A WORKFLOW UTILIZING POINTCLOUDS AND LOD3 GEOMETRY FOR NEIGHBORHOOD-LEVEL BUILDING PERFORMANCE ASSESSMENT

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Abstract

This study addresses the geometry aspect of urban energy modeling (UBEM). A novel workflow is advanced to gather, prepare, and integrate data from different sources to enable building performance modeling and simulation at the neighborhood scale. The building typology-specific geometry templates to generate LOD3 models and airborne point cloud data to model surrounding trees are used to establish an integrated workflow. The benefits of the workflow are demonstrated through a solar exposure study, showing the significant impact of detailed building geometry, surrounding buildings, and trees on buildings' solar exposure, ranging from the 0% difference between LOD2 and LOD3 to 47%.

Introduction

Building renovation and digitalization of products and processes are considered strategic measures for decarbonizing the European building stock by 2050 (European Commission, 2020). Traditional single-site or building-based approaches, processes, methods, and tools do not fit such purposes (Iliste, 2023; Parts *et al.*, 2023). Digital capabilities are needed to evaluate existing building stock or buildings in the neighborhood and plan, develop, and evaluate renovation strategies and solutions.

UBEM research is developed to assess building performance and facilitate the creation of renovation strategies on a scale beyond individual buildings. Bottom-up methods and two data types are commonly used in UBEM, including building geometry and envelope information. These data, however, are often not readily available. Methods to address data gaps have been introduced, including building archetypes (statistically average buildings per use type) or reference buildings (similar buildings assigned to target buildings).

Most studies have focused on methods to assign building envelope data to buildings. In contrast, simplified shoebox models or 3D models are used for geometry data, commonly at the level of detail 1 (LOD1) or 2 (LOD2). Using the shoebox, LOD1 and LOD2 models have important limitations (Parts *et al.*, 2023). For example, LOD1 and LOD2 geometry models at lower levels of detail and lack information on balconies and openings. These limitations become evident when assessing heat loss, solar heat gains, designing green façades, or photovoltage panels (PV) placement on the façade.

Additionally, surrounding buildings and trees influence the building's solar exposure. However, this is often overlooked due to the lack of data or increased computational cost (Abdel-Aziz *et al.*, 2015; Zhu *et al.*, 2022, 2023). Although a few studies address these limitations, few UBEM studies utilize national databases or point clouds to capture surroundings.

These gaps motivated the advancement of a novel workflow for gathering, preparing, and integrating data from various sources to enable building performance modeling and simulation at the neighborhood level. Specifically, the building typology-specific geometry templates to generate LOD3 models and the airborne LiDAR (light detection and ranging) point cloud data to model surrounding buildings and trees are used and integrated into the workflow. The benefits of such workflow are developed and demonstrated in the current solar exposure study.

Research Background

UBEM supports making informed decisions and estimating decarbonization strategies on an urban scale (Reinhart and Cerezo Davila, 2016). UBEM is the application of physics-based building energy models, often relying on bottom-up methods (Ferrando *et al.*, 2020), to predict energy use and indoor and outdoor environmental conditions for groups of buildings (Chen and Hong, 2018). UBEM tools often utilize the EnergyPlus engine (Kamel, 2022) ("EnergyPlus", 2014). As an open-source engine, it is flexible, highly customizable, and has been integrated into many popular software platforms (Kamel, 2022).

Information needs for UBEM modeling and simulation generally include building envelope and geometry data. Building envelope data is commonly assigned by using archetypes or reference buildings (Ali *et al.*, 2019). Simplified shoebox, LOD1, or LOD2 models are typically used for geometry, not containing necessary information on windows and (recessed) balconies, which significantly impact solar heat gains and shading (Wang *et al.*, 2022). Research to generate geometry data for windows has been conducted (Dochev *et al.*, 2020; Orenga Panizza and Nik-Bakht, 2023; Zhang *et al.*, 2022), but frequently either underestimate or overestimate window areas (Dochev *et al.*, 2020). The common method to address this data gap is to use window-to-wall ratios (De Jaeger *et al.*, 2020), provided in archetypes. It is easy to implement but fails to consider window positioning and orientation, affecting heat gains and potential installation of PV panels on external walls.

One study scaled all wall surfaces by the window-to-wall ratio to get window areas (Abolhassani *et al.*, 2022). However, instead of actual layout, this approach considers window orientations at the level of a single window. Furthermore, apartment buildings often do not have windows in all orientations, which is why this method is often too simplistic.

(Johari *et al.*, 2022) compared the effect of window placements and thermal zoning on heat gains. Although they used geometries that do not correspond to CityGML LOD definitions, comparisons were made between shoebox, LOD1, and LOD2 geometry. LOD1 is a shoebox model of the building block with a single centered window in each zone. LOD2 was defined as a shoebox model with window fenestration, shading devices, and position inside wall. LOD3 included building components with detailed features and shading elements, e.g., windows, shading balconies, and vertical fins. Additionally, they examined three main zoning configurations: 1 zone per building, 1 zone per floor and 5 zones per floor. The results showed that during the warmer months of the year, the energy demands of LOD1 and LOD2 were significantly lower than of LOD3 (18% and 13% respectively) (Johari *et al.*, 2022). For the heating period the differences were dismissible. Regarding zone configurations, the 1 zone per building and 1 zone per floor were deemed sufficient due to the high computational costs of implementing multiple zone models. The effect of the orientation of windows was not thoroughly examined.

Furthermore, two distinct UBEM study areas can be distinguished (Kamel, 2022): (1) independent simulation (not considering surroundings) of multiple buildings and aggregation of results, and (2) simulation of a microclimate in selected region. Most studies address the first area. However, in an urban environment, solar radiation, air temperature, and wind speed loads are significantly affected by surrounding buildings, ground surface materials, and vegetation (Shareef, 2021). This is why several studies have focused on the second area and have inspected the effect of urban microclimate in UBEM (Dougherty and Jain, 2023; Katal *et al.*, 2022; Liu *et al.*, 2023).

Still, as part of the second study area, less studied is the combination of independent building simulations with the effect of surroundings (Kamel, 2022). This area is less studied mainly due to the increased computational needs of simulating multiple buildings and surroundings together. Currently, the second study area has focused on how weather influences buildings or how surrounding shadings affect buildings. For example, one study created a dataset of wall center points of neighborhood buildings, with ground and roof heights stored as attributes (Faure *et al.*, 2022). The points were then utilized to regenerate shadowing objects. This allowed to regenerate objects within 250m radius as shadows to the target building, lowering the computational cost. They found that at a district scale, differences below 2% could be achieved by including all shadowing building surfaces within 50m radius from the building's centroid while surfaces farther than 150m did not seem to have any effect at the district level (Faure *et al.*, 2022).

Another study developed a SketchUp plug-in (MOOSAS-FastSolar), where the shadowing effects were accounted for by two indicators: Surrounding Building Factor (SBF) and Impact Factor (IF). The SBF considers the height and length of the surrounding buildings and the their distance from the target building, and IF describes the total shading effect on the energy demand of the target building (Wen *et al.*, 2022).

Due to the computational burden, shading effects of trees on building energy consumption have been assessed in fewer studies (Abdel-Aziz *et al.*, 2015; Zhu *et al.*, 2022, 2023). (Simpson, 2002) examined the effect of trees as shading objects and created lookup tables to provide a simple way of accounting for the effect of trees. Still considering vegetation in addition to surrounding buildings should be examined further. With the climate pact (Directorate-General for Climate Action (European Commission), 2020) goal of incorporating more green areas in cities, the effect of the vegetation will likely increase.

This study will address the following gaps in UBEM: (1) oversimplified geometry, and (2) impact of surrounding buildings and trees.

Research Methods

A workflow is proposed and developed for neighborhood scale building performance assessment, specifically for solar exposure study of the selected pilot site. First, information needs are specified, pilot site is selected, and data sources and availability are described. Second, data is gathered, prepared, and integrated from different sources to enable building performance modeling and simulation at the neighborhood scale. Specifically, point clouds for modeling trees and typology-specific geometry templates are developed and integrated into a common workflow. Finally, the benefits are demonstrated through solar exposure study, discussed and conclusions are presented.

Defining Information Needs for Solar Exposure Study

For solar exposure study of buildings in a neighborhood, the following information is needed: target building geometry, surroundings (landscape, buildings, and trees), geographic information, the solar path across the sky (throughout the day and year), and climate and weather conditions (including direct and indirect solar exposure). These data on buildings, surroundings, and location form a common information for solar exposure simulation. The simulation aims to quantify solar exposure (both direct and indirect) measured in kWh/(m^2 yr) for entire buildings as well as per floor.

For the purpose of this study, to assess solar exposure effectively, it is necessary to identify the surfaces of the target building based on the surface type, number of floors and orientation. In this study, surfaces were categorized based on building number, surface type (external wall, window, balcony railing, illustrated in Figure 1), surface orientation, and floor numbers. This identification allows to evaluate how the positioning and orientation of specific surfaces impact solar exposure, offering insights into variations across different surfaces at various heights. Additionally, this approach allows to exclude the north-facing facades, which lack direct solar exposure, from the overall average values.

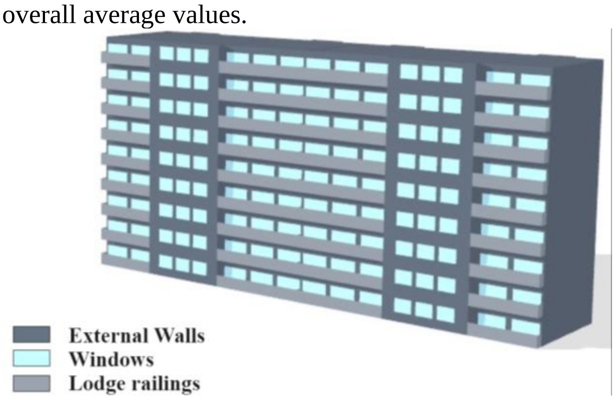


Figure 1: Vertical surfaces of the building.

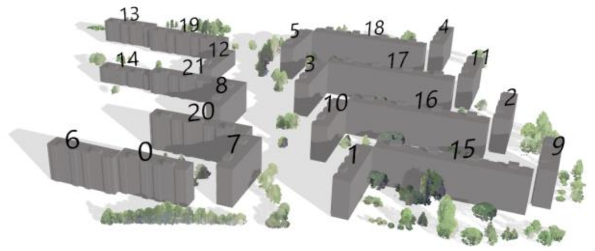
The study considers the surrounding environment, incorporating both neighboring buildings and trees. The shapes of these elements serve as shading objects in the simulation. To accurately model solar exposure, the material properties of these shading objects must be considered. Particularly for trees, where the selected material accounts for light passing through the voxelated shapes.

Selected Pilot Site

A neighborhood with 22 apartment buildings was chosen to develop and evaluate the workflow in the context of solar exposure study. Buildings in selected pilot site represent one common Estonian archetype (Iliste, 2023): a typical not renovated apartment building with precast concrete external walls, built between 1970s and 1990s. The main differences were in the number of floors and staircases, and orientation. It was also observed that all these buildings were constructed from different combinations of two staircase modules: (1) a side module, and (2) a middle module. This level of standardization makes them a suitable for developing and applying geometry templates.

Table 1: Studied buildings' number of floors and staircases, and the neighborhood visualization.

Building numbers	Number of floors	Number of staircases
12, 13	2	2
13	6	2
19	6	3
8	8	2
0, 1 ,2 ,3 ,4 ,5 ,6 ,7,9 ,10 ,11	9	2
20,21	9	3
15,16,17,18	9	4



Typical Floor Plan Geometry Template

Geometry templates were developed to facilitate the generation of LOD3 models. Geometry template is a 2D representation of typical floor plan, consisting of a set of lines and points categorized according to their function or position (Figure 2). Two distinct templates were designed: one for a side module and another for a center module. Each represents a staircase along with its connected apartments. Currently, the templates are prepared for one zone per floor. Additional details like internal walls can be added, which will be addressed within future research.

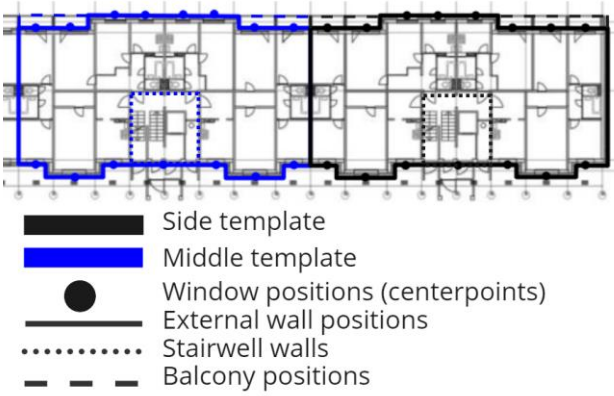


Figure 2: Extraction of geometry templates from design documents.

In addition to general and technical information of buildings, the point cloud data, LOD2 models and design documents were acquired from Estonian Building Register (EBR). The point cloud data for the pilot neighborhood was acquired and processed and segmented into landscape, trees, and buildings. The EBR LOD2 geometry, generated from LiDAR data, was used to position and orient the floor models to target buildings and to compare simulation results to current practices utilizing LOD1 or LOD2 models. For developing and constructing geometry templates, the dimensions of the buildings were acquired from floor plans and elevations of the buildings that had the design documentation available in EBR.

An important issue in utilizing more detailed models and considering the surroundings is the computational cost. The simulations were run on a desktop setup: CPU: i7-13700 2.10 GHz, Graphic Card: Nvidia RTX A4500, Memory: 128GB. Rhinoceros software was chosen to develop the workflow. The built-in Grasshopper plug-in for visual programming was used to develop computational workflows. For solar exposure study, the ClimateStudio plugin, utilizing the well validated EnergyPlus engine, for Rhino was employed.

Results: Proposed Workflow

The proposed workflow (illustrated in Figure 4) is divided into four phases: (1) Data Gathering and Aggregation; (2) Point cloud Processing, Segmentation and Voxelization; (3) Generation of LOD3 Building Models; (4) Simulation and Visualization of Solar Exposure Study. The main criteria for developing the workflow include:

- **Integration of Existing Data Sources and Systems:** Ensuring seamless integration with existing data sources, systems and tools to avoid redundancy, reduce manual data entry, and prototype the workflow.
- **Automation:** Automate gathering, preparing and integrating data sources to reduce manual effort, minimize errors, and accelerate the overall workflow.
- **Flexibility and Scalability:** Ensuring the flexibility to adapt to changes in processes or requirements and accommodating growth.

In the following, the workflow phases and steps are described in detail.

EBR Data Gathering and Aggregation

First phase involved data gathering and aggregation (see Figure 4). For selected pilot site and its buildings, four types of data were gathered from the EBR and organized into common database, including pointclouds for selected pilot site, design documentation, building LOD2 geometry, and EBR data on buildings. These data were acquired by directly downloading datasets or queried through EBR's open API services.

Pointcloud Processing, Segmentation and Voxelization

The second phase involved two steps for pointcloud processing, segmentation and voxelization to create the contextual information (See Figure 4 2.1 and 2.2). For modelling and simulating solar exposure, the airborne LiDAR (light detection and ranging) data available for the chosen neighborhood was acquired from the EBR. The point cloud was first separated into ground and non-ground measurements utilizing the cloth-based data filtering method (Zhang *et al.*, 2016), implemented in CloudCompare (Girardeau-Montaut, 2016). Second, off-ground points were categorized into buildings, trees and rest through several iterations of applying statistical outlier filter, application of scalar fields (i.e., Planarity, Verticality, Sphericity), labelling of connected elements, and manual segmentation of clouds. The output was three sets of point clouds for ground, buildings and trees in *.e57 file format.

Ground, buildings and trees datasets were imported into Rhino, and voxel method on trees' point cloud was applied to generate tree like geometries. Different voxel sizes were tested and for this study 1m voxel was used. In the future, the impact of voxel size will be studied in more detail.

Generation of LOD3 Models

This phase involved two steps for generating LOD3 building models, including creating building archetype specific geometry templates and floor models, positioning and orientating to the right location and generating the entire LOD3 building model (Figure 4).

For creating a building geometry template, design documents for buildings in selected pilot site were analyzed and two different basic modules were created: building side and middle modules. Depending on the number of staircases, these modules were aggregated into floor models. For example, building with two staircases had only two mirrored side modules, building with three staircases had two mirrored side modules and one middle module between the two mirrored side modules (see Figure 3).

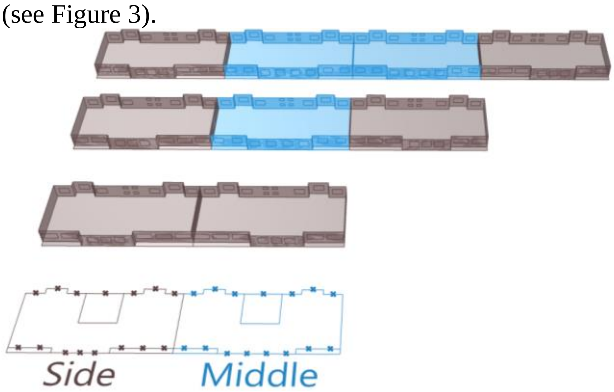


Figure 3: Geometry templates and aggregated floor models.

After the creation of a floor model, it was positioned and orientated to the right location based on the LOD2 models from the EBR. After moving floor models to the right location, these are copied and moved vertically as many times as the buildings had floors.

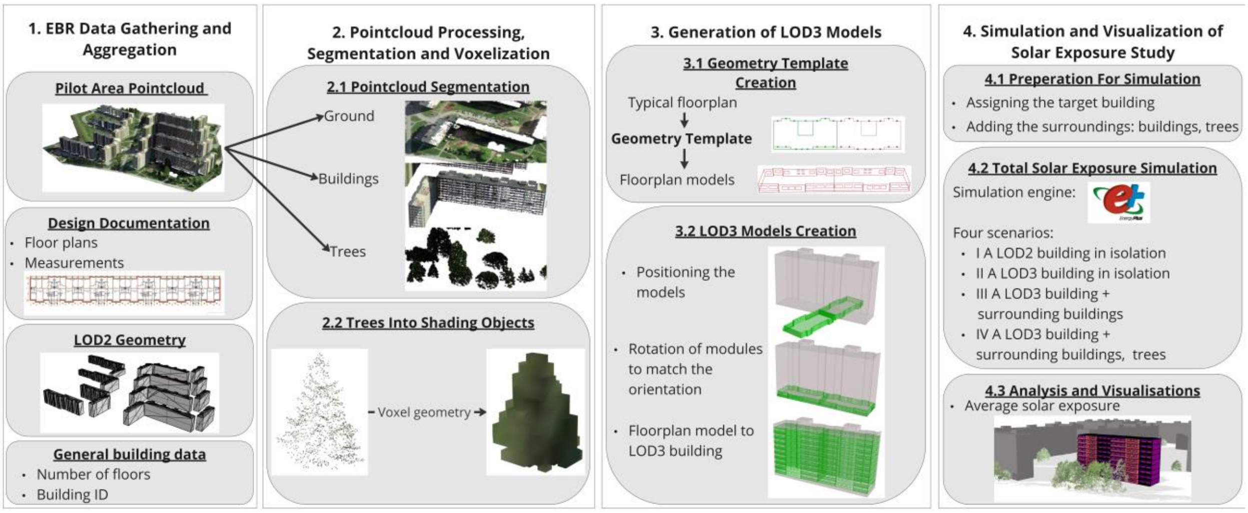


Figure 4: A workflow proposed and developed for neighborhood scale building performance assessment

Results: Simulation and Visualization of Solar Exposure Study

The fourth phase involved three steps for simulation and visualization of solar exposure results (see 4.1 – 4.3). In the first step, all previously generated data were integrated into a common simulation model.

In the second step, solar exposure simulations were performed for all 22 buildings of the selected pilot site. The study focused on assessing the impact of more detailed geometry and the surrounding microclimate on solar exposure of buildings. Specifically, the focus was on vertical surfaces (external walls, windows, balcony railings see Figure 1) that are more likely to be affected by surroundings, especially when there is minimal variation in building heights. Four solar exposure scenarios were established for simulations:

1. A LOD2 building in isolation (without surroundings).
2. A LOD3 building with detailed information on external walls, windows and balconies in isolation (without surroundings).
3. A LOD3 building together with its surrounding buildings.
4. A LOD3 building surrounded by both other buildings and trees.

In the first scenario, LOD2 geometry was employed. Sensor points were placed only on external walls since the LOD2 models lack additional components such as windows and balconies. Surroundings were not considered. In the second scenario, solar exposure was simulated for walls, windows, and balconies, utilizing LOD3 building geometry. Similarly, to the first scenario, the only shading object considered was the target building itself. In the third scenario, surrounding buildings were introduced as shading objects and used together with LOD3 building models. To optimize computational efficiency, LOD2 geometry was utilized for shading, while the target building retained LOD3 detail. In the fourth scenario, trees were incorporated as additional shading objects.

Demonstration: Solar Exposure Simulations

Solar exposure simulations were conducted for four scenarios and compared based on the total average solar exposure (kWh/(m²·yr)). North-facing surfaces were excluded, given their minimal exposure to solar. Climate Studio`s grasshopper plug-in was utilized for simulations.

Solar Exposure Comparison for LOD2 and LOD3 Models

In the first stage, a comparison between the average solar exposure of LOD2 and LOD3 vertical surfaces was performed. The LOD2 and LOD3 models for 22 buildings have similar side walls. Compared to the LOD3, LOD2 does not have different vertical wall, window and balcony surfaces on the main facades, but represent it as one common surface. In this stage, the overall average values were compared: all vertical surfaces of the LOD2, and the average of all external walls and windows for LOD3. LOD2 was used as the reference case and LOD3 results were compared against it.

The results revealed an average difference of 16% in solar exposure between the LOD2 and LOD3 geometry. The minimum difference between LOD2 and LOD3 buildings was 0% and highest 47%. Notably, LOD2 overestimated solar exposure for buildings with the main facades facing East and West, while underestimated it for other buildings (Figure 5). For the East and West facing buildings, the average solar exposure of LOD2 was 34% higher than LOD3. For North and South facing buildings, the average exposure of LOD2 was 1% smaller than LOD3.

These results demonstrate how the building's geometry level of detail impact solar exposure. The main differences between LOD2 and LOD3 are in their main facades, in their level of detail. LOD2 simplifies main facades, excluding balconies (together with floors and railings), significantly influencing solar exposure on external walls and windows. This is why LOD2 overestimates the solar exposure for the East and West facing buildings.

For the North and South facing buildings, South walls are side walls (similar for LOD2 and LOD3 geometry), receiving most of the sunlight. Also, these buildings have proportionally smaller main facades than East and West facing buildings have. This is why there are not that big differences in terms of solar exposure.

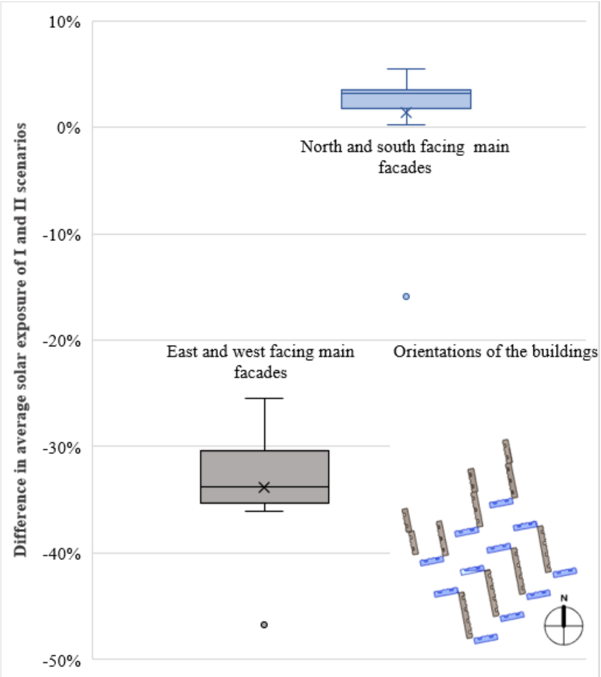


Figure 5: Difference in Average Solar Exposure of Scenario I (LOD2, reference case) and Scenario II (LOD3).

Solar Exposure Comparison between II, III and IV Scenarios

A comparative analysis was conducted for the second, third, and fourth scenario solar exposure results. The second scenario was used as a reference case that the others were compared against.

Within these scenarios, three distinct surfaces were separately evaluated: (1) external walls, (2) windows and (3) balcony railings. Additionally, the results were distinguished based on the floor level. Significant differences were observed on lower floors (see Figure 6). For the lower floors, the third and fourth scenarios exhibited a 17% and 27% reduction in solar exposure compared to the second scenario where only the target building without surroundings was considered.

When comparing the results of the three scenarios for higher floors, the disparities were minimal averaging only 4-6%. Overall, the average reduction in solar exposure over all the floors compared to scenario two was 12% for scenario three and 17% for scenario four.

Notably, the most substantial difference was observed in solar exposure on balcony railings with a notable 18% and 34% reduction on the first floor contributed to additional shading. This occurs because railings serve as shading objects for other surfaces (external walls and windows), while other components do not offer shading for the railings themselves.

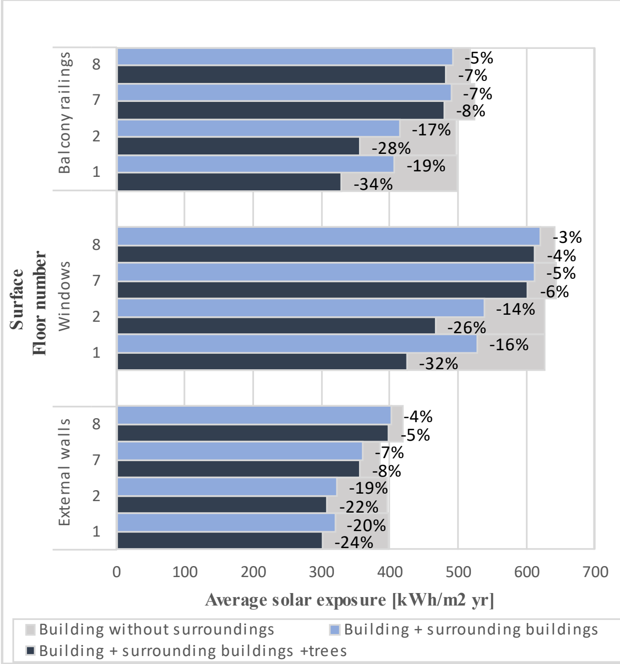


Figure 6: variations in solar exposure across different surfaces and floors of lod3: scenario II (reference case) vs. scenarios III and IV.

Notably a small difference (3 % on average) in solar exposure between floors can be identified even when no surrounding objects are considered. This effect occurs due to the upper protruding parts of the façade being exposed to the sun before the rest of the façade (see Figure 7) but also when the protruding parts cast a shadow on the lower part of the façade leaving the upper parts exposed to sun.

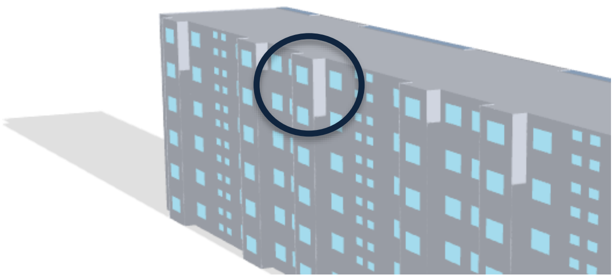


Figure 7: Early Solar Exposure on Upper Protruding part of the facade.

Discussion

A workflow for UBEM using LOD3 building geometry was developed. In addition, the workflow incorporated surrounding buildings and trees as shading objects to facilitate neighborhood level building performance evaluation. Solar exposure was utilized as a key metric to assess the benefits of proposed workflow. Solar exposure is an important metric influencing many aspects of building performance. It could also support informed decision-making for sustainable and energy-efficient design and renovation of buildings.

The utilization of geometry templates for highly standardized apartment buildings offers a simple solution to develop LOD3 models. Solar exposure analysis demonstrated a notable 16% difference between LOD2 and LOD3 geometry. The effect is mainly due to the incorporation of balconies that act as shading objects. This aligns with the results of a study (Johari *et al.*, 2022) who demonstrated that the LOD1 and LOD2 models have 18% and 13% lower energy demand when compared to the LOD3.

Previous approaches to LOD3 creation have mainly relied on remote sensing, leading to considerable uncertainty, while making it less cost-effective due to resource-intensive implementation. The main limitation of the geometry templates is its reliance on the standardized solutions and designs. That is, geometry templates are most useful when there are multiple buildings with the same basic design.

We also identified that the incorporation of surrounding buildings on average leads to a 17% reduction of solar exposure on lower floors, with an additional 10% reduction attributed to trees. Considering that the examined neighborhood was not intensely populated, these effects could be even more significant in more intensely populated areas. Majority of UBEM solutions have focused on the aspect of surrounding buildings but have disregarded trees due to the additional computational cost. This study demonstrated the need for considering also trees. However, the reliability of developer approach and computational cost were not examined and need to be considered in more detail in the future studies.

This study primarily focused on solar exposure as an indicator, which influences various building performance aspects. Future research could extend this work to include overheating modelling and simulation studies, additional shading requirements, heat gains, and their collective impact on building energy performance. This would allow to further examine the benefits of accurate window placements and impact of shading objects. Moreover, our developed workflow enables the incorporation of the ground surface. This could be also utilized for site analysis, incorporating flood predictions and risks.

Conclusions

The study developed and demonstrated UBEM workflow incorporating LOD3 models, surrounding buildings, and trees for building performance assessment at the neighborhood scale. Solar exposure was used to evaluate the workflow benefits. The proposed workflow was tested in a selected pilot site with 22 apartment buildings. The findings from our solar exposure study demonstrated the impact and need for LOD3 models of buildings with balconies and protruding façade elements. Additionally, it showed how the surrounding buildings and trees on lower floors significantly influence solar exposure and consequently the reliability of UBEM workflows in general, ranging from the 0% difference between LOD2 and LOD3 to 47%. As a first step, this research contributes to the ongoing efforts towards renovation and digitalization as strategic measures for decarbonizing the European building stock by 2050. However, further studies regarding the reliability of typology-specific geometry templates and point cloud-based building trees are needed.

Acknowledgments

This work has been supported by the Estonian Research Council grant (PSG963); by the European Commission through LIFE IP BUILDEST (LIFE20 IPC/EE/000010), Horizon projects EBENTO (VHE22038) and oPEN Lab (VFP21038); and by the Estonian Centre of Excellence in Energy Efficiency, ENER (grant TK230) funded by the Estonian Ministry of Education and Research.

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