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Solar Panels on Historic Roofs? A Digital Tool for Assessing Sensitive Roof Areas

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Abstract
The approval of solar installations on the roofs of listed buildings is a challenge that requires extensive knowledge of the building's roofing materiality, construction and cultural significance. The Lower Saxony State Office for Heritage Preservation (NLD) is leading an interdisciplinary research project with the Institute for Geodesy and Photogrammetry at the Technische Universität Braunschweig (IGP) to develop a Lower Saxony-wide heritage roof cadastre which enables an initial assessment of the suitability of roofs. The project focuses on creating tools that analyze and evaluate roofs based on their solar potential, roof material, geometry, and visibility in public space. The results can be made publicly accessible by integration into Lower Saxony's geographic information system. This should assist local preservation authorities and those involved in planning to ensure an appropriate and sustainable development of listed buildings in the future.

1. Introduction

Historic roofs not only shape the character of our towns and villages but also embody vast "stored energy" - the material, transport, construction and maintenance investment of past generations - as well as priceless cultural and technical knowledge. Preserving these roofs reduces CO_2 emissions, protects natural resources and safeguards craftsmanship and architectural intent [HKW99, Kas01]. German heritage preservation authorities have developed recommendations for owners, planners and the industry which are fundamental for carefully handling monument roofs (e.g. [Lan06]). Nevertheless, it can be observed that historical roof structures and coverings are subject to considerable transformation and are often lost during renovations or conversions. The potential full lifespan of roof material is rarely achieved. Energetic upgrading of historic buildings contributes to this issue in a large number although strategies and best-practice examples for careful conversion have been implemented for a long time [Gar13]. In this context, the demand of owners of historical buildings to mount Photovoltaic (PV) installations is adding to the discussions. In the Federal states of Germany, the monument protection laws are being revised so solar roofs can be approved for listed buildings. For example, since 2022, permission for PV on-roof mounting systems in Lower Saxony's listed buildings is usually granted if only minor interventions are made to the existing structure or roofing material (Section 7, Subsection 2, Sentence 4 NDschG 2022). As a result, numerous cities and municipalities are about to revoke their design statutes, which were once created for preservation. A roof cadastre map with information about material and value that provides information not only on the solar potential but also additional information would be of great interest to assess and oversee future developments. The historic roof cadastre should identify sensitive roof areas and thus provide a decision-making aid for possible changes to listed roofs. For this purpose, the Lower Saxony State Office for Heritage Preservation (NLD) is conducting an interdisciplinary research project with the Institute for Geodesy and Photogrammetry (IGP) at the Technische Universität Braunschweig to develop an automated analysis process for creating a roof cadastre. We have determined three factors apart from the solar potential that influence the suitability of a listed roof for solar systems: Material, visibility and historic value. Some roofs have materials that are particularly worthy of protection or are not suitable for the installation of solar systems. Considering the visibility of the roofs in public space helps the decision makers to rather select roofs that aren't visible in public space, so that the solar system installation would not detract from the impression of the roof. This in turn adds to the historical value of the monument. In this short paper we present the components of the project, sketch the methods employed and show preliminary results.

2. Related Work

The most common tools for decision-makers or private individuals are used to decide whether the installation of solar systems is economically viable or not. This means that most tools are solar cadastres that show the solar potential for individual roof areas, e.g. [LEA23]. However, these cadastres do not include information about the visibility of the observed roof, nor do they include information about the roofing material. Nevertheless, the calculation of the visibility of a roof area or the estimation of the roofing material has been described in several works.

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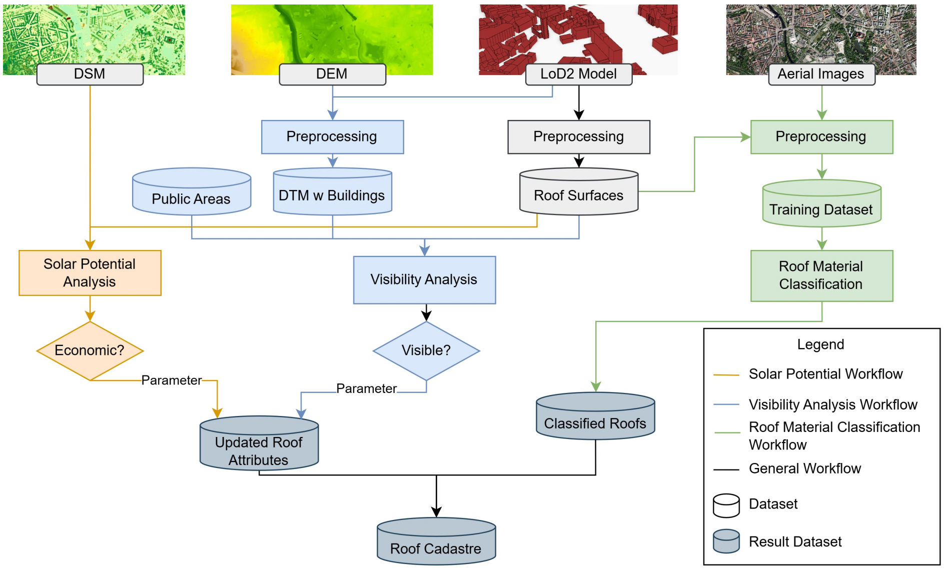

Figure 1: *General workflow for creating the roof cadastre*

Solar radiation is calculated based on geographic location, roof inclination and aspect and time (for clear-sky potential) and can be adjusted using meteorological data like cloud cover and sunshine duration to reflect real-world conditions. Assouline et al. [AMS18] review six methods for calculating large-scale solar potential: physical/empirical, geostatistical, constant values, sampling, GIS/LiDAR and machine learning. However, the available data limit the choice of a possible method. Based on the input data, Krapf et al. [KKK*21] group methods into statistical, geospatial, aerial and 3D. Solar potential itself can be divided into four types: physical, geographical, technical and economic potential. Physical potential focuses on the solar radiation at a specific geographical location [ŠH04]. Technical potential factors in systems efficiency and the area actually available for installation [NG20] and economic potential evaluates the usable technical potential over the system's lifetime, accounting for all costs [MSŠ*19].
Solar systems and their visibility have been analysed in general and in the context of social acceptance in several studies [ZWZ*23]. Common input data for the visibility analysis are 3D point clouds, Digital Elevation Models (DEM), Digital Surface Models (DSM) or (3D) vector data. When using vector data and/or DEM, Isovists [Ben79] and viewshed methods [Fis96] are often used. Since DSM and DEM are open-source data for Lower Saxony in Germany, we decided to implement viewshed methods that use DSM and vector data.
For roof material classification, either RGB or multispectral imagery is used. For the mapping of asbestos-containing roofing material, Abbasi et al. [AMV*22] have identified three general approaches: pixel-based image analysis, object-based image analysis and deep learning approaches. Pixel-based methods, for example, compare the spectral curves of individual pixels against a multispectral library to distinguish materials [ZPJR*23, WMH23]. More recent work uses deep learning to classify different roofing materials [WFP*23, Sol20]. Deep learning (DL) approaches offer high accuracy and an alternative to pixel- or object-based methods. However, to train a deep learning model, relatively large datasets are required, which are – to the best of our knowledge – not available for the task of roofing classification.

3. Materials and Methods

The roof cadastre is the overall result of several analysis processes, which are shown as workflow diagram in figure 1. The workflow is divided into automated work packages. Each process either leads to a new data set or generates the parameter values for a roof area. The final process combines all these parameters to produce the overall result.
As shown in figure 1, the input data of our workflow consists of DSM, DEM, 3D building models in Level of Detail 2 (LoD2), and aerial images. First, we use the LoD2 model to generate a roof surface layer, which is represented by the black arrow under the LoD2 model. The created roof surface layer is a mandatory input for every analysis step in our workflow. The process for calculating the solar potential as the first analysis step is indicated by the light orange arrows. In addition to the roof surface layer, the DSM is an input for the solar potential calculation (cf. section 3.1). A pre-processed grid, containing the terrain elevation and the 3D building information, public areas, and the roof surface layer, is used to determine whether the roof surface is visible from public places. This second process is highlighted in blue in figure 1 and described in section 3.2. For the third analysis step, the roof material classification, we use a custom training dataset. The dataset is created from aerial imagery, field inspections, and the roof surface layer. The classification process is shown in green and also described in section 3.3. Results of the individual analysis steps are either parameter values, namely a value for the solar potential or the visibility, or the roof material class, which will be added to the roof surface layer

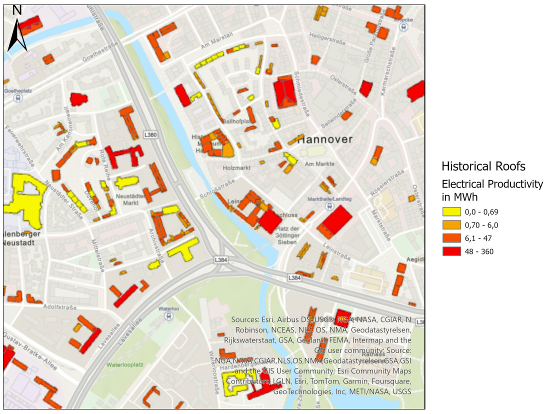

Figure 2: *Result of the solar potential analysis for a section of the study area in Hanover.*

as an attribute. Two study areas were selected to develop the prototype of the roof cadastre. The first one covers the city centre of Hanover, while the second study area is the city centre of Goslar. They contain various building types from different eras with different roof shapes and materials. The Lower Saxony State Office for Geoinformation and Land Surveying (LGLN) provided the data for the study area. It consists of LoD2 models, True Orthoimage (TrueDOP), DSM and DEM. The LoD2 model is stored in CityGML format. The 3D city model was created using building outlines from cadastral data, digital terrain model (DTM) and 3D data from laser scan or matching point cloud [Lan25].

3.1. Estimation of PV Potential

The solar irradiation on the roof surfaces is determined using the Solar Radiation Toolbox of ArcGIS Pro, employing the LoD2 models and the DSM. The algorithm takes into account the general topology specified by the DSM as well as atmospheric and shading effects. The result is presented in megawatt hours per square metre on the basis of one year, which is then computed for each roof, using the known surface area. We calculate the total roof area using the LoD2 models by converting these into vector layers in order to extract the roof surfaces and then calculate the roof area. We do not include the entire roof area, as this cannot be fully utilised to install PV modules. Instead, we determine the actual usable roof area in two ways: a) by reducing the total area by a factor, and b) by identifying objects on the roof area applying straightforward image interpretation. Finally, to calculate the electrical power, the irradiation is multiplied by the power ratio and the efficiency of standard PV modules. The result is a new dataset of listed buildings with a certain solar potential, but a threshold could be added to exclude non-economic configurations from the next steps.

3.2. Visibility Analysis

We also use ArcGIS Pro for the visibility analysis. Visibility is determined by lines of sight that connect an observer point with a target point. The observer point is placed in the centre of the roof surface, while the target points represent people looking towards the roof surface from the public space. The target points are derived from each cell of the calculated grid located in public areas. The observer points are evenly distributed 3D points on the respective roof surfaces. By distributing the observer points over the roof surface, we ensure that the visibility is checked for each roof surface and that each target point, i.e. each grid cell, is checked for visibility. The line of sight is divided into several points and projected onto the terrain's surface. The distance between the line of sight and the projected point on the surface is then calculated. If the distance is greater than zero, the target point is visible. If the distance is zero or less than zero, the target point is not visible as the line of sight is interrupted. A second line of sight indicates that the distance is positive up to the point of intersection with the building, but then becomes negative. Visibility is therefore calculated considering the surface, the observer points, and the target points. Only the roofs remaining after the first step of the solar potential analysis are analysed concerning their visibility from public areas. Hence, each of those roof gets assigned a parameter value corresponding to its visibility. The public areas, e.g. streets, squares and green spaces, were defined by the LGLN and provided as layers in our case. However, in principle, the layer definition is subject to several considerations by the final user. We decided against using the DSM to represent the surface to minimise seasonal influences such as tree foliage and thus eliminate the entire influence of trees. Instead, we created a new raster from the DEM and the 3D city model, i.e. a DSM that only contains buildings.

3.3. Roof Material Classification

To determine the roof material, we have decided to use DL models. As indicated in section 2, to train DL models roofing material datasets are required, but are currently relatively rare. Hence, we decided to create our own training dataset. Through field inspections, the roofing material of individual roof surfaces is determined according to 13 different, predefined material classes and manually entered as an attribute in a roof surface layer. The roof areas are then extracted from the georeferenced orthoimage using the coordinates from the roof area layer. The training dataset thus contains 13 different roof coverings. We fine train and validate existing classification models and test them with our own data.

4. Preliminary Results

Since our work is still ongoing, we present in this section some preliminary results. For the first estimation of the yearly electrical productivity in megawatt per hour for our study area in Hanover. The result of the solar potential analysis for a section of the test area is shown in figure 2. Figure 3 shows the result for the visibility analysis of one individual roof surface in the study area in Hanover. The investigated roof surface is marked in red. The areas from which the roof surface is visible are plotted in black. The visible area shown in figure 3 has not yet been subjected to the intersection with the public areas.

5. Conclusion

In this paper, we present our ongoing work to create a roof cadastre that combines properties we have identified to help decision makers or private individuals understand where solar systems would

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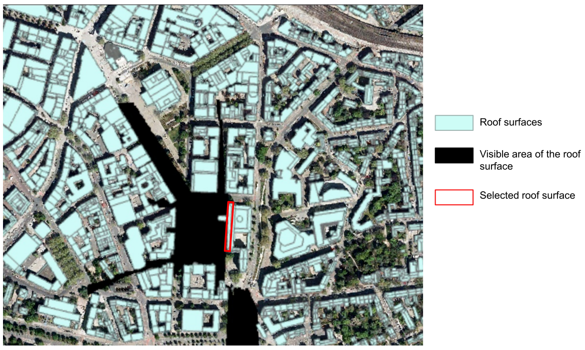

Figure 3: *Result of the visibility analysis for one selected roof surface in the study area in Hanover.*

unlikely affect the historic value of listed buildings and on which roofs solar systems would significantly influence the historic value. Therefore, we introduced a first draft for the solar potential analysis and the visibility analysis for our study area in Hanover. In future work, we will expand the solar potential analysis with the improved calculation of the usable roof area and finalise the visibility analysis. We encountered the problem of the limited availability of datasets on roofing materials. We decided to create our own dataset for the study area in Goslar. The field inspections to identify the roof coverings have been completed. The training data was generated using the labels from the field inspection and the trueDOP. In the next steps, the generated image patches are augmented and further processed. Further pre-processing also depends on the choice of the DL model. We will test various models and pre-processing steps in the future. In addition, we plan to investigate the improvement by considering multispectral information of the roof materials in the classification step. To this end, drone flights have already been carried out in the study area in Goslar.

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