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# Solar radiation over the urban texture: LIDAR data and image processing techniques for environmental analysis at city scale

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## Abstract

A complete methodology from the extraction of Light Detection and Ranging (LIDAR) data to the environmental analysis of urban models and the visualization of results is presented. Aim of the work is to establish a process to investigate digital urban models integrating cross-disciplinary competences, like remote sensing, GIS, image processing and urban and environmental studies. Toward this goal, working on several interfaces, tools and datasets was necessary to provide a consequent structure to the introduced methodology.

Case study for application was a squared area 300 metres wide in central Geneva where LIDAR data are available. The use of a hybrid approach from raw LIDAR data and vectorial digital maps (GIS data) of buildings footprints for the interpolation of a 2.5-D urban surface model, with a resolution grid of 0.50 by 0.50 metres, allowed to refine vertical surfaces of buildings and to process facades and roofs separately. This step reveals itself as fundamental for processing the environmental analysis of the urban texture. In particular, the implemented tool calculates solar radiation and solar accessibility on urban surfaces, in order to investigate the energy-performance of cities.

**Keywords:** 3D data analysis, LIDAR, 2.5-D urban surface models, urban morphology, image processing, solar radiation, 2-D and 3-D visualization

## 1. Introduction

Today's availability of 3-D information about cities offers the possibility to analyse the urban fabric in a very innovative way. In fact, even if LIDAR data permit to derive precious and precise information about the physical layout of cities, still very few applications have been implemented in order to process these data for the environmental analysis and to get a quick understanding about the performance of the urban form. For instance, the increasing interest in the quantification of energy-based indicators at the scale of the city, strongly suggests the integration of 3-D geography and urban studies in order to provide useful applications for the urban planning. In particular, we introduce a novel cross-disciplinary approach that covers the whole procedure from data acquisition from Airborne Laser Scanning (ALS) to the environmental analysis through the image processing of digital urban models.

The use of raw LIDAR data with fine density of points (at least 4 to 6 points per square metre) jointly with 2-D vectorial digital maps of buildings footprints, both originally on the same geodetic reference system and, later on, converted to the same projected coordinate system, allows the construction of a 2.5-D urban surface model. Due to its highest level of accuracy, the use of detailed vectorial buildings footprints in order to classify LIDAR points contained within buildings is crucial for the improvement of the final result of the 2.5-D urban surface model interpolated and constructed, especially along buildings facades.

Thus, using the capability of LIDAR data in order to construct an accurate 3-D urban surface model, solar accessibility analysis at different heights (for existing buildings facades) is implemented and integrated in a tool for calculating urban radiation. As presented by Osaragi and Otani (2007), all visibility and sunshine analysis in urban areas based on 3-D urban surface models must take into consideration the geographical relief of the terrain.

The investigation of solar radiation in architecture is not new and there are already several tools that calculate radiation performance of buildings very accurately. Nevertheless, these tools are very useful at the micro-scale of architecture (environmental performance software) or at the macro-scale of landscape and regional geography (GIS tools), but the focus on urban texture is mostly lacking. Recently, the increasing attention to environmental policies in urban studies has opened up many questions about how planners should manage those indicators in the design process. In fact, numerous authors and architects are convinced that cities play a leading role in controlling sustainability: strategies for redefining more efficient cities in terms of energy performance and environmental quality were the centre of attention in seminal work by Richard Rogers in defining policies for UK cities (Rogers 1997; Urban Task Force 1999) and supported the debate around the promotion of more compact cities (Jenks et al. 1996, 2000). For instance, the need to overcome traditional solar laws based on trivial angular criteria, such as obstruction angles rules, would be very welcome. Anyway, a comprehensive and reliable toolkit for sustainable urban design is lacking among practicing professionals.

The tool presented here can be intended just as one tile of a larger mosaic aiming at the quantification of environmental parameters at the urban scale. In particular, the calculation of solar radiation gives us some clues about the energy-performance of the urban fabric concerning a general understanding of the different contributions of vertical and sloped surfaces in the urban context. Hence, some critical questions in urban design and planning arise: can we build denser cities without decreasing the potential for passive solar architecture? Which is the incidence of beam versus diffuse solar irradiance contributions in typical urban textures? Those questions could benefit from comparative studies between different urban design solutions using the methodology introduced here.

The area selected for the analysis is a square 300 metres wide near the Rhone River and the old town of Geneva, in Switzerland, such as presented in shadowed yellow zone of Figure 1. 36 different buildings with average height of 18.5 metres were counted on site. The urban texture is quite compact and densely built, and we want to verify if buildings are sufficiently separated from each others, so that overshadowing does not limit solar accessibility of indoor spaces. The reconstruction of the model, as explained later in text is shown in figure 2.

**Fig. 1**.  Pre-defined area of the case study in Geneva's city, near the Rhone River and the old town

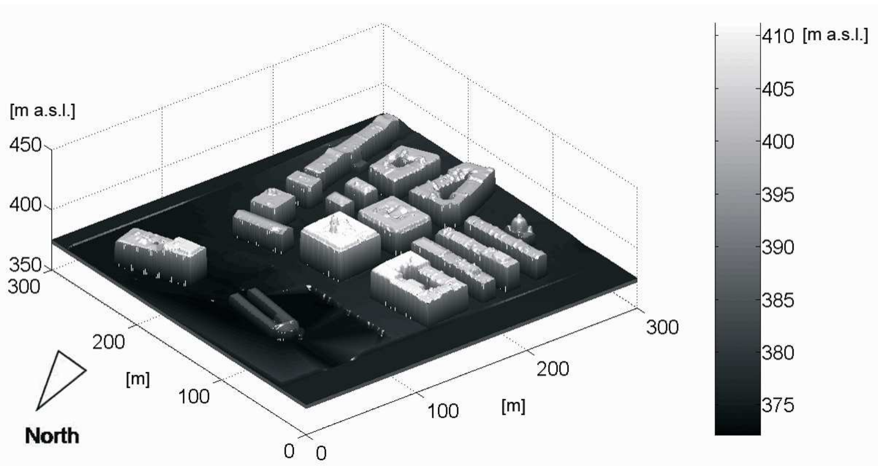



**Fig. 2.** The 2.5-D urban surface model visualized on Matlab. Heights are expressed in meters above sea level.

## 2. Research context

Reference to this work is both literature in the remote sensing, 3-D geography field and literature in the environmental and morphological analysis of digital urban models.

Previous literature on interpolation of LIDAR point clouds is vast. The advantages and disadvantages of several interpolation methods, such as triangle-based linear interpolation, nearest neighbour interpolation and kriging interpolation were presented by Zinger et al. (2002). The most accurate surfaces are created using a grid with a sampling size that relates as close as possible to the LIDAR point density during the acquisition phase (Behan 2000). For applications where high level of accuracy is demanded, control techniques that analyse the quality of digital terrain models can be carried out (Menezes et al. 2005).

A method to interpolate and construct a 2.5-D urban surface model (incorporating the geographical relief), based on LIDAR and GIS buildings data, has been proposed by Osaragi and Otani (2007). As related research, there are some semi-automatic methods available to create 3-D GIS data from LIDAR data, such as the Virtual London at UCL (Steed et al. 1999) and the MapCube at Tokyo CadCenter Corporation (Takase et al. 2003).

Concerning literature about the application of raster images in urban studies, pioneers in the use of image processing techniques to analyse environmental indicators and morphology of digital urban models was a group of researchers at the Martin Centre, University of Cambridge (Ratti 2001; Ratti and Richens 2004; Ratti et al. 2005). Today's increasing availability of 3-D information from user generated contents and remote sensing surveys, makes this technique promising and very useful for a general understanding of the performance of our cities.

The technique is based on the use of very simple raster models of cities, called 2.5-D urban surface models. These models reproduce the geometry of the urban fabric and are produced by regularly spaced matrices of elevation values, which contain 3-D information on 2-D digital support, stored in Bitmap format. Developing software algorithms derived from image processing, it is possible to develop efficient strategic tools for analysing and planning the sustainable urban form, measuring geometric parameters and assessing radiation exchange, energy consumption, wind porosity, visibility, spatial analyses, etc. Results are extremely fast and accurate.

## 3. Methodology: The implementation of the 2.5-D urban surface model from LiDAR data to environmental analysis

The process for structuring the proposed methodology is based on four major steps as represented in the scheme of figure 3: the construction of the 2.5-D urban surface model, the environmental analysis through the image processing of urban models, the visualizations of results and their evaluation by users (this latter step will be part of future work).

For the 2.5-D urban surface model interpolation of the case study of the city of Geneva here presented three data sources are required: raw LIDAR data, 2-D vectorial digital maps of buildings footprints and alphanumerical data containing altimetric information about buildings heights.

First, we interpolate a digital terrain model (DTM) by classifying the LIDAR points according to the following sequential operations:

- Using a GIS software, LIDAR points contained within building polygons and in the 2 metres buffer generated from building polygons are eliminated.
- Using the classification tools provided by TerraScan software, LIDAR points whose elevation value vary significantly from surrounding points are considered to be points indicating features such as aerial points (for example, if the laser beam touches a bird), trees and vehicles, and thus are removed.

After eliminating the points indicating all these features, a DTM can be interpolated only from ground points – with good density of LIDAR points (such as in our testing areas, located in Geneva city, where LIDAR points were acquired with a density of 4 to 6 points per square metre) there is no great difference among some of the existing gridding interpolation methods that can be employed, such as the nearest neighbour binning, inverse distance weighting, triangulation with linear interpolation, minimum curvature, kriging and radial basis functions (Gonçalves, 2006). All these interpolation methods are accessible in common GIS software available on the market.

For its generalised use by the scientific community for DTM interpolation, the triangular interpolation was chosen. Secondly, we interpolate (using only the LIDAR points classified as being contained within vectorial building footprints) a value for each grid cell corresponding to a roof value contained within the area defined by building facades, for all the existing buildings on the areas of study. Thus, a triangulation with linear interpolation is also applied to each one of the roofs of the buildings. It is important to note that along building facades, LIDAR points whose elevation value vary significantly from surrounding points are considered to be points indicating features such as low points and are removed (using the classification tools provided by TerraScan software). For each building, and more specifically for each grid cell contained within, the building height (also defined as nDSM of buildings) is taken to be the value of subtraction of the terrain elevation (calculated in the DTM interpolated) from the building elevation. Due to the presence of obstacles, such as trees, in the few cases where a lack of LIDAR points exists in buildings roofs, the grid cells corresponding to each of these roofs have assigned an average building height value extracted from the attribute "building height" of the cadastral database.

Lastly, each building is added to the DTM as a column (whose borders are defined from the vectorial buildings footprints), using the building height found previously for each cell contained within, as described in last paragraph. The final result allows the construction of a 2.5-D urban surface model (2.5-DUSM), which is composed of only terrain and buildings heights information (DTM + nDSM). Data source and parameters needed for generating the 2.5-D urban surface model are shown in figure 4.

Finally, in order to complete the image enhancement of the model, we have to refine the facades of buildings that are sloped because of interpolation (figure 5c). In order to achieve this goal, we applied an image smoothing using a 3 by 3 low-pass filtering. Each building's contour pixel was deleted and then expanded again, in order to assign more constant values to facades. Among these perimeter pixels, the maximum value was later selected as the upper limit for running the computation of irradiances on facades (figure 6).

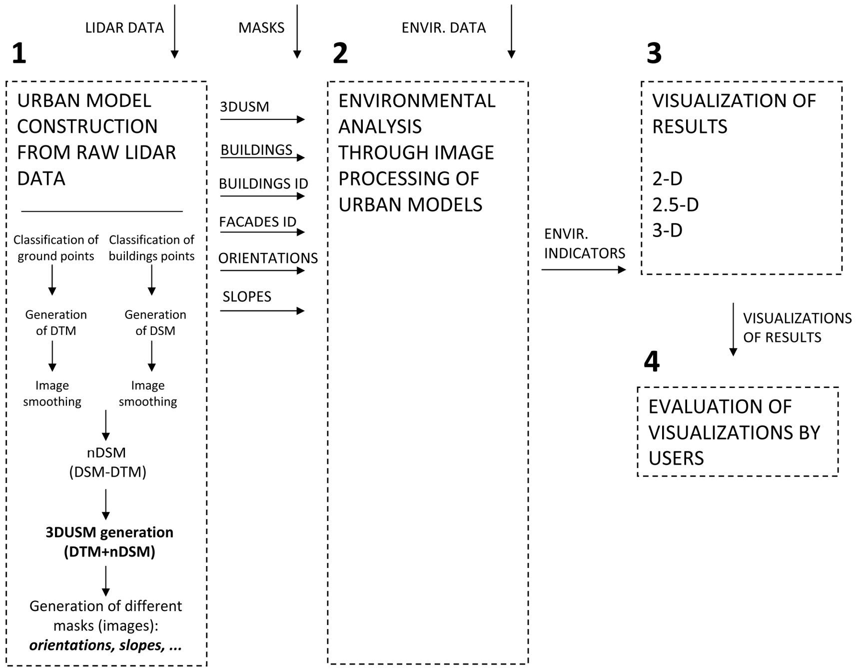



**Fig. 3.** The structure of the proposed methodology from the reconstruction of LIDAR data to the environmental analysis and visualization of results

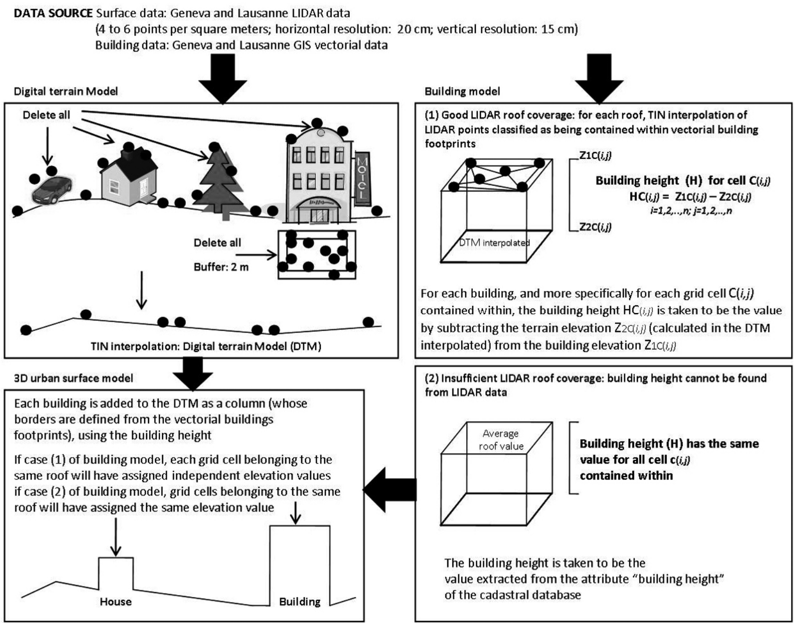



**Fig. 4.** Interpolation and construction of 3-D urban surface model

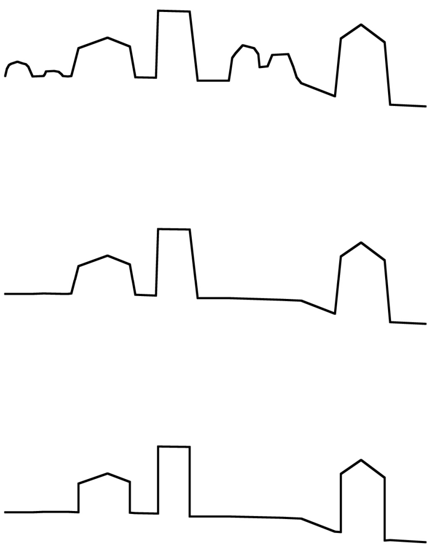


**Fig. 5.** The process of reconstruction of the urban model; from the top: (a) original LIDAR survey data; (b) removal of trees, cars and other minor details and interpolation of the terrain; (c) adjustment of building facades through image filtering, whereby the detection of facades and roofs is based on a hybrid approach using both LIDAR data and cartography

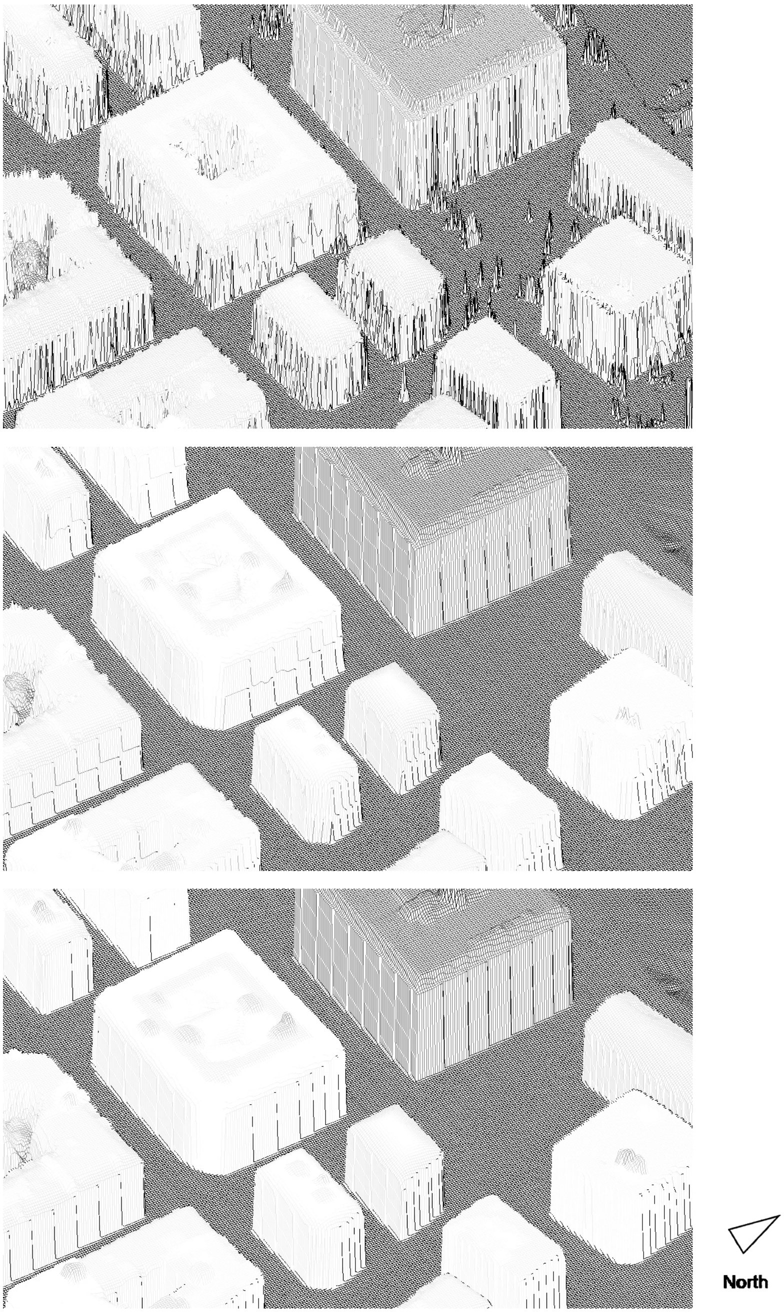



**Fig. 6.** The enhancement of the urban model; from the top: (a) the raw LIDAR data, (b) the original DEM, (c) the reconstruction of vertical facades

## 4. Image processing of raster images for the study of solar radiation

In this study the reconstruction of the 2.5-D urban model was applied for implementing a specific tool for calculating the solar irradiance intercepted by urban surfaces. Aim of the proposed application is first to determine the rate of accessibility of urban surfaces to direct solar radiation and second to exactly quantify solar irradiance (diffuse and beam) both on facades and roofs. The computation distinguishes calculations for irradiation of facades and roofs. Therefore, outputs of the tool are irradiation values stored in two different arrays: one table contains radiations computed on every storey and on every facade of each building; a second table outlines the irradiance values on roofs for each building. Finally, beside this quantitative content, visualizations of results on the physical map are provided.

The technique used in this application is based on the image processing of the provided models that are interpreted as raster images, i.e. 2-D arrays where every intensity value represents the height of the pixel in metres. The density[1] and accuracy[2] of the LIDAR data used is relatively high. Thus, a 2.5-D urban surface model (grid) of 0.50 by 0.50 metres, which has a sampling size that relates as close as possible to the LIDAR point density during the acquisition phase (Behan 2000), was interpolated and constructed. The technique computes irradiance values on all target points (building facades) being visible from a viewpoint location represented by the position of the sun.

Two types of input data are required for running the tool: first, geographical and climatic data that inform the location of the case-study area and the mean daily irradiance received by horizontal surfaces for each month of the year for that location; second, a set of urban models, as result of the reconstruction process presented above.

To the first set of data we have to provide the geographical coordinates of the case-study area, the height above sea level and the physical extension of the site in metres.

Regarding climatic data, the mean daily beam and diffuse irradiances on horizontal surfaces can be obtained from statistical data collected for the city, often reported by local or national norms. In this case, irradiance values were obtained by the statistical analysis of

[1] 4 to 6 points per $m^2$

[2] Planimetric precision of 20 centimetres and altimetric precision of 15 centimetres

historical data. From these letter irradiances on horizontal surfaces it is possible to derive irradiance values for every orientation and inclination of surface, according to solar geometry formulae (Duffie 1980). Other minor input information can be used if provided, like for example the quote of ground-reflected radiation, which default value can be assumed as 0.2, but this can vary during the winter season in presence of snow.

A list of six masks necessary in order to run the model follows:

- The digital elevation model (DEM), here also called 2.5-D urban surface model, whereby intensity values of pixels represent the height above the sea level. This input image is the main 2.5-D information to run the script.
- The mask of the buildings alone contains the absolute height of each building and is useful in the process of slicing the model in several storeys; in this image the terrain model was removed and substituted with 0 values, so that it can also be used as mask for detecting and labelling buildings.
- The masks including labels of buildings and facades. It is possible to determine the exact identifications of buildings and facades through cadastral data (digital vectorial maps of buildings); a simple object recognition process in Matlab would distinguish between independent blocks, but would fail in the identification of different properties in case for example of contiguous row houses.
- The masks for describing roofs are essentially two and inform about orientations and inclinations of roof pixels. These latter masks might be also implemented as part of the Matlab code, but would require a longer calculation process.

This procedure allows to precisely distinguish between roofs and facades of buildings and represents a noticeable innovation in digital urban analysis. For instance, all outputs in this work are stored in separated arrays in order to analyse the different contribution to solar gains of vertical and sloped surfaces in the urban context.

Solar geometry formulae allow to derive the beam and diffuse components of hourly radiations just starting from the previous mentioned inputs. In the computation of the time distribution of radiations during the day, however, we can just assess values representative for clear sky conditions, even if they tend to produce conservative estimates (Duffie 1980, p.77). Therefore, even if accurate, results of the application should be used mostly in comparative studies to evaluate differences of solar caption in time.

Hence, we store a set of possible radiations in dedicated arrays that will be useful later when applied on the physical context. In particular, the typical array is a 3-D matrix (24x12x9) where the columns represent the 12 months of the year, the rows are 24 hourly intervals and the 9 z-layers are the computed values for 8 different orientations (S, SE, E, NE, N, NW, W, SW) plus the irradiance on horizontal surfaces. We computed this typical array for vertical surfaces and for sloped surfaces at intervals of 15 degrees between 0 and 90.

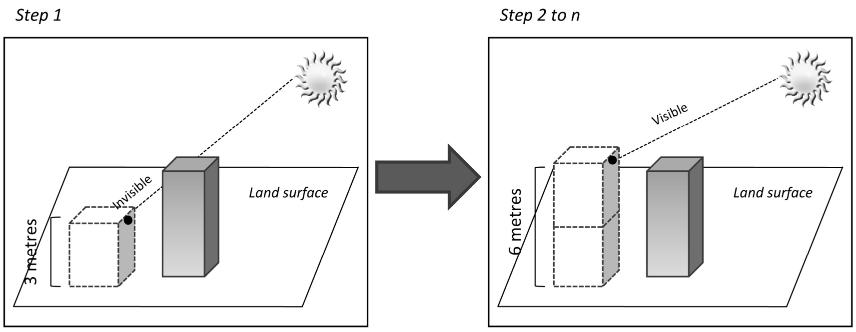
Once the irradiance arrays are calculated and the input images are defined, the core of the computation can run. The shadow casting routine first introduced by Ratti (2001) is applied here at a specific hour of the day and is used to detect which pixels on the facades are in shadow and which collect direct sunlight. The script computes the shadow casting routine slicing the urban model at every storey (3 metres is assumed to be the average storey height) of each building. Since the technique deals with 2.5-D models, slicing each building at different heights is necessary in order to compute the real irradiance condition in the vertical direction. In other words, reciprocal overshadowing by buildings can affect only part of the facade and this method allows distinguishing at which height vertical aligned pixels on the facade start to be irradiated (see figure 7); otherwise, with simple shadow casting routine applied to the entire model, facades that are shaded at the basement only result totally shaded until the roof.

Moreover, we need to define the linear length of pixels on the perimeter of buildings: depending on their inclination, pixels can assume values between 1 and √2. This can be easily calculated applying sobel filters (Ratti and Morello 2005).

Hence, when we are able to determine for every facade at every storey, if each perimetral pixel is under shadow or light, which is its orientation and its linear extension, we can assign the incident solar irradiance calculated in Watt per square metre. For roof pixels instead, we need to add the information of slope and orientation contained in the input masks. The area of each roof pixel was calculated considering the slope of the pixel.

Finally, we have to store irradiance values in a convenient way, depending on the results we are interested in. In this work we were basically investigating about the ratio of direct solar irradiation on urban surfaces and an energy-based evaluation of collected radiation on surfaces. Therefore, results were stored listing all pixels by facade identification and by orientation; regarding roofs, results were stored following building labels.

Furthermore, it is important to provide also general morphological indicators for the case-study area, because it could be interesting to correlate urban shape indicators to environmental performance in future comparative studies. These morphological indicators include among others: built volume, built area, densities, mean and maximum height of buildings.




1 – White building: building under analysis
2 – Blue building: built environment
3 – The sun is considered to be the viewpoint location
4 – For each building façade under analysis (target area), every 3 metres (assumed storey height) for all grid cells (C(*i,j*)) on the horizontal direction of the image, evaluation of visible cells from the viewpoint (sun) location

**Fig. 7.** Method implemented (using a 2.5-D urban surface model) for the calculation of the solar radiation along each building facade at a specific date of the year. Slicing the model at different heights allows taking into consideration pixels in shadow or in light

## 5. Results of the analysis

A general overview about the energetic performance of vertical surfaces in an urban site is very useful if we want to compare different fabrics or if we want to assess the impact of new buildings inside the city. The tool presented here is accurate at the scale of the neighbourhood, if we do not consider the inevitable edge effect due to the absence of obstructions generated by buildings located right outside of the area of investigation.

Different profiles describing the solar irradiation can be traced for an urban site. We consider two main graphs, introduced later in figure 12 and figure 13. Both types of analysis were computed at different times on an hourly basis. We can observe that absolute irradiance values slightly decrease with height (figure 8a) and this is mostly caused by the parallel decrement of the amount of vertical surfaces when we move to upper storeys. Anyway, if we normalize results in respect to the areas of related vertical surfaces, the average irradiation per square metre clearly increases with height (figure 8b). This phenomenon occurs in part also with the analysis of direct solar irradiation, whereas here on the upper storeys the percentage of surfaces under direct radiation increases again and this is due to the lower reciprocal overshadowing by buildings (figure 8c).

Beside the calculation on vertical surfaces, the tool computes the irradiance values collected on roofs and their solar exposure (light or shadow) on an hourly basis (figures 9 and 10). The chosen case-study area is composed by a very uniform urban fabric, whereby big gaps in the skyline do not occur. Therefore, roofs are mostly interested by proper shadows on pitch slopes opposite the sun and represent in general the location where it is easier to collect solar energy. Even if a general quantification of irradiance values on roofs is fundamental in order to have a general understanding of the passive solar potential of the city, further work should investigate limitations concerning solar energy collection occurring at pitched roofs and considering for instance the most efficient way to install solar and/or photovoltaic panels at the neighbourhood scale.

Moreover, polar plots of solar irradiances on vertical surfaces computed for Geneva show the contributions of beam and diffuse irradiance on the site (figure 11). Great part of the solar irradiation collected by vertical urban surfaces is due to diffuse irradiance, considering also the fact that the sky is not always clear. In terms of energy performance, increasing the direct solar contribution on vertical surfaces does not bring a consequent improvement of energy collection. It means that we can build more compact urban spaces and delegate roofs to collect beam radiation for the production of electric energy and/or hot water. Nevertheless, in terms of environmental quality in general, assuring a minimum amount of direct solar radiation on each building is recommendable for increasing the perceived comfort inside buildings. Anyway, if we aim at providing sufficient light for living conditions inside indoor spaces, the constant diffuse radiation is in most cases satisfactory. Concerning the case study-area in central Geneva and according to the irradiations at that latitude, the layout of buildings already guarantees good solar radiation.

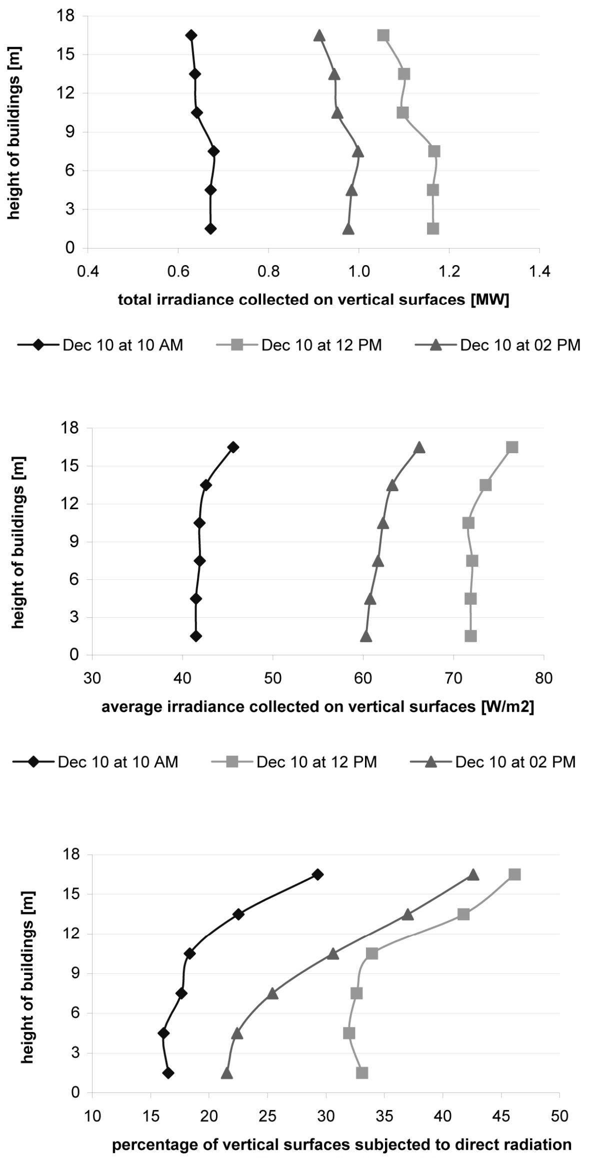



**Fig. 8.** Total irradiance falling on vertical surfaces for the case-study area on the average day of December at 10 AM, 12 PM and 2 PM with increasing heights of buildings; from the top: (a) absolute irradiances in MW; (b) mean irradiances in W/m$^2$; (c) percentages of vertical surfaces subjected to direct radiation

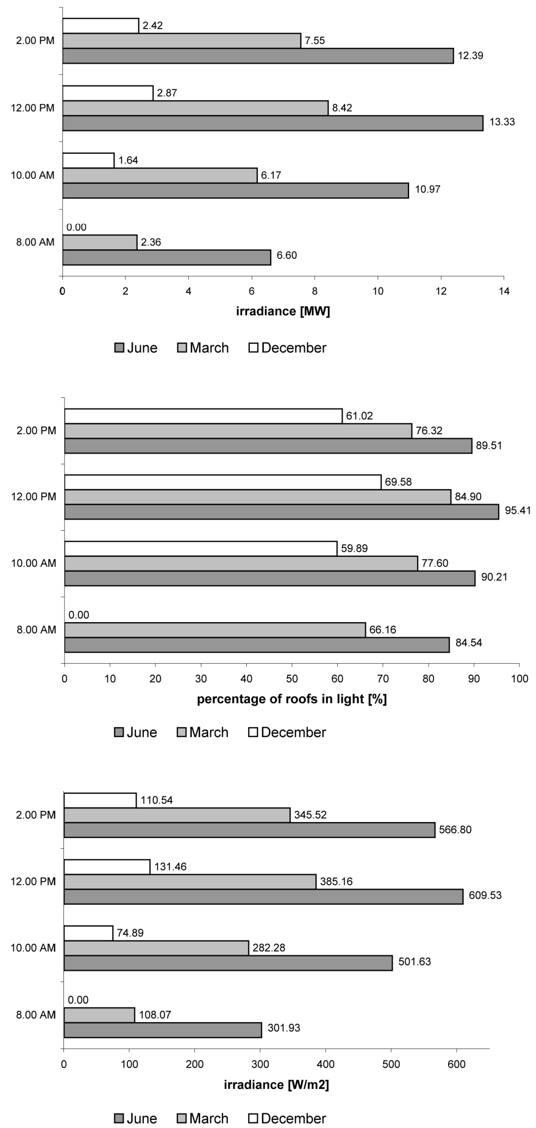



**Fig. 9.** From the top: (a) Total irradiance collected by roofs at 8 AM, 10 AM, 12 PM and 2 PM in the average day for the months of March, June and December (values are expressed in MW); (b) Percentage of roof surfaces in light at 8 AM, 10 AM, 12 PM and 2 PM in the average day for the months of March, June and December; (c) Mean irradiance collected by roofs at 8 AM, 10 AM, 12 PM and 2 PM in the average day for the months of March, June and December (values are expressed in Watt per square metre)

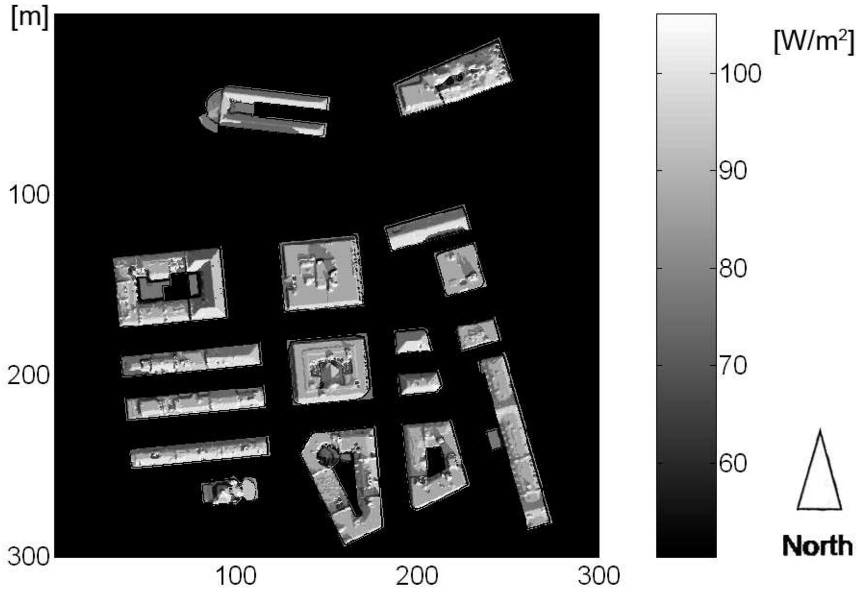



**Fig. 10.** Top view with irradiance values (in W/m$^2$) on roofs at 10 AM in the morning on December 10

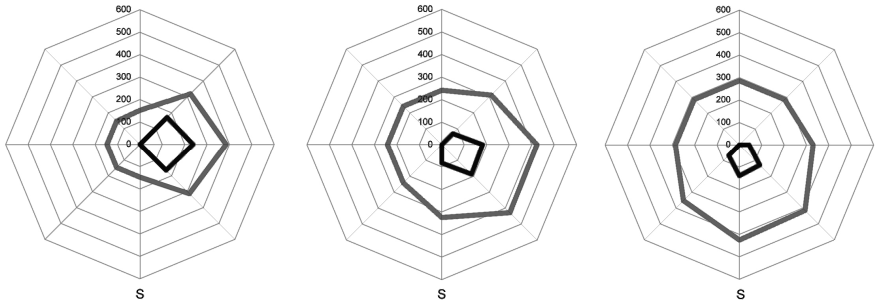



**Fig. 11.** Polar plots of solar irradiances on vertical surfaces for Geneva on the average day of June; in black beam radiation, in dark gray diffuse radiation (values are expressed in W/m$^2$). From left: irradiances at (a) 8 AM, (b) 10 AM, (c) 12 PM

## 6. Visualization of results: 2-D and 3-D displays for communicating results

According to Nielsen (1993), the acceptability of any visual exploratory system is strictly related to its utility (feasibility of the information to be visualized) and its usability (cognitive visual interpretation of the 3-D urban models proposed).

This combination between utility and usability determines the level of acceptability among the different users (in particular for architects and urban planners) of the proposed 3-D urban models (Reichenbacher and Swienty, 2007).

User requirements concerning the utility and usability of 3-D urban models for communication and visualization purposes have not yet caused much attention within the world of researchers and developers. Thus, for different users and applications, it is fundamental to clearly distinguish which levels of detail (LOD) should be implemented and, based on this classification, which urban objects should be or should not be visualized. This filter of criteria is essential, in order to avoid too dense and confusing urban scenes.

The visualization of results here proposed is based on the user requirements study undertaken for the city of Geneva, such as presented by Carneiro (2008).

The representations of maps indicating the performance of facades on a 2-D-plot are displayed in figures 12 and 13: the first accounts the total irradiance (expressed in Watt per square metre) falling on vertical surfaces with increasing heights of buildings; the second plot represents the percentage of facades subjected to direct solar radiation with increasing heights of buildings. These synthetic maps reveal themselves to be very immediate because they give an omni-comprehensive understanding of irradiation conditions on the entire site.

For 3-D visualization we used the available model, developed by the DCMO[3] in Geneva. The 3-D urban model of the city of Geneva was constructed using many data sources, such as: 2-D vectorial data, 2.5-D raster data, alphanumerical data containing altimetric information about buildings heights, LIDAR and terrestrial laser data, aerial photos orthorectified and terrestrial photos. We used this model to present our analysis of results. Results showed in figure 14 display the average

[3] DCMO, Direction Cantonale de la Mensuration Officielle, responsible for the management of the topographical, cartographical and GIS information of the city of Geneva.

irradiance (expressed in Watt per square metre) falling on each building. Irradiance values collected on the facades of each building were divided by the total area of vertical surfaces, whereby facades that do not receive radiation at all were discarded (mostly separation walls between two buildings). Results tend to be quite uniform, due to the operation of averaging of irradiation values on all facades, lighted and shaded.

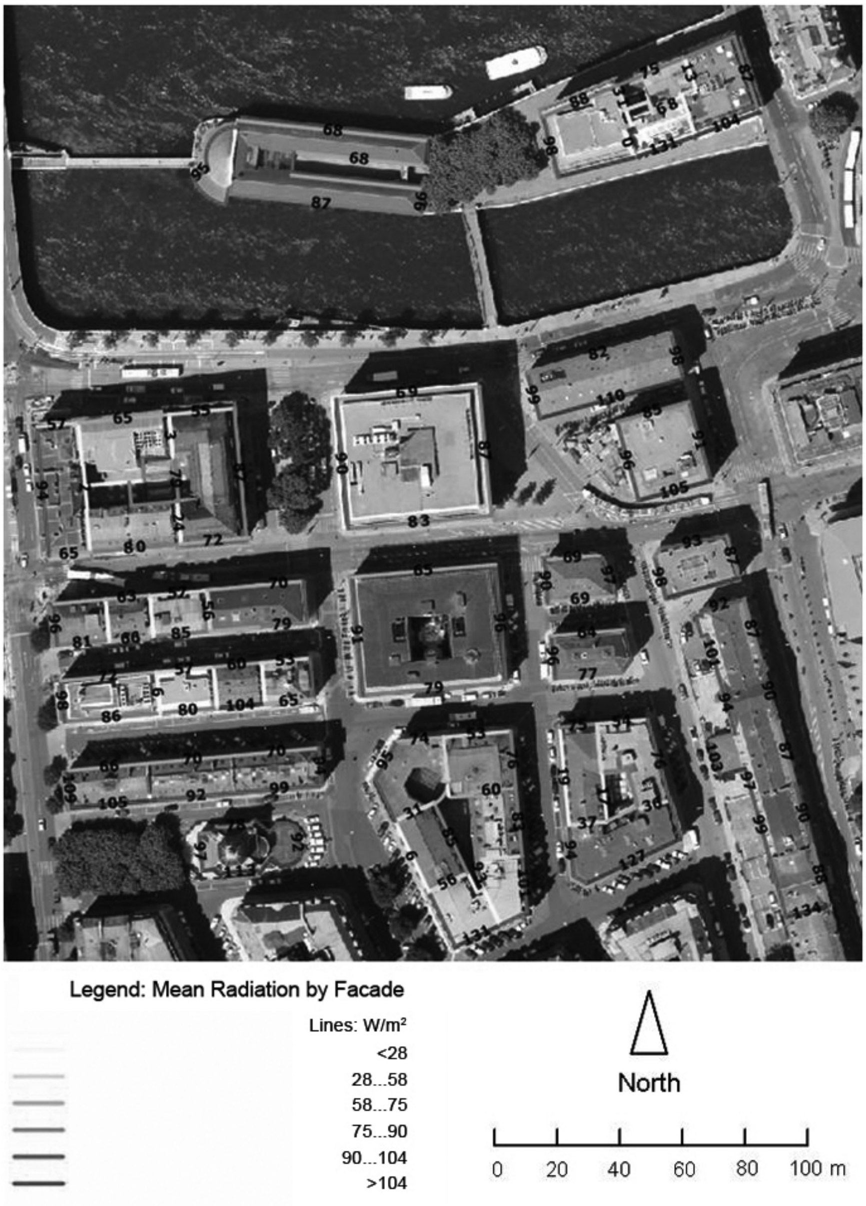



**Fig. 12.** The mean solar irradiance collected by each facade on the second storey on December 10 at 12 PM, considering both beam and diffuse contributions.

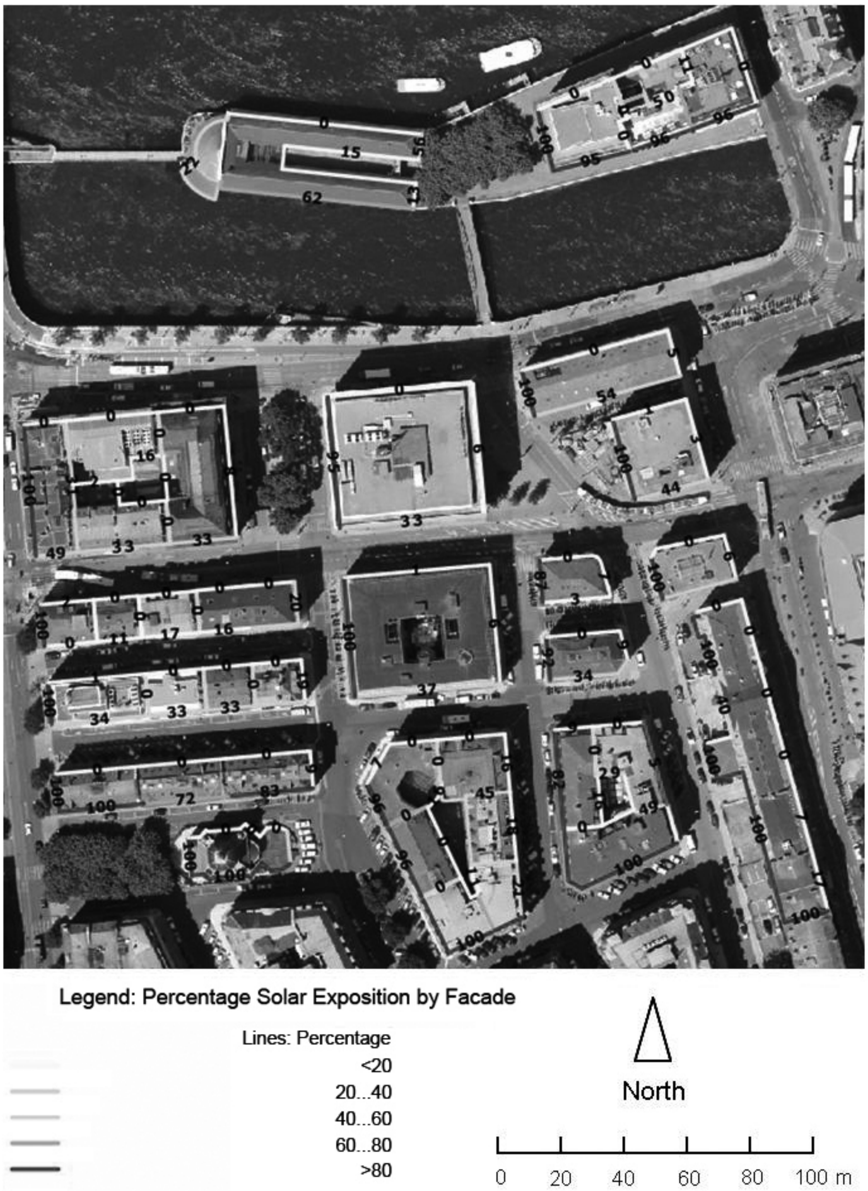



**Fig. 13.** On each facade on the second storey, the percentage of surface interested by direct solar radiation on December 10 at 12 PM is displayed.

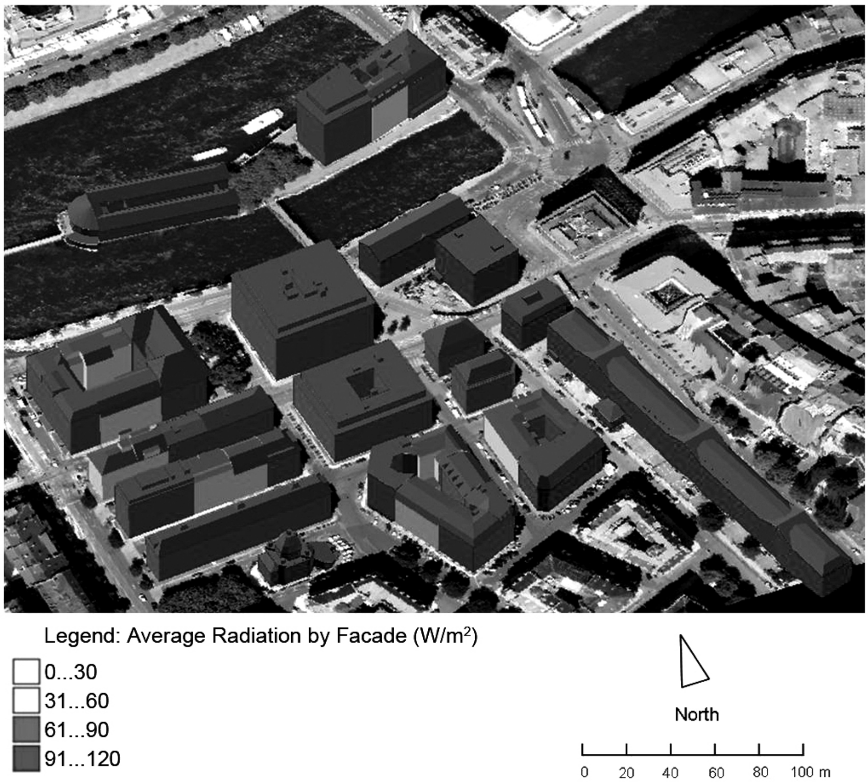



**Fig. 14.** 3-D visualization of average irradiance values per building (expressed in W/m$^2$) on December 10 at 12 AM

## 7. Conclusions

In this paper a complete methodology from the extraction of LIDAR data to the environmental analysis of urban models and the visualization of results was introduced. Combining different disciplines interfaces and datasets reveal constrains of today's applicability of LIDAR images for the environmental prediction of the urban form. Hence, a first result is to bring 3-D geography and urban studies together in a process that goes from data acquisition and processing to urban modelling and urban design application.

Applications of this methodology in urban design and planning are very promising. In our case study we limit the analysis to the physical built environment, but we could extend the investigation to assess the impact of new buildings in the city and use the technique for improving design schemes based on an evaluation of quantitative indicators before and after changes are introduced. The methodology has been tested for a small case-study area, but calculations can run also at a city level if LIDAR data are available.

The accuracy of results depends mainly on two issues that we tried to overcome: the quality of input LIDAR data and the constraints of the image processing technique of 2.5-D urban surface models. First, in order to enhance the precision of LIDAR data, a process of image reconstruction was implemented and a hybrid approach that integrates the use of vectorial building footprints data was proposed in order to reconstruct the perimeters of buildings. Second, the use of the image processing technique of raster images permits time-saving computation, but needed to be improved through multiple slicing of the model to consider different shadowing conditions on vertical aligned pixels. In general, the aim is to achieve a real understanding of the energetic performance of the urban fabric. Comparative studies conducted not only at different times, but also on different sites or on the same site introducing changes (like for example a new building or adding one storey to all buildings) could give more clues for interpreting results.

As here presented, existing vectorial digital maps (GIS data) can be used if available and updated, but outlines of buildings from this source of information should be always handled with special care. In fact, the 2-D outlines of buildings footprints do not have to represent the outline of the building roof. Modifications between GIS data and laser data can have numerous reasons which can not automatically be recognized. Proposals using vectorial digital maps as input for 2.5-D urban surface model interpolation and construction should be attentive of the fact that in some cases map information might not give the correct hints about 3-D buildings shapes.

Finally, future work should:

- improve the technique for the construction of the model through a method for roof segmentation/interpolation, in order to take into account more accurately different footprints of buildings and roofs;
- ameliorate the quality of the urban model with the integration of trees, which remains one of the most delicate aspects concerning environmental analysis using 2.5-D urban surface models;
- optimise the efficiency of the proposed code and consequently intensifying the number of slices on the model;
- provide a statistical analysis on 2.5-D urban surface models;

- investigate the utility and usability of the proposed visualizations outputs through users' evaluation.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