An image-based method to evaluate solar and daylight potential in urban areas

Christina Chatzipoulka[1], **Raphaël Compagnon**[1] **and Jérôme Kaempf**[1]

[1]Haute Ecole d'Ingénierie et d'Architecture de Fribourg, 1700 Fribourg, Switzerland
E-mail addresses: chatzipoulka@gmail.com; raphael.compagnon@hefr.ch; jerome.kaempf@hefr.ch

ABSTRACT

Solar irradiance and illuminance are important renewable resources that can significantly increase buildings' energy efficiency, associated to solar passive and active techniques and use of daylighting. In addition, it is widely acknowledged that the presence of natural light and some sunlight indoors is essential for inhabitants' well-being. This paper presents a new method to assess solar and daylight availability in the built environment at different scales. The method is based on two types of images where the mutual obstruction between neighbouring buildings is represented over stereographic projections of the sky vault. The images can be used in two ways, either for the visual assessment of the examined surface(s) or, to be processed as to obtain a series of numeric performance indicators. In both ways, they can be combined with similar projections of the sun path or sky radiance/luminance distributions, for considering locations' latitude and climate, respectively. To exemplify the use and relevance of the tools, especially at the early-design stages, the method is applied to compare the proposals submitted in a masterplan competition. The five finalists are examined in relation to the performance of their façades and roofs, as well as their impact on an existing façade. Last, a targeted analysis showed a good correlation between performance indicators, readily computed by the method, and predicted annual energy demands.

Author Keywords

solar access; daylight potential; sky view factor; urban form; shading masks

ACM Classification Keywords:

- Applied computing > Architecture (buildings) / Engineering > Computer-aided design
- Human-centered computing > Visualisation design and evaluation methods

1 INTRODUCTION

There has been an increasing awareness among architects and urban designers of the significance of solar and diffuse radiation for achieving comfortable and energy-efficient buildings, and promoting occupants' satisfaction and wellbeing. Since solar and daylight availability in the built environment is strongly related to buildings' geometry and configuration, the solar and daylight potential is decided to a large degree during the early stages of the design process. Hence, rather than performing solar and energy analysis for a predefined building or urban design in the late stages of its development, it would be more effective and creative if designers could obtain immediate performance feedback on their early decisions as to optimise them. A major restriction to the consideration of solar and daylight accessibility, and to making deliberate decisions for its modification and exploitation, is the lack of appropriate to professionals' needs tools, especially at the early-design stage [9].

This paper introduces a new method for assessing solar and daylight access on building envelopes, to support design decisions regarding the geometry and positioning of new buildings. It is based on two types of images, visualisations of the mutual obstruction of urban surfaces on a stereographic projection of the sky vault, which can be also processed to compute a series of relevant performance indicators. Therefore, the method provides means for quantitative assessment of the performance of building façades and roofs, as well as the visual comparison of the obstruction caused by different designs. Compared to more sophisticated simulation-based methods (e.g. [4], [5]), the proposed one does not require further assumptions, such as about building construction, equipment, etc., relevant only to a later stage of the design process, to produce results.

The paper consists in two parts. The first part presents the proposed method, and more specifically, the two types of images and solar/daylight performance indicators computed by processing them. The second part focuses on an application example where the method is employed for assessing the performance of façades and roofs of five design proposals submitted in a masterplan competition. Except for the solar and daylight potential of their buildings, the proposals were also examined with respect to their impact on an existing façade,

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adjacent to the site. The paper completes with a brief investigation on the correlation between energy simulation results and performance indicators' values derived from the analysis of the five designs.

2 OUTLINE OF THE METHOD

The proposed method is intended to facilitate the decision-making process for architects and urban planners in the early-design phase where buildings' shape and position within the site are explored to be optimised. Accordingly, the digital 3D models of urban areas used in the method are of LOD1 or LOD2 level of detail [8]. The input information required are: (i) the geometric definition of the building envelopes (i.e. façades and roofs), and (ii) a series of sample points spread over grids located just in front of the surfaces for which solar/daylight access is to be evaluated. In order to generate these files, the 3D building geometry needs to be modelled using common CAD tools and then, exported in appropriate formats using specific translators. The models presented in the second part of this paper have been generated using the free, 2017 version of SketchUp Make software and a specific export plug-in associated to the CitySimPro software (`www.kaemco.ch`).

2.1 Multi-shading masks and effective envelope area pictures

At the next stage, the files containing the 3D model and sample points information are combined to compute "multi-shading masks" (MsM) and "effective envelope area pictures" (EEAP) (examples provided in Fig. 5, 7 and 8). Their computation is feasible by specifically developed programs which are based on the RADIANCE open source ray-tracing software (`http://radiance-online.org/`). Both types of images represent ways of "mapping" the buildings' geometry onto a stereographic projection of the sky vault. It should be noted that the pictures produced retain only the geometric information that is useful for evaluating the solar/daylight access.

For a given surface or group of surfaces, the corresponding "multi-shading mask" contains pixels whose value M_p ranges from 0 (black) to 1 (white) indicating the proportion of the total surface area considered that has an unobstructed view to the sky patch associated to each pixel. The concept of "effective envelope area picture" is slightly different: it contains pixels whose value U_p is calculated as the total area of the surface/surfaces considered that is seen from the corresponding sky patch in the sky vault. More precisely, the area that is "seen" is the projected area of the surfaces on the plane normal to the direction of the patch. In other words, the actual surface area is "scaled down", multiplied by the cosine of the normal of the surface and that of the patch. The formulas used to compute M_p and U_p values are detailed in Annex 1.

In order for the geometric information aggregated in MsMs and EEAPs to be assessed for a specific location, i.e. latitude and climate, the images can be combined with similar stereographic projections of the sun path and sky radiance/luminance distributions. The latter are known as "sky model pictures", and generated by processing hourly climatic data, i.e. diffuse and direct irradiance values, for selected time intervals [2]. Irradiance values can be obtained either from a dedicated software, such as Meteonorm (`www.meteonorm.com`), or databases (e.g. `http://satel-light.com`). The time interval for which a sky model is produced is related to the design objective examined. For instance, if the objective for a new project is to maximize solar irradiance on the building façades during the heating season, the EEAP containing all façades' surfaces should be compared to the sky model picture computed for the respective interval, i.e. heating season. (Figure 3 shows three sky models of a Swiss location, used later in the application example). Simply put, the solar objective is best achieved if visually, the brightest zones of the EEAP match well the brightest zones of the sky model picture. This intuitive assessment forms the core idea of the method: the urban solar resource results from the combination of a purely climatic component, as contained in the sky model picture, and a man-built component, as contained in the EEAP. The combination of the two pictures involves their superimposition, using pixel-by-pixel multiplication. The resulting "product picture" encapsulates all that is needed for the computation of global irradiance (I_g) or irradiation (G_g) values.

Overall, this new method based on MsM and EEAP presents several advantages among which, major ones are:

- The method offers great flexibility regarding the surface/surfaces to be examined. Depending on the users' needs, it can be applied for a single point, a plane (e.g. a window, façade or roof), a set of similar elements (e.g. group of windows, façades, or roofs) or even the entire external envelope of one or many buildings.
- As MsM and EEAP map the visibility between building surfaces and the sky vault, when visually observed, they provide a graphical mean to qualify in precision the "overall orientation" of multiple surfaces, such as the façades of a new urban development. Although there is extensive reference to "good", "bad", "best" orientations regarding buildings, on the urban scale, the orientation of built forms remains very loosely defined up to now.
- The readiness of tools involved in the method makes it appropriate for demonstration purposes in the urban and architecture education context. MsM and EEAP are produced independently of location, which allows a library of images for typical urban forms to be created. Similarly, a library of sky model pictures can be produced in advance for a series of locations. The combinations of images from these two sets and their products can illustrate the interaction of built forms' geometry and location-specified data.

2.2 Performance indicators

Several indicators characterizing the provision of daylight or sunlight can be computed from the MsM and EEAP (Fig. 1). These indicators fall into three categories: those that are completely independent of the location, those that are latitude-dependent, and finally, those that depend on the location's specific climate. Some of them are directly inspired by [7]. The next three sections present the indicators, later used in

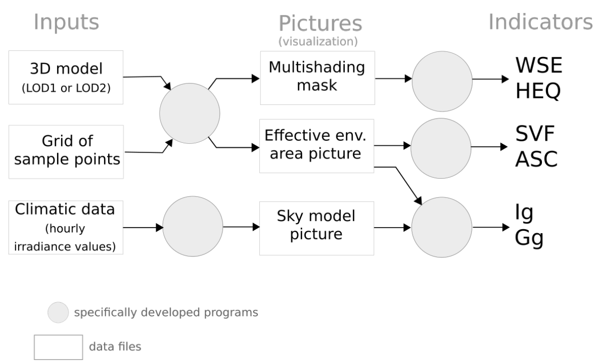

Figure 1. Schematic drawing illustrating how input data is processed to obtain MsM, EEAP and sky model pictures, next used in computing various indicators.

Section 3, by category. The formulas for their calculation are provided in Annex 2.

Indicators independent from the location

The average sky component (ASC) indicator is used to evaluate the provision of sufficient daylight. It is computed as the ratio of the illuminance received directly from the sky (assuming a standard CIE overcast sky luminance distribution) at the sample points' locations to illuminance received on a horizontal unobstructed plane. For vertical façades, the indicator ASC matches the "Vertical Sky Component" as defined in [7]. For a horizontal unobstructed surface, the ASC value is 1, whereas, for a vertical unobstructed façade, it is equal to 0.396.

The sky view factor (SVF) is computed similarly to ASC, but considering a uniform sky luminance distribution. Its value expresses the fraction of the considered area that has an unobstructed view of the sky vault. For a horizontal unobstructed surface, the SVF value is 1, whereas, for a vertical unobstructed façade, it is 0.5. A recent study has shown that SVF can serve to assess the average annual solar irradiance received by building façades [1]. Furthermore, SVF affects the long wave infrared exchanges between the urban fabric and the sky, and thus, it can be also used as indicator of the urban heat island effect.

Latitude-dependent indicators

The potential sunlight exposure (WSE) indicator is intended to quantify the provision of sunlight, mainly in term of its amenity for the inhabitants. WSE derives from summing daytime hours, i.e. hours between sunrise and sunset, weighted by the values stored in the multi-shading mask. For instance, if for a specific hour, the multi-shading mask contains a value equal to 0.5 for the corresponding sunray's direction, then, this hour is weighted by 0.5 in the sum. In other words, the particular hour is accounted just half because half the surface considered is sunlit.

HEQ is computed as the number of hours during which at least 50% of the considered surface(s) can potentially benefit from sunlight during an equinox day. This indicator makes sense only for a single façade or group of façades of the same orientation, and is more likely to be usable for locations found in middle latitudes. It is meant to assess if a façade is sufficiently exposed to direct sunlight to satisfy the inhabitants.

Climate-dependent indicators

Mean global solar irradiance I_g and irradiation G_g can be estimated by combining EEAPs with sky model pictures computed for various time intervals (e.g. the whole year or the heating season) for a given location. These indicators are used to assess the potential of the building envelope considered in the EEAP for integration of active or passive solar systems, such as PV modules, solar thermal collectors or simply window openings.

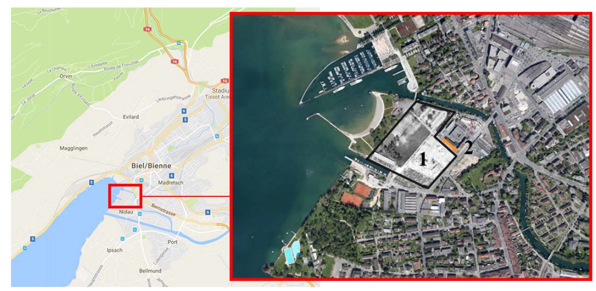

Figure 2. The area by the lake between Bienne and Nidau, in Switzerland, where the competition site (1) and the existing façade (2) considered in the analysis are shown.

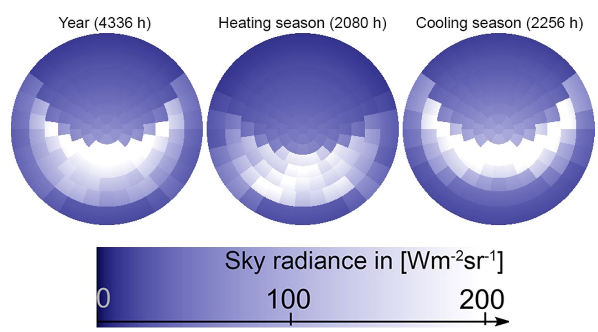

Figure 3. Stereographic representation of the sky models of Bienne, used in the application example.

3 APPLICATION EXAMPLES

This section presents the application of the presented method to assess design proposals submitted for a masterplan competition. The purpose is to exemplify the use of the MsM and EEAP for evaluating the solar and daylight performance of new building developments, as well as their impact on existing buildings, and thus their immediate relevance to the purposes of the early-design stage.

The competition was held in the context of the AGGLOlac project, and concerns the creation of a new district between the Swiss towns, Bienne and Nidau (lat. 47.14°), by the lake Bielersee (Fig. 2). The site was a former area of the National Expo, and the masterplan proposals had to envisage a mix-used neighbourhood, of high urban qualities, in a sustainable manner. After the evaluation of the initial submissions, five design proposals were selected for the second phase of the competition, in which the participant teams were asked to refine and evolve their designs. Drawings and perspectives of those projects became available to the public online (`www.agglolac.ch`). The present study made use

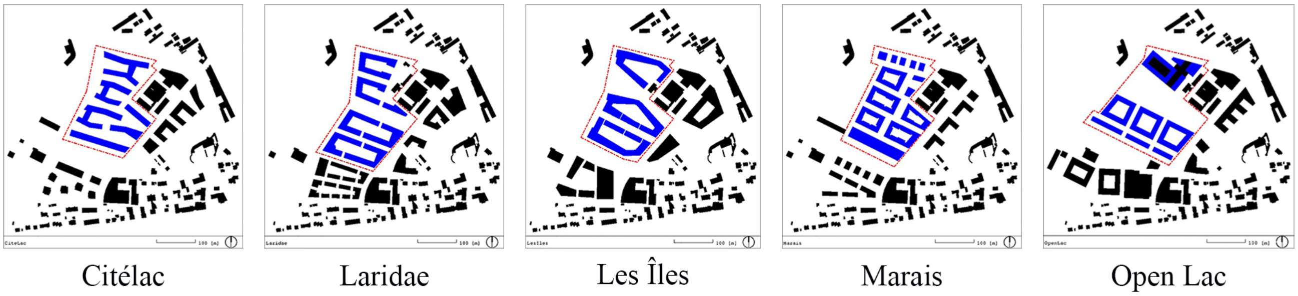

Figure 4. Ground maps of the five design proposals. The red lines outline the area of the analysis and, MsMs and EAAP were generated considering all the buildings within them (blue colour).

of that information in order to reproduce the proposed 3D building geometries in SketchUp and then, compare them in terms of daylight and solar availability using the proposed method. For the analysis, three sky models were produced based on the local climatic data: year, heating season and cooling season (Fig. 3). Heating season refers to the period of the year during which solar gains are considered beneficial as they may offset energy demands for buildings' space heating. Cooling season covers the rest of the year, when heating systems are presumably off and solar gains may cause overheating in buildings. However, it is noted that, during this "cooling" season, the use of active cooling systems is not necessarily, or systematically required. Figure 4 depicts the ground maps of the projects, i.e. Citélac, Laridae, Les Îles de la Vie (referred to, hereafter, as simply Les Îles), Marais, and Open Lac (in an alphabetical order). The analysis focuses on the area outlined in red, which is mainly reserved for residential use and features a relative continuity and homogeneity, in all the proposals.

3.1 Applying the MsM and EEAP method

Comparison of new buildings' solar and daylight potential

MsMs and EEAPs were generated for each proposal, considering façades and roofs within the analysed area separately. Processing the obtained images, performance indicators related to daylighting, sun exposure and solar gains/energy potential were computed. Table 1 presents the values of performance indicators, as computed for the new buildings in the five proposals. Façades are examined in terms of daylight potential, welcome solar gains in the heating season, and unwelcome ones in the cooling season. Roofs are examined for their annual solar irradiation for PV and solar thermal systems' implementation. Along with the indicators' values, basic geometric metrics derived from the analysis are provided for comparison.

Both for façades and roofs, the indicator values are found to correlate with respective SVF values. Considering the meaning of the SVF measure, this can be interpreted as: the more open the surfaces to the sky, the higher their solar and daylight potential. With respect to the façades, it is observed that Les Îles and Marais have the highest and lowest values, respectively, in all indicators examined. This means that Les Îles is the design that performs best in relation to daylighting and solar gains when these are needed, but at the same time, its façades receive on average more solar radiation in cooling period, associated to overheating risks indoors. The opposite applies in the Marais project which is ranked last in terms of daylight potential and solar gains over the heating season, reduced respectively by 12% and 9% compared to the best-performing Les Îles. In the cooling season though, Marais performs best in preventing unwelcome gains, reduced by 11% compared to Les Îles.

The difference between the two projects becomes evident comparing their MsMs and EEAPs provided in Figure 5, and particularly by the contour lines plotted on them which indicate that the brightest areas in both types of images are larger for Les Îles that for Marais. (The scale followed by the contour lines in both types of images is shown in Figure 6). The 3D perspectives of the two proposals that accompany the images are informative, and reveal the role of geometry. In Marais, the building volumes are more in number, and their design is more complex resulting in many façades being at a small distance to each other. In contrast, the Les Îles design features fewer and more regular in shape building blocks, which ensures greater distances between opposite buildings.

For assessing the performance of different design proposals in absolute terms, the indicators' values could be compared to relevant guidelines and threshold values found in the literature. For instance, [7] suggests 0.24 as minimum ASC value for ensuring adequate daylight indoors, at latitudes between 45° and 50°. Based on that, all the design proposals seem to provide -on average- adequate daylighting conditions on their façades, as their ASC exceed 0.24. Similarly, threshold values can be used to assess the suitability of façades for implementation of solar passive and active strategies [2].

Examining the performance of the design proposals in terms of roofs' annual solar irradiation, the Les Îles project is found again to outperform the competitor designs, achieving the highest PV energy potential. In this case, the proposal with the worst performance is Citélac. The higher degree of obstruction of the roofs of Citélac becomes apparent comparing especially the MsMs computed for the roofs of the two designs (Fig. 7). As seen in the 3D perspective, the buildings in Citélac are formed by smaller volumes of varying height, with the taller ones to obstruct and overshadow the lower roof levels.

Assessment of the impact on an existing façade

	Geometric metrics				Façades				Roofs	
	Volume [m^3]	Roof area [m^2]	Façade area [m^2]	Envel. area/Vol. [m^{-1}]	SVF [-]	ASC [-]	I_g $[W/m^2]$ Heating	Cooling	SVF [-]	G_g [kWh/m^2] Year
Citélac	234503	13312	41849	0.235	0.37	0.32	85	116	0.86	991
Laridae	237157	15580	38108	0.226	0.37	0.32	85	115	0.95	1095
Les Îles	266672	15164	36375	0.193	0.40	0.33	92	123	0.95	1108
Marais	241293	26817	44389	0.295	0.34	0.29	76	109	0.93	1064
Open Lac	251776	29019	43541	0.288	0.37	0.31	83	115	0.90	1043

Table 1. Indicators' values computed for façades and roofs of five proposals, and basic metrics of their geometry.

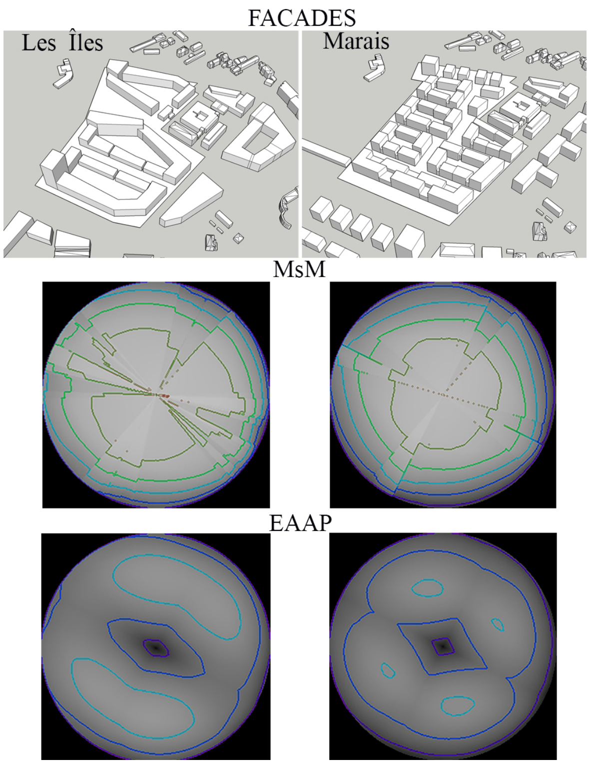

Figure 5. Best- (Les Îles) and worst- (Marais) performing designs in relation to façades' solar (referring to overheating season) and daylight performance: 3D perspectives of their models, façades' MsMs and EAAPs.

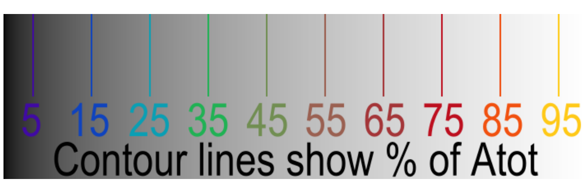

Figure 6. Scale of the contour lines, for both types of images.

Apart from the daylight and solar potential on new buildings' envelopes, the method can be equally applied to compare the impact of new developments on existing buildings' daylight and solar rights. To demonstrate that, the south-west façade of an existing building in close proximity to the analysed area is selected (Fig. 2), and MsMs and EEAPs were generated for it considering successively the different proposals. Their effect on the façade was examined in terms of ASC, referring to daylight conditions, and HEQ, referring to solar exposure. The ASC and HEQ values obtained for the five cases are presented in Table 2, along with those corresponding to the existing situation, i.e. assuming completely unobstructed façade. As before regarding façades' and roofs' performances, the decrease of indicators' values for the existing façade -caused by different designs- follows the decrease in the SVF: the lower the SVF, the lower the values of the indicators.

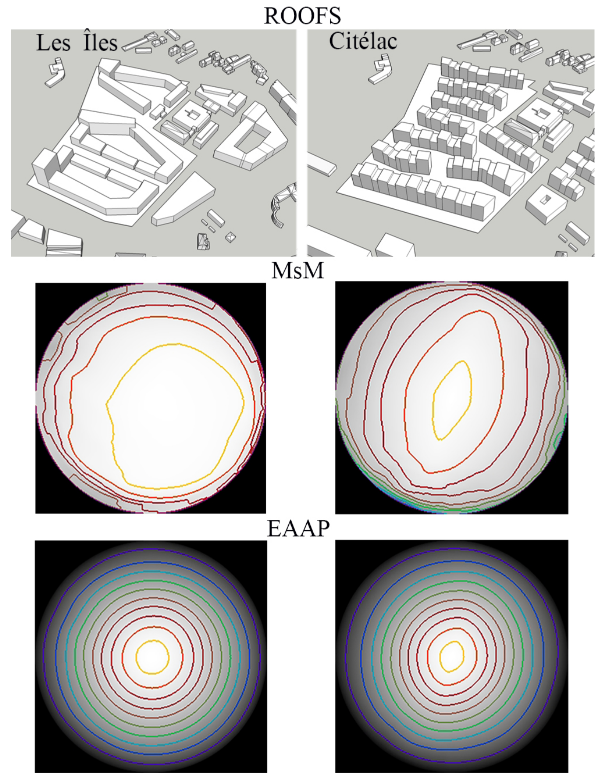

Figure 7. Best- (Les Îles) and worst- (Citélac) performing designs in relation to roofs' solar irradiation: 3D perspectives of their models, roofs' MsMs and EEAPs.

The proposals which cause the most and least obstruction on the existing façade are Laridae and Open Lac, respectively. As seen in the perspective view in Figure 8, in Laridae, a new building is placed just opposite to the existing façade, at about 9m distance, whereas, in Open Lac, a large open area is created in front of it. The great difference between the two cases is visualised by the contour lines in the MsMs and EEAPs. Compared to Open Lac, the ASC and HEQ of the existing façade in Laridae are reduced by 44% and 53%, respectively. If considering the reduction to the existing situation, the percentages rise to 53% and 56%. Is this a significant difference?

What about the other proposals? Seeking for an answer to the question if the owner of the existing building can find some grounds for opposing any of the designs, we apply two different approaches. In the first one, we examine the indicators' values against suggested values for ensuring adequate daylight conditions and insolation in buildings [6]. With respect to daylighting, 0.24 ASC is suggested, and regarding solar exposure, 4 hours of insolation on the equinox day. (It is noted that the paper refers to possible sunshine hours based on climatic data, while here, HEQ is calculated as potential sunshine hours considering clear sky conditions). According to them, all but the Laridae project allow for sufficient daylight and sunlight on the existing façade.

Another way to examine if the change that the projects will bring about is significant or not, is to use the magnitude of change measure, m, defined as [3]:

$$m(X_1, X_2) = \frac{log(X_2/X_1)}{log(a)} \quad (1)$$

Where X_1, X_2 are the values of the same indicator X, $a > 1$ is a coefficient whose value depends on the indicator X. The a value used for ASC indicator is 1.5, and for HEQ, 1.25. If the absolute value of m, $|m|$, is higher than 1, then the difference between X_1 and X_2 values is considered significant. $|m|$ values were calculated testing the values of the indicators against the existing values (ASC=0.4 and HEQ=8.4), $|m(X)_{ex}|$, and against the best values achieved by Open Lac (ASC=0.34 and HEQ=7.9),$|m(X)_b|$. As seen in Table 2, the deterioration in the case of Laridae is significant not only when compared to the current unobstructed conditions, but also compared to the Open Lac values, both in terms of daylighting and particularly solar exposure. Citélac, the proposal with the second greatest impact, is also found to cause a significant reduction in ASC and HEQ values of the existing façade with $|m|$ being higher to 1 in all the cases, except for one in which it is 0.9, i.e. close to be significant. Therefore, summing up, there is strong evidence that the Laridae proposal will exert a profound impact on the daylight and sunlight access on the existing façade, and changes in the design are definitely recommended for mitigating its obstruction effect. Citélac may meet the suggested indicator values, but the magnitude of the change that it brings about is noticeably great. Finally, the Les Îles proposal passes successfully all the tests and may be considered an equally good solution to Open Lac.

3.2 Correlation of indicators with building energy demands

Lastly, correlations between indicators computed by the proposed method as well as simple geometric parameters, and building energy demands were briefly examined. The hypothesis is whether readily available information at the first stages of the design can be associated to building energy use and thus, employed for the comparison of different design solutions. Energy simulations were performed in CitySimPro software using the weather file of Bienne. The input values required for running the simulations were kept constant in all

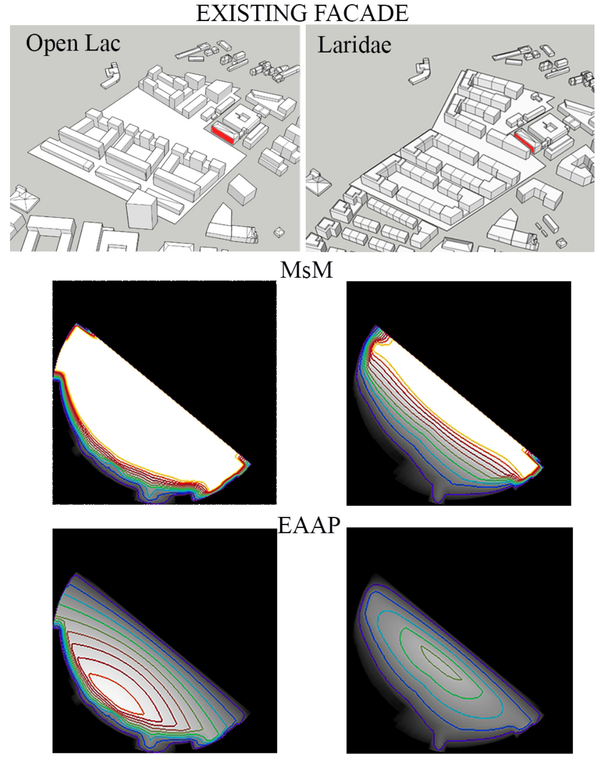

Figure 8. The design proposals with the smallest (Open Lac) and greatest (Laridae) impact on the daylight and solar access on the existing façade: 3D perspectives of their models (in which the existing façade is red-coloured), MsMs and effective EEAPs of the façade in each case.

the designs, as to focus on the effect of their building geometry and configuration. Wall, and roof constructions as well as glazing properties were set to comply with the latest building energy standards applied in Switzerland (SIA380/1). Related to the occupancy pattern, the building use was defined residential.

The discussion of the simulation results focuses on heating energy demand per floor area [kWh/m^2]. Figures 9a-c demonstrate the scatter plots and linear trendlines, for heating energy demand values against total envelope area (i.e. sum of façade and roof surface area) -to-volume ratio, façade SVF, and façade global irradiance in the heating period. Interestingly enough, all three relationships are significantly strong with R^2 being above 0.7. The envelope area-to-volume ratio expresses in a negative way the compactness of the built form; the larger the envelope area for a given volume, the less compact the volume is. In this way, the positive relationship of the ratio with the heating energy demand is justified by that a higher ratio implies greater heat exchange with the ambient environment (heat losses). The other two correlations are found to be negative. As pointed out previously, the openness to the sky, expressed by SVF, is associated positively with daylight and solar access on façades and roofs. Its negative relationship with heating energy demand can be hence interpreted as that higher SVF means more solar gains offsetting the need for heating. However, the increased strength of the relationship may be also related to the strong nega-

	Existing façade						
	SVF[-]	ASC [-]	$\lvert m(ASC)_{ex}\rvert$	$\lvert m(ASC)_b\rvert$	HEQ [h]	$\lvert m(HEQ)_{ex}\rvert$	$\lvert m(HEQ)_b\rvert$
existing	0.50	0.40			8.4		
Citélac	0.25	0.24	1.3	0.9	5.3	2.1	1.79
Laridae	0.20	0.19	1.8	1.5	3.7	3.7	3.4
Les Îles	0.33	0.30	0.7	0.3	6.9	0.9	0.61
Marais	0.30	0.27	0.9	0.5	6.4	1.2	0.94
Open Lac	0.39	0.34	0.4	-	7.9	0.3	-

Table 2. Indicators' values computed for an existing façade comparing the impact of the five design proposals on its daylight and sunlight access, and magnitude of change (m) absolute values in relation to the existing situation, $|m(X)_{ex}|$, and the highest achieved among the projects, $|m(X)_b|$.

tive correlation of SVF to the envelope area-to-volume ratio (R^2=0.748), as the more undulated and complex a building form is, the higher the ratio and the lower the SVF. The same applies to the relationship between façades' solar irradiance over the heating season and heating energy demand, which is the strongest among those examined. Their negative correlation is reasonable and may be also forced by the negative association of solar radiation availability and the envelope area-to-volume ratio (R^2=0.731).

To summarise, compactness of built form, SVF and solar gains in the heating season were found to interrelate to each other, and to strongly correlate with heating energy demands. The significance of this finding lies in that simple measures, such as those derived from applying the proposed method, can be considered at the early stages of the design process - instead of complex and time-consuming energy simulations- for assessing different design concepts.

4 CONCLUSIONS

Two ways of visualising the mutual obstruction of urban surfaces to the sky vault, multi-shading masks (MsM) and effective envelope area picture (EEAP), are introduced as integral parts of the proposed method. The method allows architects and urban designers to assess daylight and solar access in the urban environment, visually as well as quantitatively, in a convenient way. It is developed to meet their needs in the early phase of the design when various building geometries need to be tested, and is flexible to be applied on all kinds and scales of urban surfaces, and groups of them. In this paper, the focus was on the application of the method on building envelope surfaces, i.e. façades and roofs; however, it can be equally used for outdoor spaces [3]. Furthermore, the correlation of indicators derived from the processing of the MsM and EEAP with building energy demands highlights their relevance to optimising the built geometry for achieving more energy-efficient buildings.

Finally, the method can considerably contribute to exploring the orientation effect at the urban scale. In a study to be published in the near future, MsMs and EEAPs have been produced for a series of generic urban models, varying their density. Due to the regularity of the models, in the produced images prominent façades' and streets' orientations are identified. Their comparison with sun path diagrams reveals the significance of the symmetry of the urban form, latitude and built density in amplifying or offsetting the impact of the orientation on the solar access.

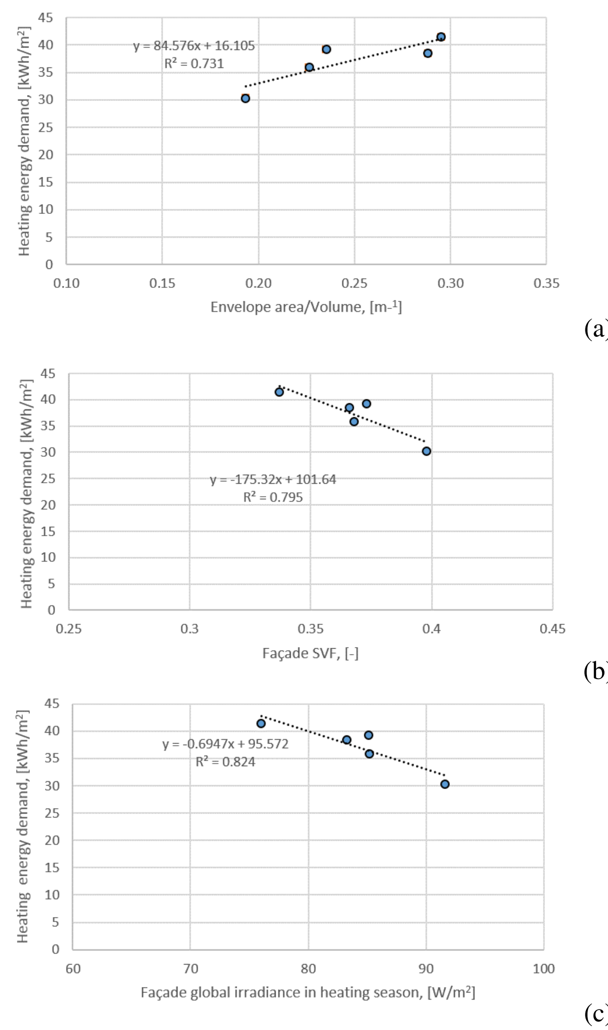

Figure 9. Scatter plots and trendlines for heating energy demand against envelope-to-volume ratio (a), façade average SVF (b) and solar irradiance over the heating season (c).

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Annex 1: Multi-shading mask and effective envelope area picture

First, a grid of N sample points has to be defined in front of the building envelope elements (i.e. façades or roofs) that are being analysed. A grid is defined by the x, y, z coordinates of each point as well as the xdir, ydir, zdir components of the direction vectors normal to the surfaces to which the points belong. Since each sample point is used to characterize the solar/daylight access over a tiny patch of a building envelope element, its area A_k has to be provided as well. Thus, the total envelope area considered is defined as:

$$A_{tot} = \sum_{k=1}^{N} A_k \quad \text{in } [\text{m}^2] \tag{2}$$

where: k is indexing the grid points and N is the total number of points in the grid.

A multi-shading mask stereographic picture is formed by pixels whose values are computed as:

$$M_p = N^{-1} \cdot \sum_{k=1}^{N} vis(p.k) \quad \text{in [-]} \tag{3}$$

where: p is indexing all pixels which are tiny patches by which the entire sky vault hemisphere is subdivided, and $vis(p,k)$ is a function characterizing the visibility between sky patch p and sample point k of the grid. The latter is equal to 1 if a light ray coming from sky patch p can reach point k without any obstruction and 0 otherwise.

An effective envelope area stereographic picture is formed by pixels whose values U_p are computed as:

$$U_p = \sum_{k=1}^{N} A_k \cdot vis(p,k) \cdot cos(\theta_{pk}) \quad \text{in } [\text{m}^2] \tag{4}$$

where: A_k is the area (in m^2) of the building envelope sample referred by point k, and $_{pk}$ is the angle between the vector linking point k to sky patch p and the sample's surface normal vector.

Annex 2: Indicators computed from multi-shading masks and effective envelope area pictures

The following site independent indicators are computed from effective envelope area pictures:

$$SVF = \frac{1}{\pi \cdot A_{tot}} \cdot \sum_{p} U_p \cdot \Omega_p \quad \text{in [-]} \tag{5}$$

$$ASC = \frac{3}{7\pi \cdot A_{tot}} \cdot \sum_{p} U_p \cdot \Omega_p \cdot (1 + 2sin(h_p)) \quad \text{in [-]} \tag{6}$$

where: Ω_p is the solid angle subtended by sky patch p, an h_p is the elevation angle of sky patch p above the horizontal plane.

The potential sunlight exposure indicator (WSE) and the potential sunlit hours at equinox indicator (HEQ) are both computed from multishading masks for a specified latitude:

$$WSE = \sum_{t \in \Delta t} M_{P(lattitude,t)} \quad \text{in [hours]} \tag{7}$$

$$HEQ = \sum_{t \in equinox\ day} s(M_{P(lattitude,t)}, 0.5) \quad \text{in [hours]} \tag{8}$$

where: $P(latitude, t)$ is essentially a solar geometry function returning the patch's index where the sun is located at time t. The sum is computed for every hourly time step indexed by t which belong to the time interval Δt (in hours) considered. $s(v, w)$ is a "step" function which takes value 1 when $v \geq w$ and 0 otherwise.

The global irradiance I_g is computed from the pixel-by-pixel multiplication of an EEAP by a sky model picture for a specific location:

$$I_g = \frac{1}{A_{tot}} \cdot \sum_{p} \sum_{k} [U_p \cdot R_p \cdot \Omega_p] \quad \text{in } [\text{W/m}^2] \tag{9}$$

where: R_p is the sky global radiance in [Wm^{-2}sr^{-1}] at patch p for the location and the time interval Δt considered. Typically, the distribution of the product $R_p \cdot \Omega_p$ in [Wm^{-2}] on the sky vault is stored as a "sky model picture".

The global irradiation G_g is easily computed by:

$$G_g = \frac{I_g \cdot \Delta t}{1000} \quad [\text{kWh} \cdot \text{m}^{-2}] \tag{10}$$