Computing Solar Radiation on CityGML Building Data

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Abstract

Solar radiation calculation has been the subject of multiple studies in the past [11], highlighting the economic significance of the topic in energy management. However, most of them are based on raster data where it is difficult to represent vertical facades. This study proposes a methodology to calculate solar radiation on 3D urban objects stored in CityGML data format with different Levels of Detail (LOD). Moreover, the methodology brings in new capabilities to compute the impact of solar radiation on different surface types (horizontal, inclined and vertical) of 3D urban objects, e.g. buildings. For this reason, a python application is developed and the underlying data is gathered from CityGML files stored in a PostgreSQL database with a PostGIS extension. The method is applied on 13000 buildings in the city of Karlsruhe in Germany. The outcome of this study i.e. the solar radiation values allows further applications e.g. to compute passive solar heat gains of residential buildings or analysis of urban heat island impacts.

Keywords: Solar radiation, CityGML, 3D City Database, PostgreSQL, PostGIS.

1 Introduction

Solar radiation plays an important role in the planning of sustainable city structures and in the development of energy models related to urban areas [5]. Depending on several factors such as urban morphology or building designs, solar radiation can contribute significantly to the reduction of heat energy demand or it can lead to an increased need for space cooling [11]. For instance, in member states of the International Energy Agency (IEA) more than half of the residential energy consumption accounts for heating of buildings [6]. In general, energy demand of households and buildings has a considerable stake in global energy consumption. In Europe for example, buildings contribute 40-45% to the total energy demand [2].

In order to understand the spatial aspects of energy demand, especially in future distributed energy systems, it is necessary to not only consider single buildings but also extend the focus on neighbourhoods or cities as a whole.

As a result, localization, dynamics and patterns of energy demand can lead to an improved exploitation of energy efficiency potentials [7]. Therefore, 3D city models and GIS methodologies can contribute towards spatial aspects of energy modelling by taking geometry representation and spatial analysis into account [1].

Previous studies on the impact of solar radiation on buildings at the urban scale often focus only on roofs and mostly make use of raster data. However, for a comprehensive study of entire buildings, facades have to be incorporated. To overcome this drawback, Freitas et al. [4] propose a 3D approach with feasible tools such as CityGML and PostGIS. These are referred to be sophisticated means for accomplishing geometrical representation as well as spatial analysis of urban objects in 3D.

With the presented approach, it is possible to compute beam and diffuse solar radiation for clear-sky and under overcast conditions for 3D city models using the CityGML format. By relying on this standard, semantic building information such as wall and roof surfaces of buildings in Level of Detail (LOD) 1 and LOD 2 can be exploited.

2 Related studies

Different approaches have been developed to compute solar radiation and photovoltaic power production in urban areas.

Redweik et al. [9] propose the usage of a digital surface model derived from LiDAR data to determine the shadow height at each raster cell. Each cell of the raster grid is casting a shadow towards the opposite direction of the sun with decreasing height corresponding to the elevation angle of the sun. If a grid cell contains a higher Z value than the shadow height calculated at this cell, the shadow is interrupted and the shadow height at this facade section is registered. The sunlit part of a facade section is determined by subtracting the facade height and the shadow height.

Furthermore, 3D city models are also suitable for the computation of solar radiation on buildings. Hofierka and Zlocha [5] store the building geometry in a 3D Shapefile. They specify two possible shading algorithms. These are either making use of a voxel bitmask or a projection of the building surfaces on a plane perpendicular to the direction of the solar rays.

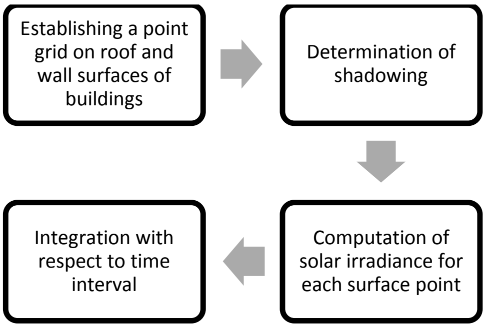
Strzalka et al. [12] create a 3D city model in LOD 1 from a LiDAR point cloud and store it in the CityGML format. The roof and wall surfaces are segmented into small triangles. To determine whether a triangle is shaded, a line representing a sun ray originating from the midpoint of each triangle is established for each time step. Then, the lines are intersected with surfaces, which potentially could cause shadow on the relevant triangle. The shading information is used for simulating annual photovoltaic power production.

3 Methodology

To compute solar radiation received per month by building wall and roof surfaces contained in a CityGML 3D city model, a Python application has been developed which merges specific approaches for subtasks from multiple studies [10, 12, 13] into a combined method. A PostgreSQL database and the PostGIS extension are used to store CityGML data, which enables capabilities for spatial analysis of the 3D city models.

As a database model, the 3D City Database was chosen. It represents the CityGML data model in a convenient way and comes with a comprehensive import and export tool for the exchange of CityGML data. The basic workflow of the proposed approach consists of four major steps, which are illustrated in Figure 1.

Figure 1: Basic workflow of the developed approach



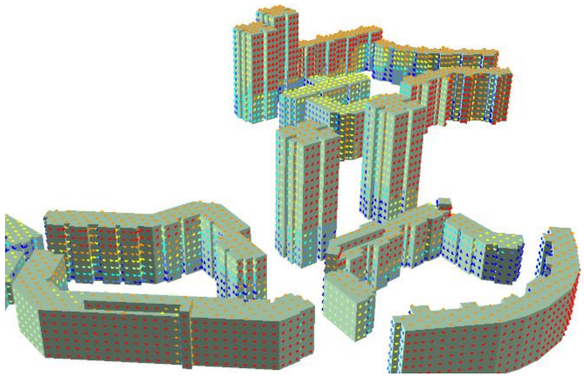
The first step of the processing sequence is the extraction of slope and aspect for each building surface derived from its geometry, by analysing the direction of the surfaces' normal vectors. Furthermore, an equally spaced grid of points is established on all surfaces potentially exposed to solar insolation, namely roof and wall surfaces. This can be conducted in LOD 1 and LOD 2. For these specific points, solar irradiance is will be computed later on.

In a highly obstructed urban area, the precise consideration of shadow casting is of high importance for the accuracy of the solar radiation calculation results [3]. In the second step, to incorporate shading effects of surrounding buildings, lines originating at each point on the surfaces where created. These lines are pointing towards the direction of the sun at the specific points in time for which solar irradiance is to be calculated. By using the PostGIS function "ST_3DIntersects", it is determined, whether a line intersects the surrounding buildings and therefore the corresponding point is shaded or not.

In the third step, based on surface orientation and the shadow information, which are extracted from the 3D geometry, the beam and diffuse component of incoming solar irradiance on each point on the building surfaces are computed. This is done by using the solar irradiance model presented by Šúri and Hofierka [13] (Figure 2).

The reflected radiation component has been neglected and the reduction of the sky view factor due to surrounding buildings, which leads to a decrease of diffuse radiation, is not yet integrated into the model.

Figure 2: High-rise buildings reveal the distribution of shaded and sunlit areas (red indicates higher irradiance values, while blue refers to low values).



Afterwards, a clear sky index is determined for each month of the year with respect to freely available monthly average radiation parameters obtained from the Photovoltaic Geographical Information System (PVGIS)[1] and the monthly average clear-sky radiation values computed by the algorithms presented by Šúri and Hofierka [13]. With this ratio of solar radiation under clear-sky and overcast conditions for each month, the beam and diffuse clear-sky horizontal irradiance for each time step can be corrected to match the local overcast conditions. It is assumed that these values are valid for the whole extent of one study area.

In the fourth step, beam and diffuse solar irradiance can be computed for each surface point by adjusting horizontal irradiance with respect to shading information and solar incidence angle at a particular time step. Then, the values are integrated in order to obtain monthly values of solar irradiation per surface point (Figure 3) and for complete building surfaces (Figure 4).

To improve computation efficiency, which can be crucial for large 3D city models of entire districts or cities, the multiprocessing package of Python is used. Additionally, to avoid irradiance computation for each consecutive day of the year, solar irradiance is computed only for days of a user-defined interval. An adequate agreement between computation time and accuracy has to be found. Afterwards, values for the same time of day are interpolated linearly in between the computed days. Finally, monthly irradiation values per surface as well as per building are computed by aggregating the daily values of solar irradiation.

[1] http://re.jrc.ec.europa.eu/pvgis/

Figure 3: Computed global radiation for LOD 1 (top) and LOD 2 (bottom) on surface points for one month (red indicates higher values, while blue refers to low values).

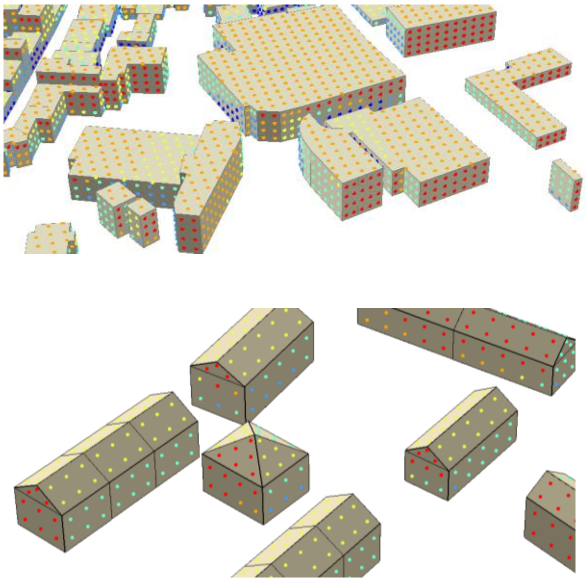
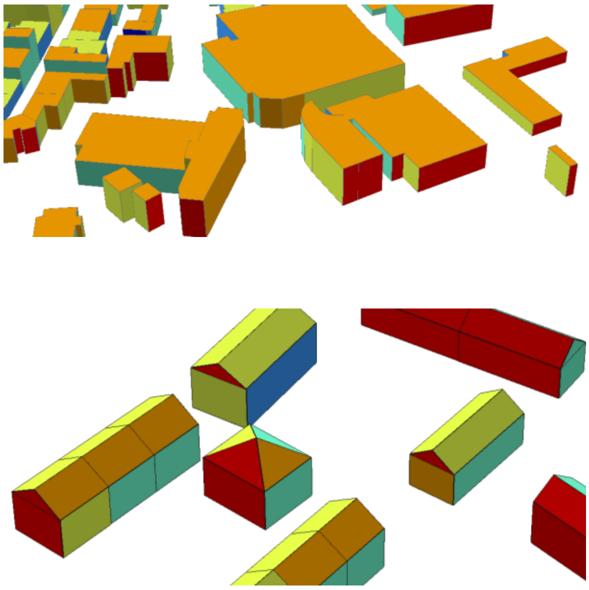


Figure 4: Global radiation on surfaces for one month computed for LOD 1 (top) and LOD 2 (bottom), normalized with respect to surface area (red indicates higher values, while blue refers to low values).



4 Results

As a proof of concept, the city of Karlsruhe, located in the southwestern part of Germany near the Franco-German border served as study area. The proposed model has been used for the computation of monthly solar radiation for CityGML data with building geometry in LOD 1 and LOD 2.

The developed methodology was applied on a LOD 1 city model of the Karlsruhe suburbs Durlach and Grötzingen containing approximately 13000 buildings in total. In the case of LOD 2, a subset of several neighborhoods of Karlsruhe with about 250 buildings was used as study area. The spacing between the surface points was set to five meters maximum, which was found to be an adequate tradeoff, regarding computation time for large city models.

Contrary to raster approaches, 3D city models contain semantical and geometrical information of buildings and the corresponding surfaces, which allows the determination of arriving solar radiation directly on buildings and specific building parts, namely wall and roof surfaces. As the geometrical representation of a building in LOD 1 is only an extruded footprint, it neglects the roof structure leading to biased results of the solar radiation computation for roofs due falsified solar incidence angles. However, the consideration of facades still is a benefit compared to the usage of raster data. Advancing to LOD 2 yields a more realistic geometrical representation of buildings, which can overcome the drawback of LOD 1 city models.

Knowing the amount and the spatial distribution of arriving solar radiation on entire buildings in a 3D city model, including roof and wall surfaces, opens possibilities for further city-wide modelling activities. For instance, the determination of solar gains can be introduced into the assessment of building heat energy demand [8].

5 Conclusion

The work presented in this paper introduces an approach for performing solar radiation calculation based on CityGML data. It allows a city-wide solar radiation calculation on individual buildings in different LODs. Moreover, the flexibility of the modelling approach allows easy application at other scales, e.g. buildings or neighborhood, without the need of developing extra tools. Drawback of the proposed approach is the high computational demand for the large amount of executed 3D intersection tests, which leads to computation times of several hours for the LOD 1 dataset with 13000 buildings. On the other hand, the tool presents a significant improvement of solar radiation calculation as it includes roofs and vertical surfaces. Therefore, the CityGML standard and the 3D City Database environment have proved flexibility and convenient usage.

The application developed in this research represents a basis for further significant improvements in the field of energy management. The results of the solar radiation computation can be used in various energy related applications e.g. assessment of photovoltaic potential, urban heat island studies, green facades and solar gains.

Acknowledgments

The authors would like to thank the colleagues at the European Institute for Energy Research (EIFER) in Karlsruhe, especially Jean-Marie Bahu and Johannes Ruf, as well as Prof. Dr.-Ing. Heinz Saler from the University of Applied Sciences Karlsruhe for their continued support. We also would like to thank Thomas Hauenstein from the city administration of Karlsruhe for providing the LOD2 data, which was used in this study.

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