DATA ACQUISITION WORKFLOW UTILIZING LOD3 GEOMETRY TEMPLATES AND POINT CLOUDS FOR URBAN BUILDING ENERGY MODELLING

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Abstract

This case study addresses the data acquisition problem for urban energy modeling (UBEM). A novel workflow is advanced to gather and integrate data from different sources to enable building performance modeling and simulation at the neighborhood scale. The building typology-specific geometry templates and airborne point cloud data to model surrounding buildings and trees were used for the integrated workflow. The benefits of the developed workflow are demonstrated through a solar exposure study, demonstrating 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

The renewed Energy Performance of Buildings Directive (EPBD) expands the scope from single buildings to district and building stock level planning, development, and implementation of renovation measures. Traditional single-site/building approaches, processes, methods, and tools are not fit for achieving the 2050 decarbonization targets (Iliste, 2023; Parts *et al.*, 2023). Moreover, the current standards overlook the integration of building surroundings in the assessment process, creating a disparity between the real-world conditions and simulation results. New digital capabilities are needed to evaluate existing building stock or buildings in the neighborhood and plan, develop, and evaluate renovation strategies and solutions.

Urban building energy modeling (UBEM) supports assessing building performance and facilitates the creation of decarbonization strategies on an urban scale for building clusters (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). Many UBEM digital tools have utilized the EnergyPlus engine (Kamel, 2022) ("EnergyPlus", 2014), which as an open-source engine, is flexible and highly customizable (Kamel, 2022).

The minimum information needed for UBEM modeling and simulation includes building envelope and geometry data. Building envelope data is commonly assigned by using archetypes or reference buildings (Ali *et al.*, 2019). In contrast, simplified shoebox models or 3D models are used for geometry data, commonly at the level of detail 1 (LOD1) or 2 (LOD2). However, these models have important limitations (Parts *et al.*, 2023). For example, these models do not contain necessary information on windows and (recessed) balconies, which significantly impact solar heat gains, shading, or photovoltage panels (PV) placement on the façade (Wang *et al.*, 2022).

Many studies to generate geometry data for windows have been conducted (Dochev *et al.*, 2020; Orenga Panizza and Nik-Bakht, 2023). The common method to address this data gap is to use window-to-wall ratios (De Jaeger *et al.*, 2020), assigned to archetypes. Abolhassani *et al.* scaled all wall surfaces by the window-to-wall ratio to get window areas (Abolhassani *et al.*, 2022). This method is easy to implement but it frequently either underestimates or overestimates window areas (Dochev *et al.*, 2020) and fails to consider the actual positioning and orientations of windows. 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 shoebox, LOD1, and LOD2 geometry and the related effect of window placements and thermal zoning on heat gains. 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 cooling period of the year, the energy demands of LOD1 and LOD2 were significantly lower than those of LOD3 (18% and 13% respectively) (Johari *et al.*, 2022). For the heating period, the differences were dismissible.The effect of the orientation of windows was not thoroughly examined.

Generally, two distinct bottom-up physics-based UBEM study approaches can be distinguished (Kamel, 2022): (1) independent simulation (not considering surroundings) of multiple buildings and aggregation of results, and (2) studying the microclimate effects in a selected region. Most studies address either the first or the second area. The combined study is less common mainly due to the increased computational needs of simulating multiple buildings and surroundings together.

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 some studies have focused on the combination of these approaches and have inspected the effect of urban microclimate in UBEM (Dougherty and Jain, 2023; Katal *et al.*, 2022; Liu *et al.*, 2023). These have 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 a 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 a 50m radius from the building's centroid. (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 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) created lookup tables to provide a simple way of accounting for the effect of trees as shading objects. Still considering vegetation in addition to surrounding buildings should be examined further. With the climate pact (Directorate-General for Climate Action (European Commission), 2020) and the goal of incorporating more green areas in cities, the effect of the vegetation will likely increase.

Shading has a great impact on both building heat gains as well as PV production potential. Especially in higher latitudes where low sun angles result in more intense shadows (Formolli *et al.*, 2023). According to the new EPBD, solar energy installations will become the norm for existing residential buildings starting in 2033 if technically suitable and economically and functionally feasible. Currently, the assessment of PV potential often occurs without contextual considerations, even at the level of individual buildings (Formolli *et al.*, 2023). This is mainly due to the lack of requirements but also due to the lack of data and increased computational cost (Abdel-Aziz *et al.*, 2015; Zhu *et al.*, 2022, 2023). This simplification can result in disparities between real-world conditions and simulation models.

The research gaps presented above motivated us to plan and develop a workflow to tackle the data acquisition problem for UBEM. Specifically, this research focuses on two research gaps in the context of data acquisition: (1) LOD2 versus LOD3 geometry, and (2) the impact of surrounding buildings and vegetation. This case study aims to streamline and automate the integration of LOD3 geometry and building surroundings into building performance assessment. The workflow consists of gathering, preparing, and integrating data from various sources to enable modeling and simulation at the neighborhood level. The benefits of such workflow are demonstrated through a solar exposure study.

Research Methods

Workflow Development and Testing

The design research method (Hevner and Chatterjee, 2010) was utilized to develop the workflow in the context of the case study. The development of the workflow for neighborhood scale building performance assessment included the following phases:

- Information needs were specified based on the literature review.
- Data availability and sources were determined.
- Data was gathered, prepared, and integrated from different sources to enable UBEM modeling and simulation at the neighborhood scale.
- Data (specifically, point clouds for modeling trees and typology-specific geometry) templates were developed and integrated into a common workflow.
- The benefits are demonstrated in a case study through a solar exposure study.

Defining Information Needs

Sufficiently accurate information about the building geometry is one major challenge in energy performance assessment at the neighborhood level. Solar exposure is an important parameter influencing heat gains and on-site electricity generation. For this the following information is needed: target building geometry, surroundings (landscape, neighbor 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).

To assess solar exposure effectively, the surfaces need to be 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. This can allow us to examine the surfaces that are most affected by solar exposure. Spaces with north-facing exteriors have a reduced risk of overheating compared to other orientations. In addition, they are usually not considered for PV installation.

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.

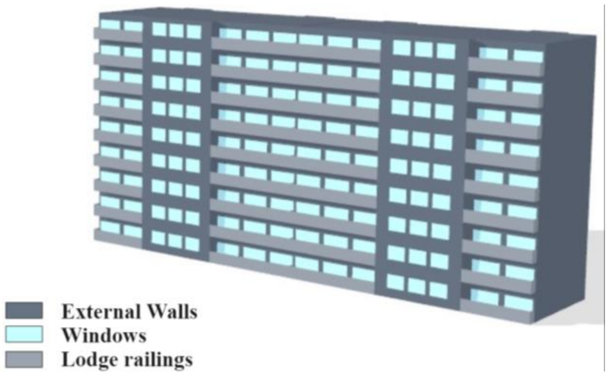

Figure 1: Vertical surfaces of the building.

Selected Pilot Site

An Estonian neighborhood (58°22' N Latitude, 26° 46' E Longitude) with 22 apartment buildings was chosen to develop and evaluate the workflow in the context of solar exposure study. The pilot area buildings represent one common Estonian archetype (Iliste, 2023): a typical not renovated apartment building with precast concrete external walls, built between the 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 suitable for developing and applying geometry templates.

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

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

Building Information and Geometry Template

General and technical information of buildings, LOD2 models, and design documents were acquired from the Estonian Building Register (EBR). It is a public database containing information for all Estonian buildings. It has an open data policy and web services to acquire data.

Geometry templates were developed to facilitate the generation of LOD3 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.

A geometry template is a 2D representation of a 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: (1) side module and (2) middle module. Each represents a staircase per floor and its apartments. Currently, the templates include one zone per floor and module. Additional details like internal walls could be added, which will be addressed within future research.

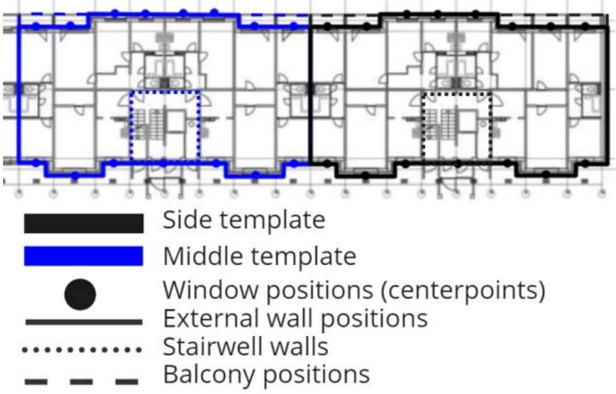

Figure 2: Extraction of geometry templates from design documents.

Point Clouds for Modelling Surrounding Trees

In addition to general and technical information of buildings, point cloud data were acquired from the Estonian Building Register (EBR). The point cloud data for the pilot neighborhood was acquired from EBR, 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.

System Setup

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 the solar exposure study, the ClimateStudio plugin, utilizing the EnergyPlus engine, for Rhino was employed. For point cloud processing, trimming, segmentation, and conversion, CloudCompare was used.

Case Study Results

Workflow Development Criteria

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 included:

- **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

The first phase involves data gathering and aggregation (see Figure 4). For the selected pilot site and its buildings, four types of data were gathered from the EBR and organized into a common database, including point clouds for the selected pilot site, design documentation, building LOD2 geometry, and EBR data on buildings. These data were acquired by directly downloading publicly available datasets or queried through EBR's open API services. The utilization of API services enables the automatization of data acquisition.

Point Cloud Processing, Segmentation and Voxelization

The second phase involved two steps for point cloud processing, segmentation, and voxelization to create the contextual information (See Figure 4 steps 2.1 and 2.2). For modeling and simulating shading effects on 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 filters, application of scalar fields (i.e., Planarity, Verticality, Sphericity), labeling of connected elements, and manual segmentation of clouds. The output was three separate sets of point clouds for ground, buildings, and trees in *.e57 file format.

Ground, buildings, and tree datasets were imported into Rhino, and the 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. The main criterion for this was the high computational cost of smaller-sized voxels. 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 the 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, a 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).

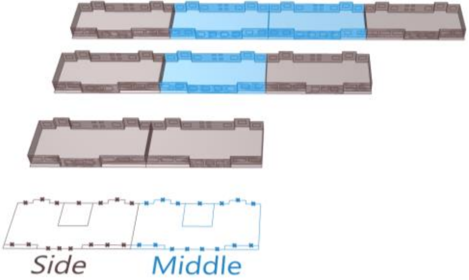

Figure 3: Geometry templates and aggregated floor models

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 were copied vertically as many times as the buildings had floors.

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 LOD3 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.

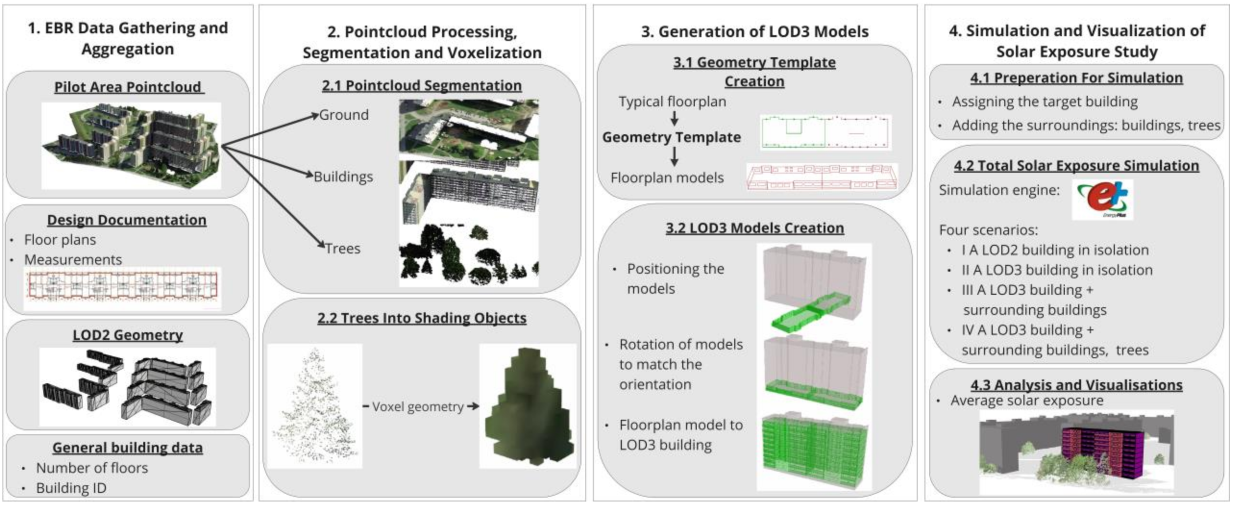

Figure 4: A workflow proposed and developed for neighborhood scale building performance assessment

In the first scenario, LOD2 geometry was employed. Sensor points were placed only on external walls since the LOD2 models lacked 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 (reference case) and LOD3 vertical surfaces was performed (see Figure 5). 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, they are represented as a single 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.

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 the highest 47%. LOD2 overestimated solar exposure for buildings with the main facades facing East and West, while underestimating 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.

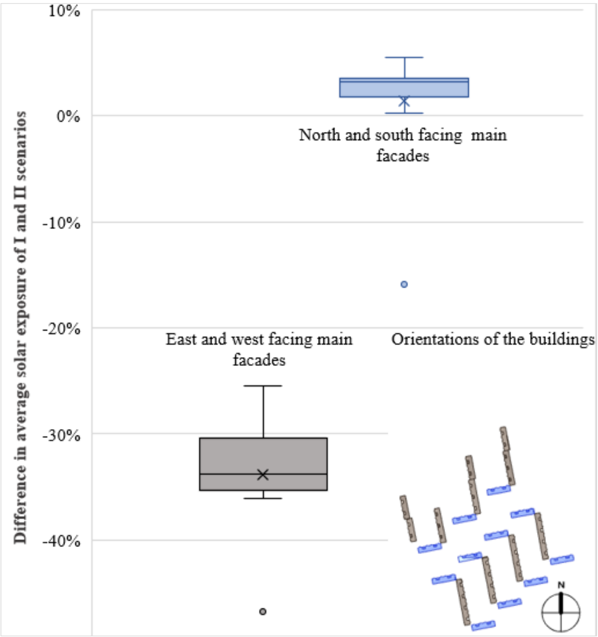

Figure 5: Difference in average solar exposure of scenario I (LOD2, reference case) and scenario II (LOD3).

These results demonstrate how the building’s geometry level of detail impacts solar exposure. The main differences are in main facades. 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, the 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.

Solar Exposure Comparison Between II, III, and IV Scenarios

A comparative analysis was conducted for the second, third, and fourth scenario solar exposure results. Here, 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.

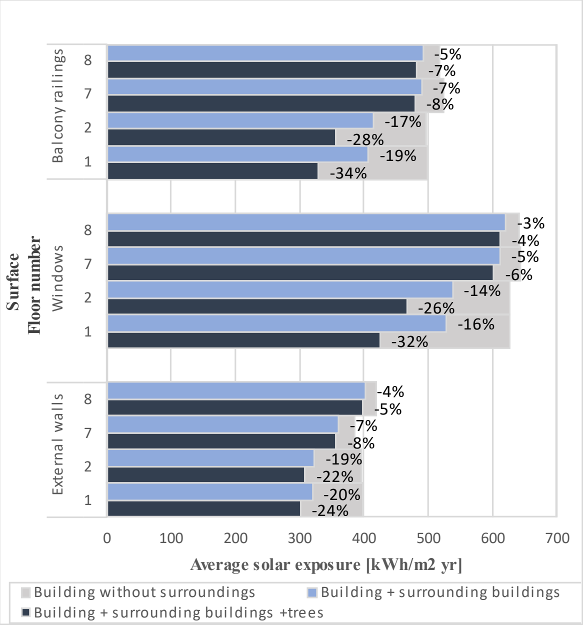

Figure 6: Variations in solar exposure across different surfaces and floors of lod3: scenario II (reference case) vs. scenarios III and IV.

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

The most substantial difference was observed in solar exposure on balcony railings with a notable 18% and 34% reduction on the first floor. 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.

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 the sun.

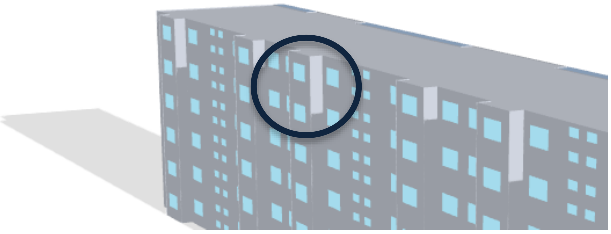

Figure 7: Early solar exposure on the upper protruding part of the facade.

Discussion

This case study approached the data acquisition problem in the field of UBEM by advancing data integration workflow. LOD3 geometry, surrounding buildings, and trees, as shading objects, were incorporated to facilitate neighborhood-level building performance evaluation. Solar exposure metric was used to assess the benefits of the developed workflow. Solar exposure is an important metric influencing many building performance aspects.

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 another study (Johari *et al.*, 2022) that demonstrated 18% and 13% lower energy demand for the LOD1 and LOD2 when compared to the LOD3.

Previous approaches to LOD3 creation have mainly relied on manual model creation, making it less cost-effective due to resource-intensive implementation. The main limitation of the geometry templates is their reliance on standardized solutions and designs. That is, geometry templates are most useful when there are multiple standardized buildings following the same design principle.

We also developed a workflow to simplify the incorporation of surroundings into building performance assessment and examined the benefits through a solar exposure study. We 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. The limitation of the solar exposure results is the exclusion of the north-facing facades. In future research, north-facing facades could be included to get a more comprehensive understanding.

Also, considering that the examined neighborhood was not intensely populated, these effects could be even more significant in more intensely populated areas. Some existing UBEM solutions have incorporated surrounding buildings but have disregarded trees due to the additional computational cost. This study demonstrated the need to also consider trees. However, the reliability of the developed approach and computational cost were not examined. This needs to be considered in more detail in future studies.

This case study primarily focused on workflow development and utilized solar exposure as an indicator to demonstrate its benefits. Future research could extend this work to include overheating modeling and simulation studies, additional shading requirements, heat gains, and their collective impact on building energy performance. This would allow us to further examine the benefits of accurate window placements and the impact of shading objects. Moreover, our developed workflow enables the incorporation of the ground surface. This could be also utilized for site analysis, for example, incorporating overflooding risk assessment.

Conclusions

This case study developed and demonstrated the utility of a data aggregation workflow for UBEM 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 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

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