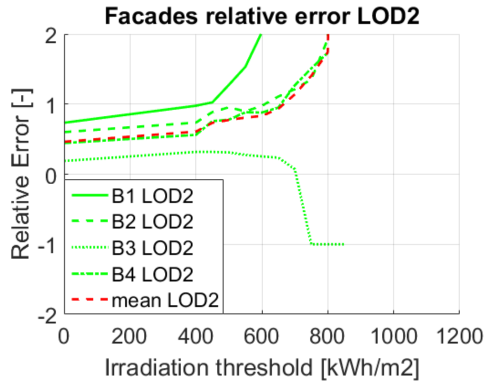
[2] This section has been written in collaboration with Stéphane Bonjour



(a) For the whole building



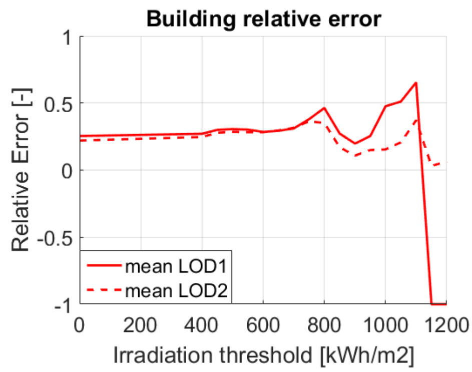
(b) On the roof



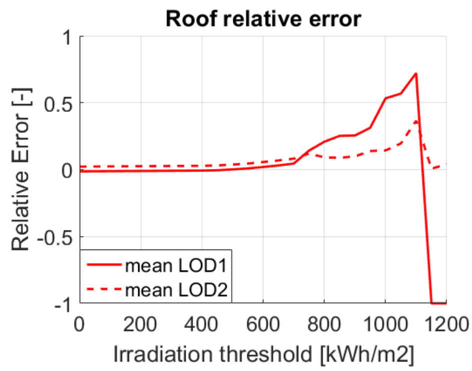
(c) On the façades

Figure 10: Relative errors of the four buildings and the mean relative error in LOD2

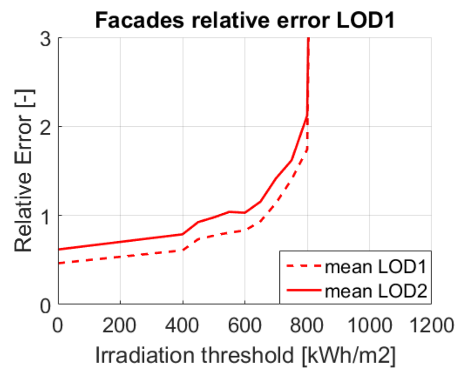
ing. In this representative sample, only one building has negative relative errors for thresholds under 1150kWh/m^2, and only for thresholds between 900 and 950kWh/m^2. This means that the probability to underestimate the PV potential of a building is really low. In LOD2 (see Fig. 10), almost the same phenomenon can be observed. The errors done are a little bit lower, especially for the roof thanks to the similar shape of the roof between LOD2 and LOD3.



(a) For the whole building



(b) On the roof



(c) On the façades

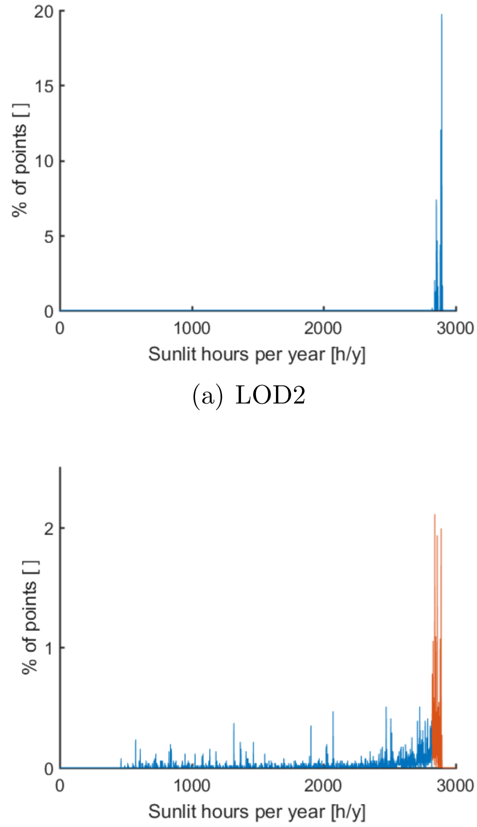
Figure 11: Comparison between LOD1 and LOD2 mean relative errors

Even though, all those curves show that the error done by using LOD1 or LOD2 models can't just be neglected, because the order of magnitude of the main error is a hundred percent for the façades and a little bit lower for the roof and the whole building, but still significant. It is also impossible to tell that the error done is the same for all the buildings, because the difference between the building with the biggest error and the one with the smallest is huge (some hundreds of percent in the worst case).

But something that could be taken out of those results is the main error done by using LOD1 or LOD2 models. Indeed, it would be useful to assess the PV potential of an urban area. Using one of those models, a lot easier to do than an LOD3 one, the results obtained by multiplying by a correction factor corresponding to this main error would be much more precise without a lot of efforts. The errors done with LOD1 and LOD2 models are of the same order of magnitude (see Fig. 11). Depending on the difference of difficulty to model in LOD1 or in LOD2, it could be good enough to use an LOD1 model only. With this method, meaning modelling in LOD1 or LOD2 and multiplying by a correction factor depending on the threshold, the error done by assessing the PV potential can be drastically reduced.

3.2 Partial shading effects

As we can see on the figure 12, the area shaded identically in LOD2 and in LOD3 is a really small part of the roof. In LOD2, all the points on the roof are concentrated between 2822 and 2902 sunlit hours, in LOD3 only twenty two percent of the points are concentrated in this range. That shows clearly why those shading effects have to be taken into account.

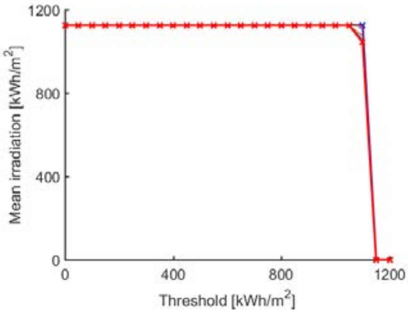


(a) LOD2

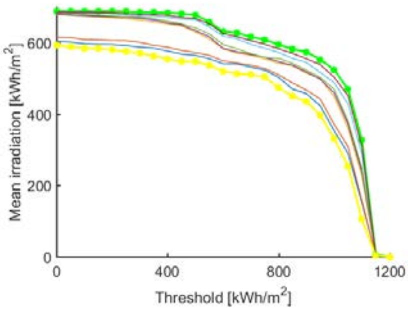
(b) LOD3

Figure 12: Percentage of points per yearly sunlit hours for building 4

With the method described in the section 2.2, an analysis was done on the building 3. The results (see Fig.13) show clearly that those effects are negligible in LOD2 for all the thresholds, except for the one of 1100kWh/m^2. This can be explained by the absence of obstructions on the roof, as well as the distance between the building and its neighbors. This last point explains the difference for the threshold of 1100kWh/m^2, because the neighbor buildings are shading a small part of the roof but only during a few hours on the year.



(a) LOD2



(b) LOD3

Figure 13: Shading effects on the building 3 for one (red curve for LOD2 and yellow curve for LOD3) to eight new grid points which are shaded, and the curve without shading effects (blue curve for LOD2 and green curve for LOD3)

But for the same threshold in LOD3, the mean irradiation without taking into account the shading effects is three times higher than the one discarding old grid points already with one new grid point which is shaded. This means that those effects cannot just be neglected. By increasing the number of new grid points which can be out of the range described in the section 2.2, we observe a convergence towards the curves which are not taking into account the shading effects.

A part of the total shading effects is already taken into account in the green curve representing the LOD3 PV potential "without shading effects". Indeed, the chimneys and other blocks modelled on the roof are shading an important area. To assess the real losses due to this phenomenon, we have to compare the yellow curve with the pink one (see Fig. 14). This curve represents the LOD2 values, but discarding the points which are totally covered in LOD3. The difference between those two curves is much bigger than the ones compared before, growing until a factor from almost ten for the threshold of 1100kWh/m^2. This result shows how important it is to consider the shading effects. But as the analysis was done only on one building, it is impossible to tell if this error is always of the same order of magnitude or not for different kinds of building.

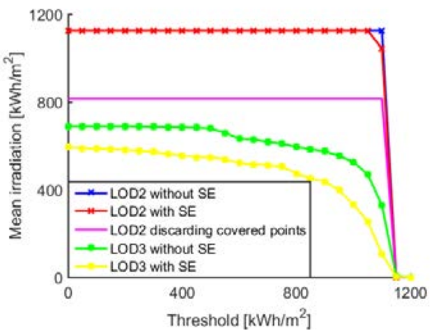


Figure 14: Summary of the shading effects (SE)

4 Conclusions and developments

The work done in the section 3.1 showed that the assessment of the PV potential using LOD1 or LOD2 models is really unprecise. It overestimates it with errors going up to two hundred percent and even more, what is clearly not precise enough. Those errors occur mainly on roofs without overhangs and on façades with a lot of windows and located in a compact neighborhood, as for example the old town of Neuchâtel.

Another important parameter of those errors is the threshold. Due to lower values of irradiation for higher thresholds, a smaller difference of irradiation represents a higher relative error.

But the method presented in the same section permits to assess the PV potential a lot more precisely and without needing an LOD3 model, which would mean a long and costly modelling. Even if an error would still exist (the quantification of this error might be done in the future), it would be clearly lower than the one done using only LOD1 or LOD2 models.

The correction factors calculated clearly depend on the city: first of all due to the latitude which highly influences the received irradiation, and secondly because of the architecture. The buildings chosen for this study are representative for a city like Neuchâtel without any skyscraper. But it would not be possible to extrapolate this result to a city like New York or Paris with such a different landscape.

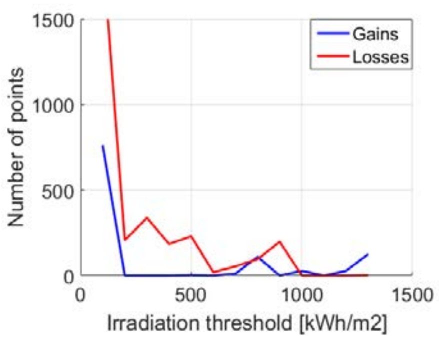


Figure 15: Gains and losses from LOD3 compared to LOD2 for each slice of 100kWh/m^2 for the building 4

As we saw it in the same section, the overhangs have an important influence on the error done with LOD1 and LOD2 models. It might be interesting to see if a mathematical relation could be found between the overhangs and the relative error. A way to know if the overhangs compensate the losses due to the chimneys and other boxes would be to represent it graphically like in the figure 15.

Doing an analysis on more buildings, the results of the section 3.2 about the shading effects could become more representative of the whole city. Nevertheless, it shows clearly that those effects do not have to be underestimated by assessing the PV potential of a building.

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