Sensitivity of calculated solar irradiation to the level of detail:
insights from the simulation of four sample buildings in urban areas

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ABSTRACT: The assessment of the solar potential in urban areas relies on a geometrical model that can be defined at different levels of detail (LOD). In this work we compare the solar irradiation simulated on the surfaces of four sample buildings, which were modeled at three different LODs as defined by the CityGML standard. Results indicate a general overestimation of the solar irradiation when using LOD1 and LOD2 models, if we consider LOD3 (i.e. the finer model) as the ground truth. However, results show also that the error varies significantly between the analyzed buildings and the considered minimum irradiation thresholds and, if we take into account only rooftops, the effect of added elements might result either in an overestimation or an underestimation of the annual total irradiation. We conclude by discussing how such findings should influence current practices in the assessment of the solar potential at the urban scale.
Keywords: level of detail (LOD), solar potential, 3D city modeling, building-integrated photovoltaics (BIPV)

INTRODUCTION

The need for solar energy to contribute a larger share of total electricity production requires a careful assessment of its possible integration in the existing built environment. In this sense, it can be estimated that the use of building-integrated photovoltaics (BIPV) on all suitable building surfaces as calculated by the IEA (2002) could cover the 29.6% of the total electricity consumption of Switzerland in 2015 (SFOE, 2015).

At a city scale, the assessment of the solar potential is usually conducted by simulating a 3D model of the urban fabric (Freitas et al., 2015). However, the accuracy of the geometric representation of the urban fabric is variable. The CityGML standard (Open Geospatial Consortium, 2012) defines five levels of detail (LODs), which are normally used in 3D city modeling (Figure 1). In historical cities, such as the ones typical of Switzerland and other European countries, buildings usually present complex roof shapes, as well as overhangs and dormers, which are represented only in LOD3 and LOD4 and limit the actual surface available for solar energy systems.

Since interiors modeled in LOD4 are not needed in solar potential assessments, LOD3 already provides a sufficiently accurate representation of the building. However, the availability of LOD3 models is mostly limited to small urban areas, probably because creating them on a large scale is laborious and requires extensive datasets, and because few applications can currently benefit from the added details (Biljecki et al., 2016a). Therefore, LOD1 and LOD2 models are normally used for solar potential assessments and reduction coefficient ratios are then applied to estimate the actual area of building surfaces that is available for the installation of solar energy systems (Fath et al., 2015).

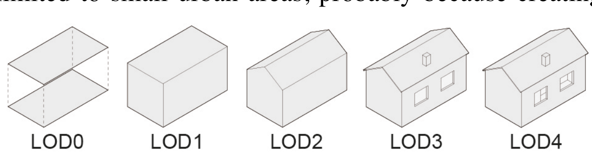

Figure 1: Example of a building modeled at different LODs.

The implications of using coarser LODs has been studied in the context of the estimation of daylight potential (Besuievsky et al., 2014), building heat demand (Strzalka et al., 2015), and shaded area (Biljecki et al., 2016b) in urban environments. However, these studies did not consider the effective availability of surfaces for the installation of solar systems at the different LODs, as it was out of their scope. On the contrary, these aspects were included in another study on solar irradiation (Biljecki et al., 2015), which was though limited to roof surfaces and focused on the propagation of positional error. Moreover, precedent studies used simplified radiation models, such as for example the Sky View Factor (SVF) for estimating the diffuse component of solar radiation (Besuievsky et al., 2014). In the case of the BIPV potential, we argue that solar radiation must be simulated through more physically-accurate simulations including inter-reflections, as these might play an important role especially in non-optimal installation conditions such as façades. The main research methodologies used in the literature are based either on a procedural modeling engine (Besuievsky et al., 2014; Biljecki et al., 2015, 2016b) to produce a large set of 3D models or on the use of sample buildings (Strzalka et al., 2015). We chose the latter approach, as we wanted to analyze a specific urban context, whose architectural grammar has not been incorporated yet in a procedural modeling engine.

In this paper we thus address the question of the most appropriate LOD for the assessment of solar irradiation - and hence of BIPV potential - on building surfaces in urban environments through the analysis of four sample buildings. We show the impact of the LOD on the solar irradiation considering different minimum irradiation thresholds, a widely-used criterion used in solar maps and normally defined by a maximum payback-time (Kanters et al., 2014). We wanted to verify whether the influence on LOD is dependent on the irradiation threshold, assuming that in the future the minimum acceptable thresholds might be smaller because of the lower costs and higher efficiency of PV cells.

METHODOLOGY

We selected four sample buildings in the city of Neuchâtel (Switzerland) from different construction periods and urban contexts that present varied roof shapes, types of façade and roof elements, as summarized in Table 1.

Table 1: Characteristics of the analyzed buildings.

Building	**1**	**2**	**3**	**4**
Period	1961-70	1946-80	1986-90	1961-70
Context	Historical center	Suburban	Urban	Urban
Main use	Residential	Residential	Offices	Residential
Roof type	Hip	Gable	Flat	Hip
Roof elements	Chimneys Overhang Windows Dormers	Chimneys Overhang	Chimneys	Chimneys Overhang Windows
Façade elements	Windows	Windows	Windows	Windows Balconies

For the purposes of this study, we used 3D models of these buildings at LOD1, LOD2 and LOD3 (Figure 2). The LOD3 model is considered here as the ground truth, i.e. a model representing the reality as much accurately as possible for what concerns the geometry of the urban canopy. The LOD1 and LOD2 models were automatically reconstructed in BuildingReconstruction (virtualcitySystems, 2014) and their geometry visually checked and manually corrected in Rhinoceros (McNeel, 2013). The LOD3 was manually 3D-modeled in Rhinoceros on the basis of the LOD2 model using photos and orthophotos as a reference for the added details. A terrain mesh was created through Rhinoceros's MeshPatch command (Delaunay's triangulation) using the points of a Digital Terrain Model (DTM) at 1-m-distance resolution. For the surrounding buildings, the automatically-reconstructed model was used at the same LOD as the simulated building, except for LOD3 for which the automatically-reconstructed LOD2 model of the context was used. The materials were defined as Lambertian diffusers with 30% reflectivity for building surfaces and 10% for the ground, as suggested by the IES LM-83-12 approved method (IESNA, 2012).

The solar radiation simulation was conducted in Diva-for-Rhino (Jakubiec and Reinhart, 2011), a graphical interface to the Radiance/Daysim (Reinhart and Herkel, 2000) simulation engine, using its default Radiance parameters. In particular, the ambient bounces (-ab) parameter was set to 2, so that one reflection from the surrounding context is taken into account in the radiation model. A sensor grid was placed with the dedicated Diva-for-Rhino tool at a 1-m interval, which is considered a suitable value for urban scale simulations (Montavon, 2010).

The total annual irradiation *Irrad* is calculated as follows:

$$Irrad = \frac{\sum_{s=1}^{n} irrad_s \cdot area_s}{area_{footprint}} \quad (1)$$

where *n* is the total number of surfaces *s* of the considered

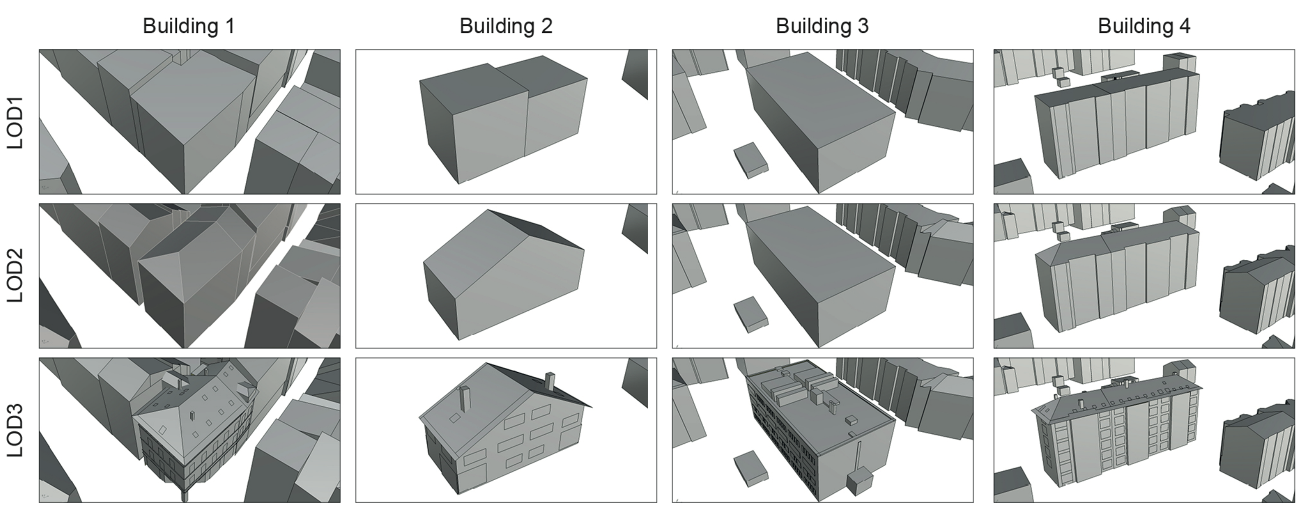

Figure 2: The 3D models of the buildings with their context at the different LODs.

building and $irrad_s$ is the mean annual irradiation expressed in kWh/m^2 of a surface s. The results are normalized by the area of the building footprint so as to be able to compare the results of different buildings.

We then calculated the relative error $R.E.$, as a whole and separately for façades and roofs, assuming the LOD3 model as the ground truth:

$$R.E. = \frac{Irrad_{LOD1,2} - Irrad_{LOD3}}{Irrad_{LOD3}} \quad (2)$$

where a positive (respectively, negative) result means an overestimation (respectively, underestimation) of the total annual solar irradiation (*Irrad*) compared to the reference LOD3 model.

RESULTS

The results of the total annual solar irradiation (*Irrad*) and Relative Error (*R.E.*) have been plotted as a function of the minimum irradiation thresholds that have been considered appropriate for this study (400-1200 kWh/m^2), in both false-color maps (e.g. in Figure 3) and line graphs (Figure 4 and Figure 5).

Figure 3 shows the irradiation of the building surfaces of building 1 for some notable thresholds. We can notice that no part of the façades can reach the 750 kWh/m^2 threshold in LOD1 and LOD2, while in LOD3 the limit is at 700 kWh/m^2, because of the effect of the overhangs. Starting from an 850 kWh/m^2 threshold, in LOD2 and LOD3 the part of the roof exposed to the North is considered as non-suitable, while in LOD1 the entire flat-modeled roof reaches that threshold. This determines an overestimation of the solar potential for LOD1 till a 1100 kWh/m^2 threshold, in which the shading from the surrounding buildings decrease the suitable area of the flat-modeled roof.

As can be seen in Figure 5, also for the other buildings the solar irradiation is often overestimated for LOD1 if we consider the entire building envelope. This is also the case of façades, where the losses are mainly due to the windows and balcony surfaces. Regarding the roofs, one would intuitively expect a general underestimation of the potential for buildings with a sloped roof (1, 2 and 4), as the roof surface is smaller than for LOD3 (and LOD2). On the contrary, we can see that $R.E.$ for roofs can be highly positive (building 3), slightly positive (buildings 1 and 2) or even negative (building 4), depending on the selected threshold. These differences are possibly due to the roof overhang, which is absent in building 3 and particularly larger in building 4. Moreover, in building 3, the presence of a large number of roof-top constructions considerably reduces the area available for solar systems. For LOD2 models, the error is generally lower but, because of the lack of many architectural details, the solar irradiation is still overestimated. However, this is not the case for the higher thresholds of building 4, for which the irradiation gained on the large overhangs exceeds the losses due to roof-top chimneys and windows. If we look at the roofs, the situation is similar and for building 4 the solar irradiation is underestimated for all thresholds.

In building 3, for both LOD1 and LOD2 relative errors, we notice a drop of the curve for façades at a threshold of 650 kWh/m^2. This is due to a vestibule which is present only in the LOD3 model (Figure 2). We decided in fact to consider this construction (including its roof) as part of the façade because it is attached to a façade that in LOD1 and LOD2 is sun exposed. The absence of the vestibule determines then an underestimation of the potential for the higher thresholds, due to the non-consideration of the irradiation gains on its rooftop.

As can be seen in Figure 4, the irradiation curves are generally distinct, meaning that each LOD provides a different estimation of the LOD at all thresholds. Only for building 3, LOD1 and LOD2 provide similar irradiation values because the geometry of the building is identical as the roof is flat and the changes are only due to the different LOD of the contexts. We can also notice that the curve slopes are generally similar for lower thresholds if

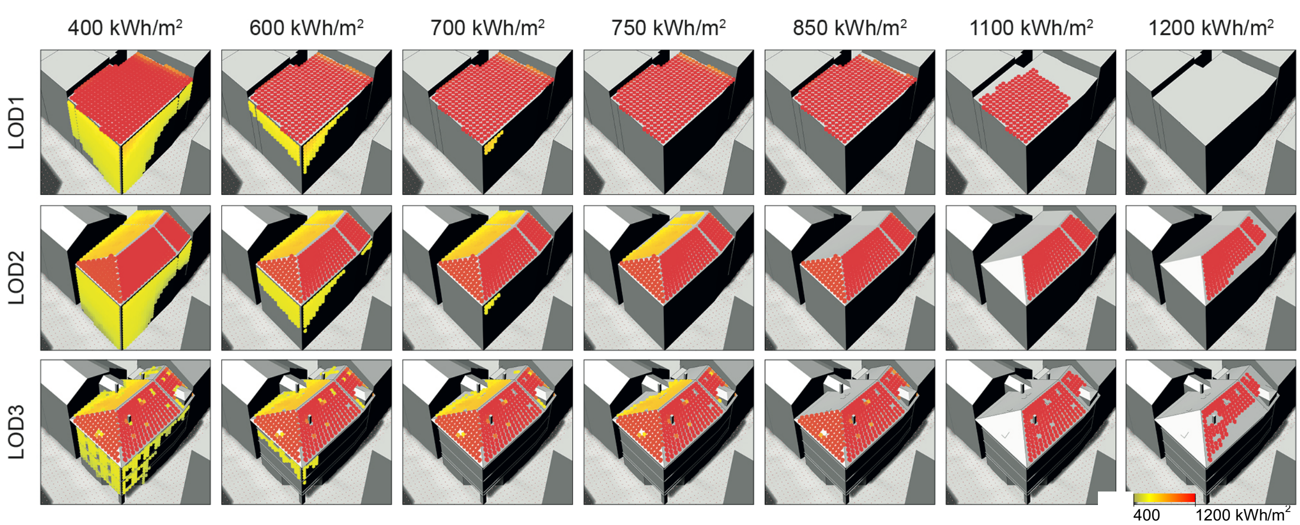

Figure 3: In false colors, suitable areas at some notable irradiation thresholds for the three LODs (Building 1).

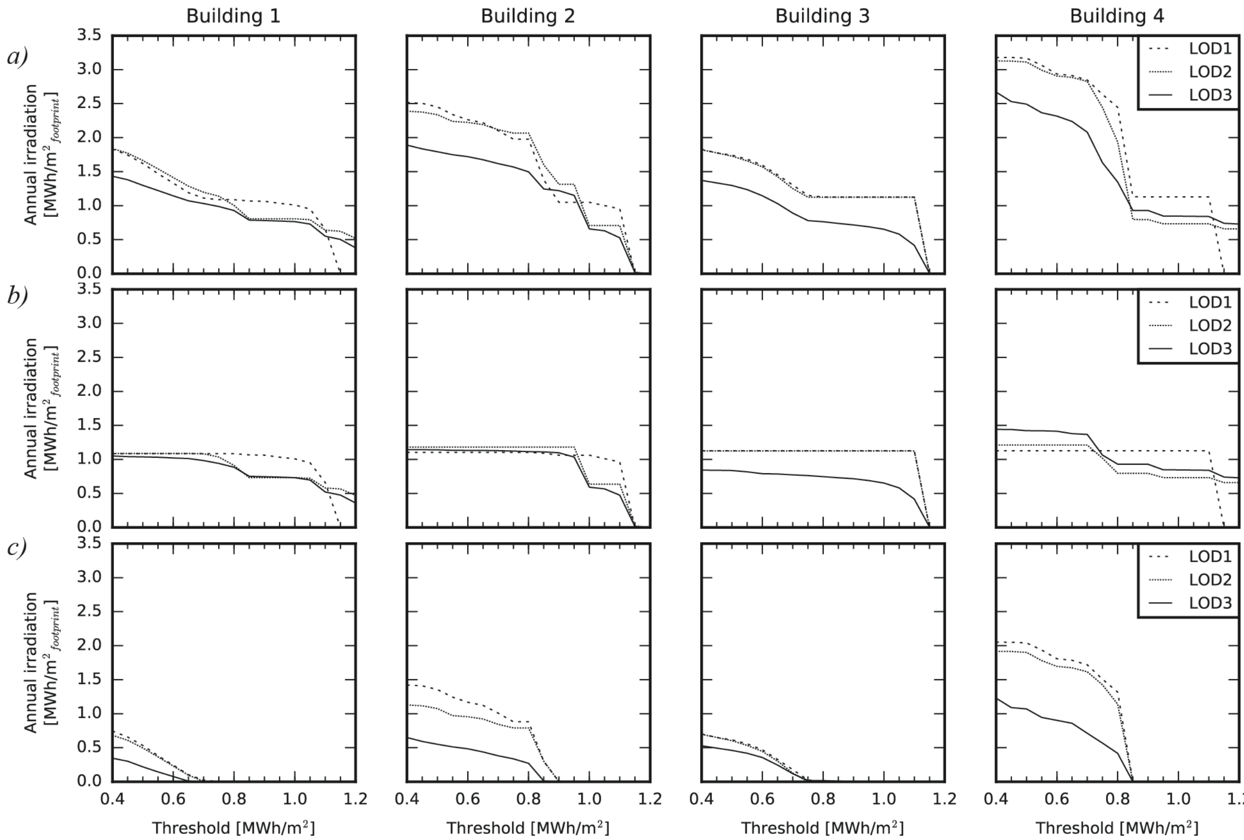

*Figure 4: Annual total irradiation (*Irrad*) for a) whole buildings, b) roofs, c) façades.*

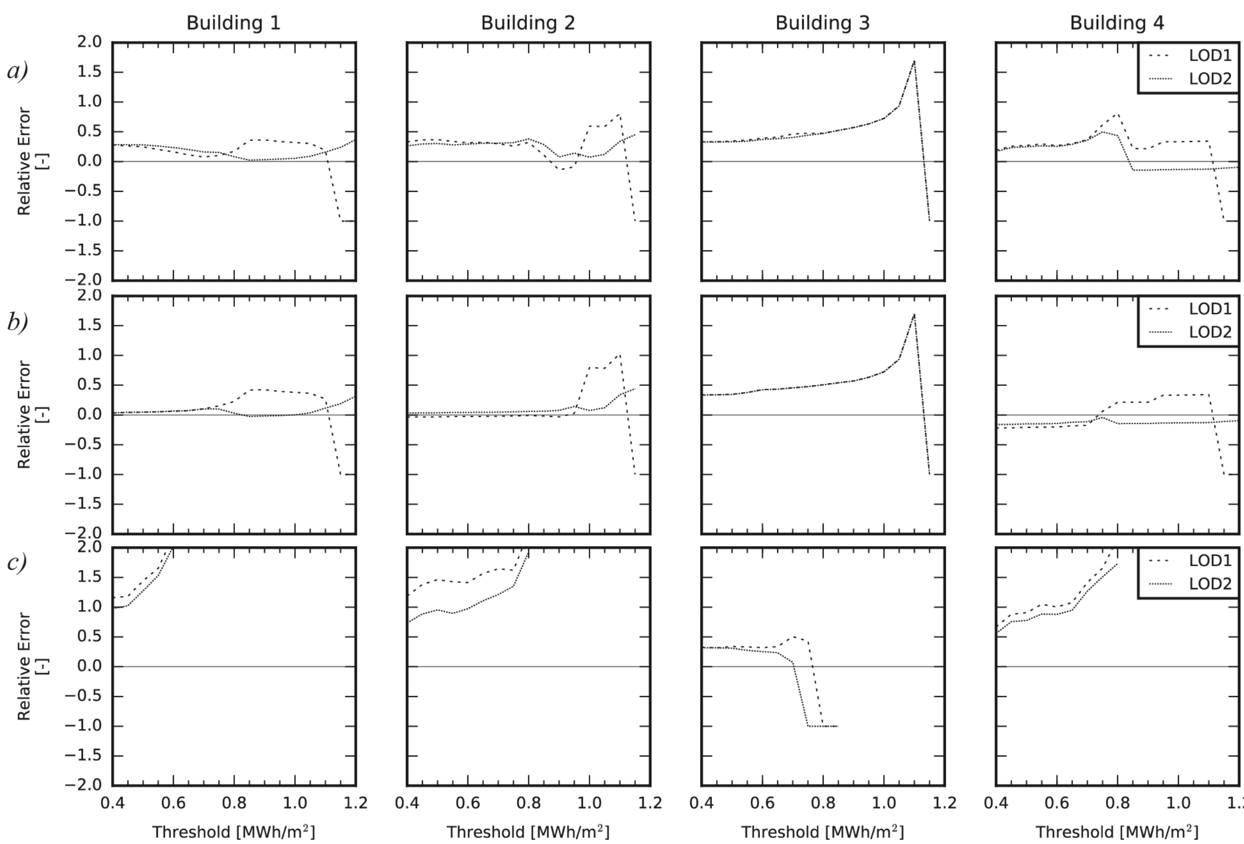

*Figure 5: Relative Error (*R.E.*) for a) whole buildings, b) roofs, c) façades.*

we consider the whole building and for all thresholds if we consider only the façades. This is because in these conditions the change in total irradiation is mostly due to windows and balconies, which are represented in neither LOD1 nor LOD2. In general, in absolute values (Figure 4) we can notice a greater difference between LOD2 and LOD3 curves at lower thresholds, as losses in façades have a great impact due to their bigger surface. However, in relative values (Figure 5) this is not the case. The relative error is higher and with more varied trends for high thresholds, usually corresponding to roof surfaces. This is because, due to the lower values of irradiation, a smaller variation represents a higher relative error. This could suggest that the effect of LOD increases the uncertainty of the effective energy yield in the present times, when only highly irradiated surfaces are considered as economically viable.

LIMITATIONS AND FUTURE WORK

The effective energy yield of a BIPV system can be influenced by several boundary conditions, such as for example module temperature, partial shading, low and diffuse light conditions. In this sense, the results of simulation of LOD1 and LOD2 models might determine for instance an overestimation of the energy production of BIPV systems, because of the effect of partial shading on series PV arrays caused by elements such chimneys and dormers that are not modeled at those LODs. On this particular point, a first exploratory study has been conducted (Stoeckli and Bonjour, 2016) and further research is planned. However, in this paper we did not take into consideration these boundary conditions as it would have gone beyond the main focus of this study. For this reason, we conservatively decided to limit the analysis to the solar irradiation.

Concerning the use of building surfaces for BIPV installations, we decided to consider glazed surfaces modeled in LOD3 as unsuitable, as we argue that the installation of transparent PV systems in existing buildings is unlikely. We also did not consider the possible installation on windows overhangs or shading systems. These assumptions may cause an underestimation of *Irrad* for LOD3 and hence of *R.E.* of LOD1 and LOD2 if overhang- and shading-related BIPV applications are considered feasible.

Some other concerns regarding the accuracy of the 3D model include vegetation which was excluded at this time, as this could have biased the study of the effect of the LOD. Similarly, for the materials reflectance, we used standard values as we considered the definition of material properties as part of another type of level of detail than the geometric LOD defined by the CityGML standard, which was the object of this study. A first exploratory research has been conducted on this particular point (Bonjour and Stoeckli, 2016) and further research is planned. Finally, because of the 1-m interspace between the sensor points, in this work we were not able to take into consideration the finer details of the LOD3 model, such as for example small chimneys and roof-top windows. We consider though the sensitivity of the solar irradiation to shading from vegetation, materials reflectance and spatial resolution of the sensor grid as very relevant aspects and we aim to explore them in our future work.

DISCUSSION

Although the use of these models is generally accepted in the assessment of the solar potential because of the difficulty to produce urban-scale LOD3 models, this study showed that the use of standard surface-availability ratios to estimate the area not occupied by architectural elements, based on the assumption that LOD2 models always overestimate the irradiation, could determine incorrect results for some buildings and irradiation thresholds. We have seen in fact that in some cases the irradiation gains due to overhangs compensate or even exceed the losses due to the rooftop superstructures. However, we cannot determine whether this error would influence the results of large-scale assessments, as we cannot judge the representativeness of our case studies in the building stock of the city nor – obviously – extrapolate such results to other urban contexts.

We also noticed that the difference between the relative error of the sample buildings we considered is extremely variable both between different buildings and at different thresholds, especially in rooftops, so that it is not possible to generalize its validity. Based on these findings, we argue that the use of a refined LOD2 model, including the main roof superstructures and overhangs, would provide a better estimation of the building solar potential. In this sense, some semi-automatic building reconstruction methods based either on LiDAR or photogrammetric data could provide at least the largest of these elements (Xiong, 2014). On the contrary, an accurate modeling of façades details is likely more complex, but the use of surface-availability ratios to consider the irradiation that can be actually exploited in façades seems more reasonable than for roofs, as our results showed that façade irradiation curves have similar slopes at all irradiation thresholds. Thus in this context it seems necessary to introduce a finer classification of LODs than the one defined by the CityGML standard, as recently proposed by Biljecki et al. (2016a).

It is also worth comparing our results to those obtained by similar works in the literature, despite their different application or study purposes. Strzalka et al. (2015) found a maximum difference in the heating demand from LOD1 to LOD3 model of about 12%, which is far less than what we obtained in our study. Biljecki et al. (2016b) concluded that the effect of dormers and chimneys is negligible in the shading prediction, because they are not present in all buildings and have an effect only at particular times. On the contrary, for solar irradiation, the effect of building elements modeled only at LOD3 cannot be neglected if we consider these surfaces as not suitable for solar installations and hence discard their contribution, as confirmed by Biljecki et al. (2015). Moreover, all sample buildings we analyzed feature some added elements on the roofs and - clearly - windows on façades.

CONCLUSION

This paper investigated the influence of the level of detail on the assessment of solar irradiation and, therefore, of BIPV potential in urban areas. Although the findings should not be extrapolated to a large scale application without further research, this work showed that the potential error due to coarser LODs on solar irradiation is not negligible, in particular because of roof elements reducing and/or increasing the availability of the most irradiated surfaces. We also showed that results are highly dependent on the selected irradiation threshold, with very large and variable relative error for the higher thresholds, which are those that are normally considered as economically-viable today.

These findings could help experts choose the appropriate LOD for solar potential assessments. Specifically, we argue that the use of a refined LOD2 model representing the larger roof elements could significantly improve the accuracy of the results, while being feasible for large-scale applications. Moreover, information about the relative error due to coarser LODs should be taken into consideration by decision-makers as a factor contributing to uncertainty in planning solar installations.

ACKNOWLEDGEMENTS

This work has been conducted in the framework of the ACTIVE INTERFACES research project (Rey et al., 2015), which is part of the National Research Program "Energy Turnaround" (NRP 70) of the Swiss National Science Foundation (SNSF). Further information on the National Research Program can be found at www.nrp70.ch. The first author acknowledges additional support from the EPFL. The geodata used in this work have been kindly provided by the Service d'Information du Territoire Neuchâtelois (SITN © 2015 / Service de la Géomatique et du Registre Foncier). The authors would like to thank Filip Biljecki for his availability and advice during the development of this research.

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