3D Solar Analysis of the Street Network and Impact Estimation of the Shade of Trees at the District Scale

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Abstract

Trees on city streets are the valuable resource for the pedestrian comfort and mitigation of effects of the urban heat island. Solar studies at the city and district scales can be conducted in 3D using various tools. However, 3D city models often lack the geometry of high vegetation in solar analysis, as tree representation is more complex compared to buildings. While this omission is not critical for the assessment of rooftops, shading from trees significantly affects pedestrian comfort on the street in the summer, building-integrated photovoltaics on façades, and energy consumption of buildings. This paper presents a 3D solar analysis that integrates trees into studies at the district scale using a widely adopted 3D raytracing algorithm. The study area covers 9.24 km², evaluating 1,056,482 faces and incorporating 34,617 trees. Tree transmissivity is accounted for with separate calculations and post-processing of the output datasets. The study demonstrated up to a 30% decrease in solar radiation on streets compared to analysis that excludes trees, as well as an 18% increase in solar access to street surfaces compared to raster-based calculations in GIS. The resulting analytical datasets are integrated into the Urban Digital Twin of Sofia using open standards such as CityGML and 3D Tiles. CityGML Vegetation ADE is reviewed to incorporate the proposed workflow. This approach offers a straightforward solution for assessing the impact of tree shade with modest computation time and can be scaled to the city level in future research.

1. Introduction

Trees on city streets play a crucial role during hot summer days due to the provision of shade and evapotranspiration. In urban areas, at 2 a.m. for every 10% of additional tree canopy, one can expect a temperature decrease of 0.3 ◦C during heat waves (Coseo and Larsen, 2014). The very presence of tree shade can influence the selection of a pedestrian route (Azegami et al., 2023). Research indicates that solar radiation has a greater influence on human thermal comfort than other microclimatic factors (Lindberg and Grimmond, 2011; Ridha et al., 2018; Liu et al., 2023). Solar radiation impacts nighttime temperatures in urban canyons by increasing heat storage in impervious surfaces and reducing cooling efficiency. Identifying street surfaces that receive solar radiation during the hottest part of the day and radiate back this energy at night is essential for understanding urban heat dynamics. Therefore, incorporating trees into the geometric analysis of solar access on a street could give a better picture at early stages of the assessment. While creating digital replicas of trees in 3D remains a complex task, omission of such urban elements can lead to wrong results.

Modelling in 3D the shadowing effect of trees on city streets allows to predict thermal conditions of urban space. At both the city and district scales, this can be simulated in a 3D virtual environment using various software. However, large-scale 3D city models often exclude vegetation from solar analysis due to the complexity of the geometry of trees, uncertainty of physical features and the impact on computation time (Peronato et al., 2018). While this omission is not critical for the assessment of rooftops, in contrast, the pedestrian comfort, as well as building-integrated photovoltaics (BIPV) and energy modelling are highly impacted by the shade of trees.

This paper extends the existing method (Shirinyan and Petrova-Antonova, 2024) for assessing solar access for large study meshes, handling up to 2,000,000 faces per calculation on a standard PC configuration at the district scale. A key contribution of this study is the integration of the geometry of trees into the solar analysis of urban streets, which enhances the accuracy of results in areas with dense street vegetation. The considered workflow can be expanded to the city scale. Discrete geometry of trees facilitates a comparison of various scenarios. Methods for post-processing of results and integration with the Urban Digital Twin (UDT) of Sofia, using open standards such as CityGML and 3D tiles are proposed as well.

The remainder of the paper is structured as follows. Section 2 provides a research background on key aspects of solar studies in urban areas, including tools for solar radiation analysis, 3D vegetation modelling and calculations, and the prediction of solar potential using machine learning. Section 3 describes the preparation of datasets, the main components of solar analysis, and usage of open geospatial formats for visualisation in the UDT. Section 4 discusses the results that were acquired. Section 5 concludes the paper and offers directions for future work.

2. Related work

Vegetation and the trees significantly affect solar radiation in the urban environment, and various tools can account for trees in calculations of thermal microclimate.

At the city scale solar analysis is often conducted in GIS using 2.5D raster data models, e.g., DSM derived from point clouds (Zhao et al., 2023). Point clouds and resulting 3D surfaces usually include vegetation, but it is a challenging task to separate trees from other structures, especially when assessing "what-if" scenarios. In GIS-based solar analyses, the space between a tree's crown and the ground is challenging to account for.

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Recent studies consider direct integration of thermal comfort calculations with trees included and Urban Digital Twins. Nevertheless, the geometry of GIS-based methods utilised in these studies is 2.5D and does not represent the street surface under crowns of trees (Sukma et al., 2024). The similar raster-based method is implemented in UMEP software (Lindberg et al., 2015); however, the space under a crown can be considered.

Urban energy modelling (UBEM) software can incorporate the shading from vegetation into calculations (Ali et al., 2021). CitySim was used to quantify the cooling potential of trees and resulting outdoor comfort of a campus of the Swiss International Scientific School of Dubai (SISD) (Coccolo et al., 2018). Despite that, CitySim appeared to be highly sensitive to the number of faces, as in the case of comparative analysis of geospatial tools it calculated relatively small area with trees for 268 h, whereas removing trees reduced the time of calculation to 65 h (León-Sánchez et al., 2025). The calculation for building surfaces only without trees and terrain took 22 mins.

ENVI-met can conduct complex microclimatic studies at the district scale and consider the geometry of a tree crown and the biophysical behaviour of vegetation (Gai et al., 2025). On the other hand, calculations in ENVI-met are quite time-consuming, restricted by resolution in the case of the city scale, slow processing speeds, and numerous inputs (Shaamala et al., 2024). The horizontal resolution of a model domain is typically 1-10 m. The size of the model domain varies between 50×50 and 500×500 grid cells in the XY plane and 20-50 grid cells along the Z-axis.

Building energy modelling tools such as Honeybee, IES VE or Archicad Ecodesigner provide functionalities that account for seasonal shading from trees on the energy consumption of a single building. Therefore, these tools are usually restricted to a small area, and the evapotranspiration is not considered.

The transparency and seasonal variations of individual trees are difficult to predict, introducing an additional source of uncertainty. The most relevant studies on this topic examined digital models of trees that were represented using the alpha shape algorithm, with solar radiation calculated in the Radiance-based Daysim software, which accounts for reflected radiation (Peronato et al., 2018, 2016). The study area was relatively small (1.2 km²), and trees were either treated as opaque or excluded from the calculation. 3D city models, a core part of UDT, can consider trees (Giannelli et al., 2022; Park et al., 2021), but many of them exclude trees from solar analysis at the city scale (Shirinyan and Petrova-Antonova, 2024). For Ladybug Tools, trees were included in solar analysis, using the principle of a low impact of shadow-casting tree objects on the overall calculation time, but the area of the study was 1*1 m (León-Sánchez et al., 2025). The modelling of the geometry of trees for a 3D city model requires attention to the level of detail (LOD) and methods of representation (van Leeuwen et al., 2013; Ortega-Córdova, 2018; Suwardhi et al., 2022; Tian et al., 2022).

One can assert, that the vegetation within the concept of UDT, stays underrepresented in research. Comprehensive state-of-the-art reviews almost do not mention vegetation (Dembski et al., 2020; Ketzler et al., 2020; Weil et al., 2023). Nevertheless, there is an interest to integrate digital replicas of urban vegetation into a wider context of planning support systems and UDT (Nummi et al., 2022). Attempts to model a geometric replica of a tree and even its behaviour appear to be promising (Chen et al., 2024), but there is a little discussion how exactly to store these digital replicas, or how to conduct environmental analyses in 3D, such noise propagation, solar access, or visibility studies. Regarding the semantic dimension of a digital replica of a tree, the conceptual model of the Application Domain Extension (ADE) of CityGML 3.0 Vegetation (Petrova-Antonova et al., 2024) provides an advanced outlook of how trees and the dynamic processes of growth can be represented in an UDT.

Recent research shows advances in the prediction of solar access at the city scale using machine learning, especially in the case when a 3D city model is not available (Ni et al., 2023). Machine learning methods can reduce the computation time from hours to seconds compared to GIS-based methods (Zhao et al., 2024). To predict solar radiation on building surfaces at the city scale in Zhengzhou, China, GIS, Ladybug Tools, and machine learning were integrated into a model, based on XGBoost (Yue et al., 2024). Nevertheless, these methods generally seem to be less suitable for analysing the shade of trees on a street with complex building geometry.

To conclude, there are various techniques in the assessment of the shading effect of trees in the city. They assume complex inputs and slow processing speed. In this context, CAD-based software was often overlooked for the usage at the district and city scales. Considering existing methods, this paper attempts to develop a rather simplified, yet flexible workflow of calculating tree shadows on urban streets and demonstrates its applicability to the field of 3D city modelling. In addition, transmissivity of tree crowns is achieved using post-processing of the output. This method cannot replace full-fledged analyses but can act as a starting point as a further development of the UDT of Sofia. The results of solar access on the streets of Sofia can serve as shading maps for more comprehensive workflows.

3. Data and methods

3.1 Study area

Situated in the western part of Bulgaria in Sofia Valley, Sofia has a population of 1,221,172 and covers 255 km² of the urbanised area. The city is surrounded by the Vitosha Mountain from the south and Balkan Mountain from the north. The sunshine in Sofia lasts in average of 2065 h annually with its maximum in July. The total solar radiation (direct and diffuse) in Sofia is 121.4 kcal/cm^2 (1412 kWh/m^2) annually, with peak values occurring in July (with an average monthly value of 17.3 kcal/cm^2, or 201.2 kWh/m^2). The lowest values of solar radiation are in December, averaging 3.3 kcal/cm2, or 38.4 kWh/m2 per month (Sustainable Energy and Climate Action Plan of Sofia Municipality 2021 – 2030 including Energy Efficiency Programme and Long-term Programme to promote the use of renewable energy and bio-fuels, 2021).

The streets of the Lozenets, a district in the south of the Sofia city, were selected for the solar analysis. The total area of the district is 9.24 km^2, while the area of the streets including sidewalks takes 1.37 km^2.

3.2 Workflow

The overall workflow for pre-processing geodata, calculations of solar radiation, and the integration with a 3D web platform are shown in Figure 1. Buildings, terrain and trees were generated from various sources of geodata and survey. All the geometry was relocated to the origin and generalised. For the assessment of solar access on street surfaces, only street boundaries were selected. Separate calculations of four cases, described in Subsection 3.5, ensured the setting of transmissivity of tree crowns. Finally, the results were rasterised and compared using

GIS tools. To visualise the streets with trees in a 3D urban context, an open-source web-based platform and open standards were utilised.

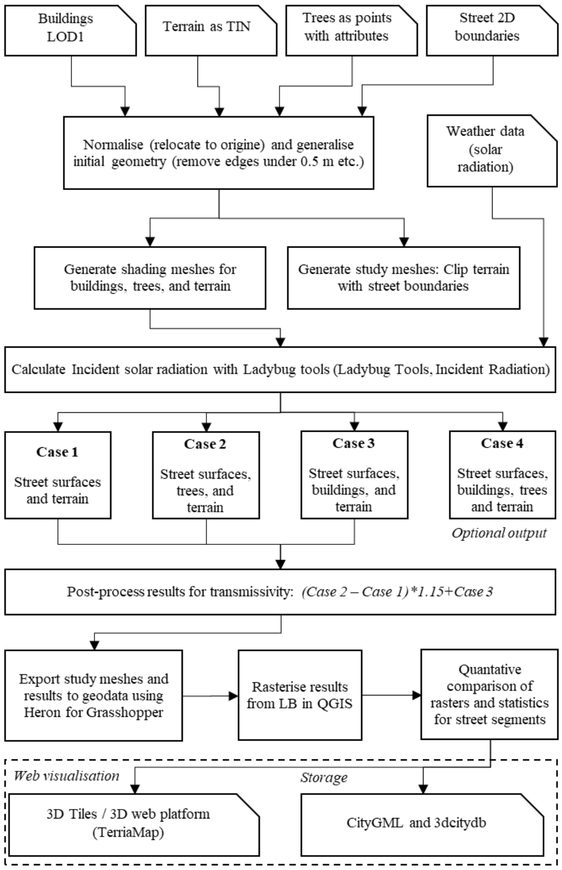

Figure 1. General workflow

The calculations of solar radiation were not validated; therefore, the results give rather a relative picture for the sensitivity analysis than absolute values. The study aims to simulate a worst-case scenario, when radiation values and air temperature are high, and the weather is windless.

3.3 Weather data and analysis period

Weather data in the EnergyPlus Weather (EPW) format from Climate.OneBuilding.org was selected (climate.onebuilding.org, 2025). The EPW file, constructed from 2007 to 2021 for the location of Sofia, contains 8,760 hourly values of one year for each meteorological parameter. This format stores Typical Meteorological Year (TMY) data and is commonly used for solar studies in applications like Ladybug Tools or energy modelling. This weather dataset does not include shadows from surrounding mountains, in contrast to PVGIS (PVGIS data sources & calculation methods - European Commission, 2022). As for the consideration of shading from distant terrain surfaces, the Vitosha Mountain blocks a small portion of direct beam radiation from the south in autumn and winter. This effect is illustrated in Figure 2, which shows a shading mask and the solar analemma from a web service Global Solar Atlas ("Global Solar Atlas," 2025). For the summer period the shadowing effect of the mountain is even less significant, especially for horizontal surfaces (Shirinyan and Petrova-Antonova, 2024). Thus, the larger shading terrain surface around the study area can be ignored.

According to the EPW dataset the highest values of solar radiation occur in July, with a cumulative result of 196 kWh/m^2. The hottest week lasts from July 13th to July 19th.

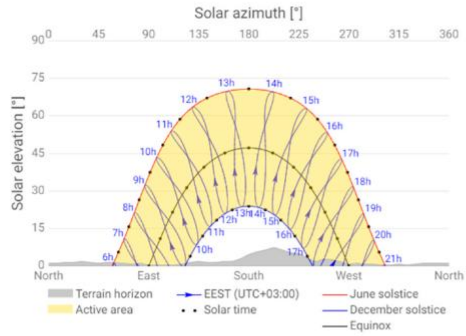

Figure 2. Shading mask, Global Solar Atlas

July, 15th can be identified as a day with a clear sky. The cooling benefits of trees are most pronounced during the hottest part of the day, from 13:00 to 15:00, when heat stress on streets with dense tree cover is significantly lower compared to those without (Ren et al., 2022). Therefore, the analysis period of the day was set to this part of the day and slightly extended to a range of 13:00-17:00.

3.4 Preparation of 3D geometry for calculations

The geometry of building footprints, trees, and the terrain surfaces were gathered from the open data portal of Sofiaplan and the Cadastral agency ("Geoportal of Geodesy, Cartography and Cadastre Agency," 2024; "Sofiaplan Open data," 2025). Street boundaries were provided by GIS-Sofia, a local geodesic company. All the geometry was simplified and normalised according to (Shirinyan and Petrova-Antonova, 2024). The 3D models were generated from geodata using Heron for Grasshopper within 3D CAD Rhino.

The building footprints were extruded in Rhino using the Heron plugin. The building heights were acquired from photogrammetric point cloud and the resulting DSM. Building parts were extracted from a raster height map with Segment Mean Shift algorithm in ArcGIS Pro and aggregated into watertight solid bodies using a grouping field with a unique building identifier. The obtained building models were tessellated in Rhino with minimum number of faces.

The terrain surface was transformed from DSM data with 1 m/pixel to a triangular irregular network (TIN). 2D boundaries of streets in the district were dissolved and projected onto the terrain using FME Form. The terrain surface was clipped with the street boundaries and separated into two types of meshes: the study mesh of the street network and shading mesh of the remaining terrain. To make the study faces uniformly distributed, the resulting 3D surface was subdivided into a mesh with quad faces in Grasshopper. An average face size was around 1 m^2, and the total count of faces consisted of 1,056,482 faces.

Trees were acquired from the Tree map of Sofia, which provides basic yet reliable information (approximately 80% accuracy) on all trees within the municipality. GIS-Sofia supplied a dataset of 3,671 high-resolution (0.1 m/pixel) georeferenced aerial orthophotos taken in the autumn of 2020. DeepForest, a variation of RetinaNet algorithm, was adapted and further trained. Then the algorithm was applied to the entire set of orthophotos. Tree crown boundaries in 95% of the images and type of a tree (deciduous or conifer) were identified (Tree Map in Sofia Municipality, 2021). The resulting dataset with tree locations is published as open data on the website of a municipal urban planning department Sofiaplan. Heights of the trees were transferred from a photogrammetric survey of the same district.

For the purposes of the study, trees were represented as 34,617 points with attributes containing the height of a tree, a crown diameter, and elevation. Trees not affecting the streets were excluded from the process.

Crown geometry was represented as a 3D mesh object with a low number of faces. The same principle was used for the trunk. The 3D model of tree was adapted for each location point using height, derived from a photogrammetric survey, and crown diameter from the tree dataset.

3.5 Solar analysis and post-processing of results

The calculation of solar radiation was conducted using Ladybug Incident Radiation component (Incident Radiation, 2024) for two main scenarios: with trees and without trees. The weather dataset, including location, direct normal radiation, and diffuse horizontal radiation, was used to generate a cumulative sky matrix. This matrix, computed using the Radiance *gendaymtx* function, represents cumulative radiation values from each segment of the sky dome over a specified period. The resolution of the sky matrix influences both precision and computation time, with the default Tregenza subdivision (145 patches) or the higher-density Reinhart subdivision (577 patches).

Once the matrix is generated, incident solar radiation is calculated for study objects while accounting for shading and self-shading effects. The Ladybug Incident Radiation component performs these calculations by determining intersections between mesh face centroids and the sky mask, without including reflected radiation. Ground-reflected radiation is approximated using an emissive virtual ground hemisphere with a default reflectance value of 0.2, but any terrain geometry will block this type of radiation. Material properties are not considered. Studies indicate that the Ladybug method closely aligns with more precise Radiance-based simulations for flat, unobstructed surfaces but diverges in shaded areas and on north-facing façades (Thebault et al., 2021).

The Ladybug Incident Radiation component can use discrete geometry to evaluate various scenarios for a new construction, seasonal changes, etc. However, there is no possibility to assign transmissive materials directly or envisage processes of evapotranspiration.

To overcome this limitation and incorporate transmissivity of tree crowns into the workflow, a post-processing of three separate calculations of solar radiation of street surfaces was performed. Cases 1-4 are listed in Table 1. Case 4 contained all the model categories to explore performance and calculation time.

The study was conducted using the following computer configuration: i7-13700F, RAM 128 GB 4000MHz, RTX GeForce 4070, SSD. Analysis period was set to July 15th, 13:00-17:00.

Case name	Face count, study geometry (street surfaces)	Model categories of shading geometry	Face count
Case 1	1,056,482	Terrain	133,799
Case 2	1,056,482	Trees, terrain	874,967
Case 3	1,056,482	Terrain, buildings	383,593
Case 4	1,056,482	All the categories	1,124,671

Table 1. Model categories of the cases

To obtain a scenario without trees and a scenario with trees, shadows of trees were computed using the subtraction of Case 1 from the Case 2. In Grasshopper, the values of solar radiation of this difference map were increased by 15% according to average values of transmissivity of tree crowns (Tian et al., 2022). Finally, the post-processed tree shadows were added to Case 3.

For further analysis in GIS, results were exported as points with Heron to QGIS and converted to georeferenced rasters.

3.6 Open formats for storage and visualisation in UDT

To comply with digital twin standards, the polygons of the street network were transformed with FME Form into a data model of a road, based on the CityGML 2.0 standard, LOD 2. Each street was aggregated by a unique identifier into a collection of objects. The parent *Road* object was generated without geometry. According to the CityGML data model, the subclasses *TrafficArea* and *AuxiliaryTrafficArea* acquired *MultiSurface* geometry of street polygons. Z-coordinates of street surfaces were transferred from a DTM raster with ground elevations. In addition, the street network was textured with an orthophoto 30 cm. To ensure future integrations with any analytical results, a unique “*gml_id*” can be used. Figure 3 shows the structure of the dataset in FKZ Viewer.

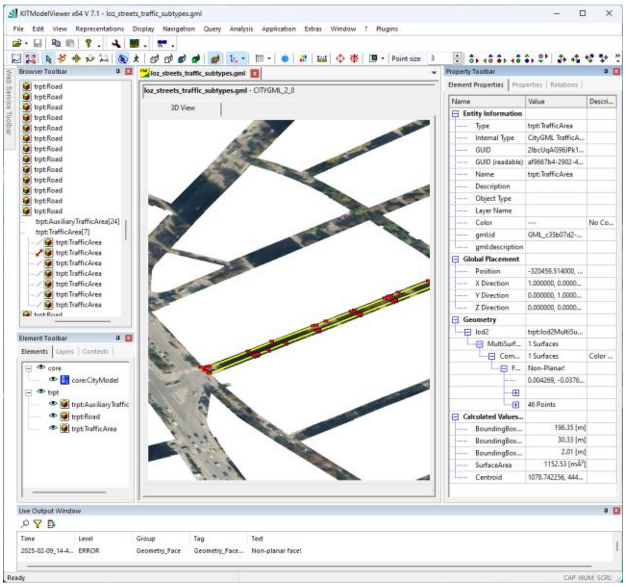

Figure 3. CityGML road model

For each location of a tree a crown geometry and a trunk were modelled according to a simplified version of a conceptual model of CityGML 3.0 Vegetation ADE (Petrova-Antonova et al., 2024) and populated as the instanced (implicit) geometry. This ADE stores inside the parent *SolitaryVegetationObject* the separate geometries and features for a crown and for a trunk, which corresponds with the modelling process of trees in this paper. For the study CityGML 2.0 was used as a base and the data model was reduced to include only *Crown* and *Trunk Abstract FeatureTypes*. Lifespans and the *Dynamizer* were omitted. For storage purposes, the CityGML road objects and trees were imported to a 3dcitydb instance. Figure 4 represents a simplified version of the data model for tree objects.

To visualise the 3D model of the district in a web-based 3D GIS platform, 3D Tiles for buildings, trees and terrain were generated. Solar radiation values, represented as raster maps, can be integrated into a web-based platform using the Web Map Tile Service (WMTS), a standard protocol for serving georeferenced images over the Internet.

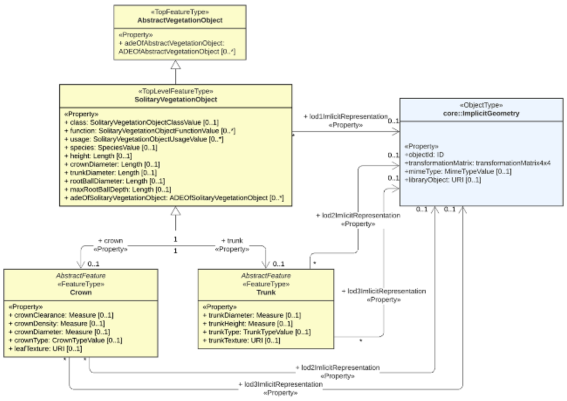

Figure 4. Adapted CityGML Vegetation ADE schema for a standalone tree. Geometric representation is shown in Figure 5

4. Results and discussion

4.1 Calculation time and performance

In Grasshopper, algorithms are constantly updated, the overall performance can significantly decrease in the case of large volumes of data, and Rhino can freeze. According to Table 2, the total time for calculating solar radiation for all the streets in the district with trees, buildings, and terrain (Case 4) was 660 seconds. There is a slight increase in computation time, as the number of faces of shading geometry increases as well. Figure 5 shows the integrated result for the district.

Case name	Face count, study geometry (street surfaces)	Face count, shading geometry	Time, s
Case 1	1,056,482	133,799	420
Case 2	1,056,482	874,967	546
Case 3	1,056,482	383,593	495
Case 4	1,056,482	1,124,671	660

Table 2. Calculation time for Cases 1-4

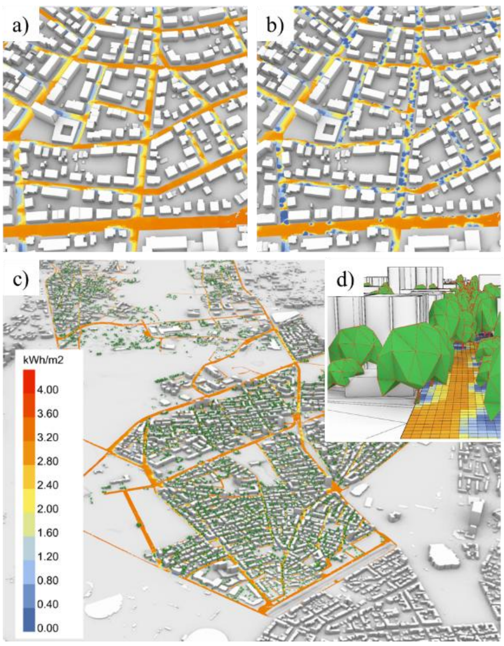

Figure 5. Solar analysis for 13:00 – 17:00, 15th of July. a) an area without trees; b) an area with the shade of trees; c) overview of the district d) a detailed view of trees

As for the performance GPU-based raytracing algorithms in GIS can surpass the method proposed in the study. For example, the total calculation time for a DSM-raster representing all the streets with trees with 15,153,672 cells (0.3 m/pixel) was 426 seconds in ArcGIS Pro. However, the 3D CAD environment provides a more flexible way to evaluate various scenarios even at the city scale. In addition, the space between the crown and the ground is accounted for as well, as the shape of a crown.

4.2 Quantitative comparison of the cases

First, the calculation in Ladybug demonstrated the difference between the scenario without trees and the scenario with trees resulted in 30% decrease in solar radiation for an E-W oriented street with the dense tree canopy. Figure 6 presents a comparison between solar analysis with Ladybug Incident Radiation and Raster Solar Radiation in ArcGIS Pro. Compared to 2.5D analysis of solar radiation in GIS, preliminary 3D based analysis showed up to 18% more of total solar radiation for a street with dense shading (1). In the area beneath trees, the difference was approximately 35% (2).

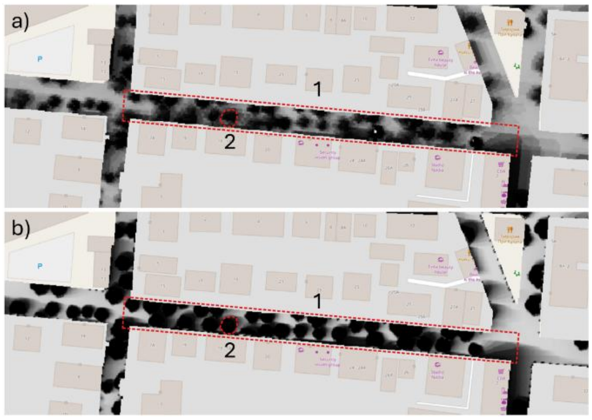

Figure 6. Comparison of solar radiation values of a street with a dense tree canopy a) Ladybug Incident Radiation; b) ArcGIS Raster Solar Radiation

To quantitatively assess and compare the differences between the two solar radiation scenarios (with and without trees), the Reclassify and Tabulate Area tools in ArcGIS Pro were used. Five classes were identified using the Natural Breaks (Jenks) method. The Change Detection tool identified areas where significant reductions in solar radiation occurred due to the hypothetical removal of trees.

Notably, streets located in the southern part of Lozenets with higher height/width ratios of street profiles displayed an increased vulnerability to high solar exposure, with trees removed, according to Figure 7. Conversely, tree canopies reduced solar radiation levels, with several streets transitioning to lower solar radiation classes (Class 1 or 2). The Change Detection analysis confirmed a shift from high solar radiation (Classes 4 and 5) to lower radiation classes (Classes 1 to 3) in areas with dense tree cover.

Zonal Statistics in ArcGIS Pro was used to calculate the mean value of solar radiation received by each street and sidewalk segment. Rasterised values of solar radiation were aggregated within predefined zones (i.e., individual street and sidewalk polygons) for both the tree and non-tree scenarios. On further steps this information can enrich CityGML datasets. In addition, according to (Park et al., 2021), raster-based shading maps can be used for the assessment of land surface temperature.

Figure 7. Magnitude of changes for classes in the northern part of the Lozenets district

4.3 Visualisation in TerriaMap

A catalogue-based web visualisation platform TerriaMap for geospatial data, based on the CesiumJS and TerriaJS libraries, is used to combine all the 2D and 3D datasets in one interactive environment. In addition, TerriaMap allows to explore the shadows cast by buildings and trees on a selected date and time. The results were imported as 3D tiles and WMTS-connections to rasters, as shown in Figure 8.

Figure 8. Visualisation of buildings, trees, and solar radiation of street surfaces in TerriaMap

4.4 Combination with sensor data

In addition, outputs from solar analysis can be combined with historical data from sensors in 3D. Figure 9 depicts an experimental attempt to represent façades of buildings and streets representing solar radiation values supplemented by sensor data in the spatiotemporal format of Space Time Cube within ArcGIS Pro. 3D representation of measurements and charts are linked. Sensor data were gathered from 12 air quality monitoring stations that track gases, fine particulate matter, and various environmental parameters like temperature, humidity, wind direction, wind speed, and noise levels (Citylab | GATE Institute, 2025). Furthermore, historical sensor data of 14 stations from an open network Sensor.Community (Sensor.Community, 2025) was merged with the sensors of Citylab. Nevertheless, to establish correlations between solar analysis and temperature measurements, a process of validation and another level of efforts are needed.

Figure 9. Solar analysis of the district combined with sensor data in the format of Space Time Cube in ArcGIS Pro

4.5 Limitations of the study

First, at the current moment this study lacks validation of calculated results with ground measurements, both for direct solar access on surfaces and transmissivity of tree crowns. However, the coefficient of transmissivity is based on relevant research and can be changed easily. At this stage, no differentiation between conifer and deciduous trees has been provided, despite that this was stored in the tree dataset. In addition, no reflected radiation and material properties were considered, according to the method used. To conclude, more sophisticated assessment can be computed with Radiance-based tools, the speed of processing will decrease.

The form of tree crowns is simplified and may produce unreliable results but can be differentiated in future using convex hulls (Giannelli et al., 2022) or manual modeling for typical cases. In some cases, tree locations need to be verified.

Regarding the integration with the UDT, it is important to envision a dynamic and secure update of solar calculations.

5. Conclusion and future work

This paper proposes a method for 3D solar analysis of streets with trees at the district scale based on widely used 3D raytracing algorithm. The area of the study itself is 9.24 km^2, 1,056,482 faces are evaluated, and 34,617 trees are considered. Streets with sparse vegetation, particularly in southern parts of the district, can be identified as high-heat zones. Findings show up to a 30% decrease in solar radiation on streets compared to analysis that excludes trees. Solar radiation values on street surfaces were higher compared to raster-based calculations in GIS. The of the study conclusions are as follows:

1. Simple vector models of trees based on the CityGML schema, variable density of a mesh for the analysis, allow to compare the impact of various categories of the 3D city model. Thus, the study bridges the gap between small-scale CAD-based simulations and city-wide GIS solar analysis, offering a more flexible and computationally efficient workflow.
2. Dividing the meshes into study meshes and shading meshes reduces time of calculations, as well as cumulative sky matrix for radiation values.
3. Transmissivity of trees was achieved by separating the calculation into scenarios and post-processing of the output. The resulting analytical datasets are incorporated into the Urban Digital Twin of Sofia using open standards such CityGML and 3D Tiles.

This approach ensures explicit control of geometry and flexibility in "what-if" scenarios. The results can be used in walkability studies, microclimatic analysis in other software packages.
The study underscores the essential role that Urban Digital Twins (UDTs), vegetation in 3D and solar analysis play in understanding and mitigating urban heat in dense environments, particularly by analyzing solar access and microclimatic comfort. Seasonal change of the geometry of crowns can be considered in future. Transmissivity can be set to 60% for periods in winter. The method can be extended to the city scale in future and applied to other cities as well.

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