The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-M-6-2025
ISPRS, EARSeL & DGPF Joint Istanbul Workshop "Topographic Mapping from Space" dedicated to Dr. Karsten Jacobsen's 80th Birthday
29–31 January 2025, Istanbul, Türkiye

Enriching Urban Digital Twins with Energy-related Information from Aerial and Street View Imagery for Precise Urban Climate Modeling

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Keywords: 3D City Models, Urban Digital Twins, CityJSON, Urban Climate, Python.

Abstract

The country-scale 3D city model of the Netherlands, 3DBAG, has been extensively utilized across multiple disciplines. Buildings in 3DBAG include many attributes, but they lack the necessary ones required for precise urban climate modeling. This study aims to enhance the 3DBAG 3D city model by incorporating energy-related attributes and vegetation data, thereby improving visualization accuracy and realism, as well as enabling more precise urban climate simulations. Automated methods were developed to extract and integrate key features such as roof textures, façade materials, albedo values, roof slopes, and urban vegetation. Roof textures extracted from orthophotos enhance the analysis of roof geometry and facilitate material identification and solar panel detection. Meanwhile, façade materials and albedo values contribute to more accurate simulations of heat absorption, energy balance, and urban heat island effects. Furthermore, the integration of detailed urban vegetation data, including tree height and crown diameter, allows for accurate modeling of vegetation's influence on urban microclimates. Developed automated workflows significantly reduce the time and effort required for manual data preparation and integration. By enriching the urban digital twins with energy-related information, this study provides researchers with a more comprehensive and precise dataset, enabling more accurate analyses in urban climate modeling. The developed automated workflows can be applied in future releases of the 3DBAG, allowing other users in utilizing the energy-enriched 3D city model effectively. Web-based visualization of the energy-enriched 3D city model can be explored at https://bit.ly/4tuheritage.

1. Introduction

1.1 Motivation

Semantically enriched 3D city models have a wide range of applications, one of the most significant being urban climate and energy modeling. Energy-related attributes and vegetation data must complement 3D building geometries to achieve more accurate urban climate modeling. Despite the critical role of energy-related attributes in accurate urban climate modeling, their generation is often manual, time-consuming, and absent from most 3D city models. This gap limits the realism of simulations, resulting in reliance on approximations for parameters like roof and façade materials and albedos.

Urban vegetation plays vital role in urban climate modeling due to its substantial impact on temperature regulation, air quality, energy balance, wind patterns, and water management within cities. Incorporating vegetation into urban climate modeling allows for more accurate predictions of the urban microclimate, pollution dispersion, and thermal comfort, supporting sustainable urban planning and climate adaptation strategies. The role of trees in mitigating the Urban Heat Island (UHI) effect and improving environmental quality makes them indispensable for these simulations.

Incorporating façade materials and albedo values allows for more accurate simulations of how different buildings contribute to local temperature variations and the overall urban climate. Façade materials and albedos are also critical components for accurate urban climate simulations, particularly in tools like PALM-4U. The thermal properties of façade materials, such as brick, concrete, glass, and metal, influence how buildings absorb, store, and release heat. Albedo, or surface reflectivity, determines how much solar radiation is reflected by building façades versus how much is absorbed, which directly affects temperature regulation and urban heat island (UHI) effects.

Urban climate modeling is often conducted using low-resolution data, such as 100-meter resolution, where approximate values are typically employed for many input parameters. However, higherresolution models with more accurate input data and integrated vegetation can produce significantly more precise results. The HERITAGE project focuses on enhancing 3D city models by incorporating detailed information such as building roof and façade materials, albedo values, vegetation, and other relevant data to improve the accuracy of urban climate modeling. Various data sources, including street view imagery, earth observation data, and other datasets, can be utilized to enrich 3D city models.

This study introduces various automated approaches to enrich the Netherlands' 3D city model, 3DBAG, with vegetation and attributes focused for urban climate modeling. These enhancements provide critical data for improving the precision and utility of simulations conducted in advanced modeling software like PALM-4U (Scherer et al., 2019a). The enrichment process focuses on automating tasks that were traditionally manual, such as assigning energy-related attributes, vegetation data, and façade-specific albedo values to individual buildings. This not only reduces the time and effort required but also ensures a higher level of consistency and accuracy across largescale datasets. The enriched 3D city models are a cornerstone of the HERITAGE (2024) project, providing input data that allows for more precise urban climate predictions and supporting sustainable urban planning initiatives. By integrating these automated solutions, the project paves the way for scalable applications in urban climate adaptation and resilience planning, making it possible to model complex interactions within the urban environment more effectively.

1.2 Related Work

Albedo values of buildings can be calculated from earth observation data (Kalantar et al, 2017). Roof and façade textures are also valuable data sources for extracting various information related to buildings. Roofs and façades of semantic 3D city models can be automatically texture-mapped using highresolution oblique and nadir imagery (Buyukdemircioglu et al., 2024, He et al., 2022). While such methods are available, an open-source solution for automatic roof texture mapping has not yet been developed. These textures not only enhance the realism of web-based visualizations but can also be used for different applications. Buyukdemircioglu et al. (2021) classified highresolution roof textures into six categories using deep learningbased approaches with 86% accuracy. Ilehag et al. (2018) analyzed energy emitted from building roofs in Perth, Australia, by examining roof orientation and materials using multispectral, thermal infrared, RGB, and LiDAR data. Heiden et al. (2012) developed a multi-stage processing system using hyperspectral remote sensing and height data to map 38 surface materials, derive urban land cover indicators with high accuracy. Trevisiol et al. (2022) presented a semi-automatic methodology for roof material classification and achieved 91% overall accuracy.

Trees plays a crucial role in urban climate studies by influencing microclimatic conditions. Xu et al. (2021) reviewed key factors influencing trees' impact on urban microclimates and approaches to 3D tree reconstruction, identifying essential geometric and physiological characteristics for urban microclimate simulations and recommending suitable reconstruction methods to effectively integrate this information. Salim et al. (2015) highlighted the importance of explicitly modeling trees in numerical simulations of urban wind flow, demonstrating significant impacts on results compared to basic and implicit approaches.

Additionally, the visualization of enriched 3D city models plays a critical role in bridging technical analyses and practical applications. Existing tools like CesiumJS (2024) provide powerful platforms for visualizing urban data, but their workflows often require extensive preprocessing and file format conversion. This study addresses these gaps by introducing various automated approaches for enriching 3D city models with energy-related attributes and vegetation data while ensuring compatibility with visualization platforms.

2. Roof Slopes

Roof slope plays a critical role in determining environmental and energy-related dynamics in urban settings. It influences radiation exchange, energy balance on buildings, and airflow patterns around structures, making it essential for urban heat island studies, microclimate modeling, and renewable energy planning, such as optimizing solar panel positioning. Additionally, roof slope serves as a key building parameter in urban surface modeling, particularly for energy balance calculations and thermal simulations.

The 3DBAG dataset, however, does not include slope values for individual roof surfaces, posing a limitation for applications requiring detailed urban climate modeling. To address this, an automated solution was developed to calculate roof slopes using the existing roof geometry. The algorithm begins by isolating roof surfaces from the building model, filtering out non-roof elements such as walls and ground surfaces to ensure calculations are applied exclusively to roof geometries. For each roof surface, the slope is derived by analyzing its orientation in 3D space, specifically the angle between the surface normal vector and the vertical z-axis. A view of calculated surface normals can be seen in Figure 1.

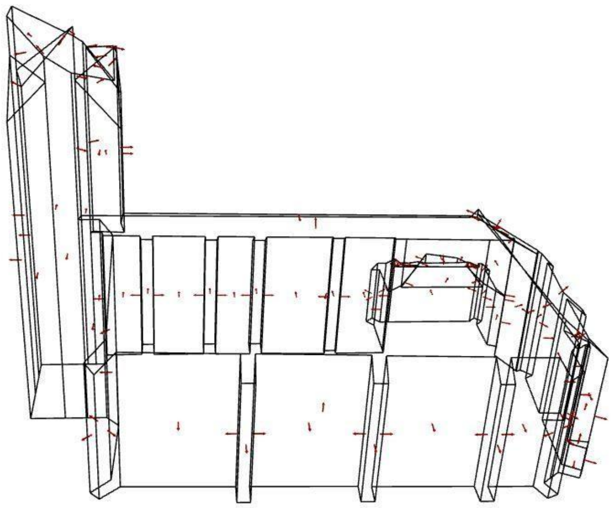

Figure 1. Calculated surface normals.

The calculation involves computing the dot product of the normal vector and the z-axis vector, along with their magnitudes. Using these values, the angle in radians is determined via the arccosine function, representing the angular difference between the two vectors. This angle is then converted to degrees for intuitive interpretation. The computed slope values are subsequently added as attributes to each roof surface in the CityJSON 3D city model, providing precise data for further analyses.

To verify the accuracy and usability of the calculated slopes, the enriched 3D city model was inspected using Ninja (Vitalis et al., 2020), a visualization tool designed for the detailed examination of CityJSON models. Ninja enables users to independently select semantic surfaces and view their associated attributes, facilitating the identification of potential inconsistencies or errors. This process ensures that roof slope attributes are correctly integrated into the CityJSON model. Figure 2 illustrates an example of the calculated roof slopes added as attributes to the corresponding roof surfaces.

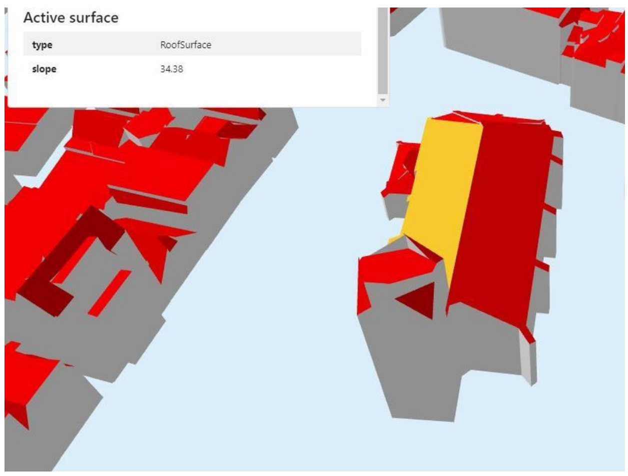

Figure 2. Calculated roof slope for the selected surface on Ninja.

3. Roof Textures and Properties

The 3DBAG dataset includes three different levels of detail (LOD) of building models: LOD1.2, LOD1.3, and LOD2.2. The LOD1 family does not include any roof details, whereas LOD2.2 provides detailed roof geometries. However, since these building models are automatically generated using LiDAR and building footprint data (Peters et al., 2022), they are not produced with 100% accurate roof geometries. In such cases, visualizing roof textures along with the building geometry can partially correct inaccurately generated geometries, resulting in a more realistic visualization. Currently, no open-source solution exists for automatically mapping roof textures from aerial photographs. Therefore, a Python-based automated roof texturing solution has been developed as part of this study.

In this study, the data sources include true orthophotos with a resolution of 8 cm from 2024, provided by PDOK (2024), along with the 3DBAG (2024), the national 3D city model of the Netherlands. Both of these datasets are accessible as open access. In some cases, particularly when working with datasets from different years, the building footprints in the 3DBAG dataset may not perfectly align with the roof boundaries visible in the true orthophotos. This misalignment can result in incorrect texture clipping and produce visually inconsistent and inaccurate results. Therefore, it is crucial to visually inspect the compatibility between these two datasets before initiating the texture mapping process. An example of building footprint vectors overlaid on a true orthophoto is shown in Figure 3.

Figure 3. Building roof outlines over true orthophoto.

The developed algorithm begins by verifying whether the roof is fully visible within the image. If the roof texture is not entirely visible—either because the roof is at the edge of the image and only partially captured, or because it extends beyond the image boundary and is completely absent—the algorithm excludes that building from the texturing process. This ensures that the resulting textured models are accurate and free from incomplete or misleading visual data. If the roof is fully visible, the software extracts the roof texture from the true orthophoto using the building footprint as a reference. Since roof overhangs are not separately modeled in the 3DBAG dataset, the boundaries of the roof surface and the building’s ground surface are identical. As a result, the roof geometry is clipped as a single texture based on the building footprint. This extracted texture is then applied to the roof geometry, effectively creating a visually accurate representation of the roof.

This method offers several advantages by clipping and mapping a single texture for each building’s roof geometry, rather than clipping multiple textures for each surface and mapping them individually. If separate textures were clipped for each roof surface, it would also require recording each image path in the CityJSON file, leading to an increase in file size and resulting in a non-optimized CityJSON model. Additionally, since textures can only be clipped as rectangular shapes, unused pixels in each texture would also be retained, further contributing to larger file sizes compared to using a single texture. Moreover, individually clipped roof textures would lack cohesion, making them unsuitable for other applications where a consistent, unified visual representation of the roof is required. By employing a single texture for the entire roof, this method ensures a more efficient, optimized, and versatile approach.

After clipping the roof textures, the corresponding texture coordinates for the roof geometry's vertices must be accurately calculated for clipped texture image. This process involves a twostep transformation. First, the real-world coordinates of the vertices are converted into the pixel coordinate system of the texture image, ensuring alignment between the spatial data and the texture. Subsequently, the pixel coordinates are transformed into UV-based texture coordinates, which are widely used in 3D modeling to represent the mapping of a 2D texture onto a 3D surface. Once the UV-based texture coordinates are calculated for each roof vertice, they are written into the CityJSON file. In addition to these coordinates, the path to the associated texture file is also recorded in the CityJSON file.

The CityJSON file structure is primarily designed for the optimized storage of urban digital twins rather than for direct visualization. As a result, several file format conversions are necessary to visualize building models with roof textures applied. One of the most widely used solutions for web-based visualization is CesiumJS, which supports rendering in the 3D Tiles format. However, since Cesium ION does not currently support direct conversion from CityJSON to 3D Tiles, an intermediate step is required. The CityJSON file is first converted to CityGML, a format supported by Cesium ION, and then the textured building models in CityGML format are further converted into 3D Tiles for visualization in CesiumJS. Figure 4 illustrates the visualization of the roof textured buildings rendered in CesiumJS.

Figure 4. Buildings with mapped roof textures on CesiumJS.

https://doi.org/10.5194/isprs-archives-XLVIII-M-6-2025-79-2025

4. Urban Vegetation

An automated workflow was created to incorporate vegetation data into the 3D city model, allowing for the web-based visualization of trees at their actual dimensions and precise locations. This integration enhances the ability to analyze the impact of vegetation on the urban environment with greater accuracy and detail. Furthermore, visualizing trees alongside the 3D city model enables a more accurate analysis of various factors, such as the impact of tree shadows on buildings and other elements throughout the day. This integration facilitates a comprehensive understanding of the interactions between vegetation and the urban environment.

This study utilized a dataset comprising approximately 1,709 trees located in the city center of Enschede. The dataset is a subset derived from a larger collection encompassing over 100,000 trees distributed across the entire city. The shapefile containing tree attributes and spatial data was developed by the company Cobra Groeninzich (2024). This dataset includes detailed attributes such as tree locations, heights, and crown diameter, which were generated automatically through the integration of laser scanning data and aerial imagery. The accuracy of the dataset was subsequently validated through field measurements. A general view of the dataset is given in Figure 5.

Figure 5. A view of tree locations as point shape file.

Effectively visualizing large datasets requires various optimization techniques to ensure both performance and accuracy. In this study, the CesiumJS library was utilized for web-based visualization, providing an interactive and efficient platform for displaying complex 3D models. CesiumJS was chosen primarily for its support of the CZML file structure, which facilitates the visualization of extensive datasets by significantly reducing file sizes without compromising detail. This capability is particularly important for urban-scale datasets, where precision and performance must coexist. To leverage this, a Python-based workflow was developed to automate the conversion of shapefile data into the CZML format. The workflow extracts critical attributes, such as tree locations, heights, and crown diameters, from shapefiles and translates them into a structured CZML representation. This automated process ensures that data integrity is preserved while scaling and positioning each tree model accurately. By streamlining this conversion, the workflow not only reduces manual effort but also enables the seamless integration of large-scale vegetation datasets into 3D web-based visualizations, enhancing both usability and scalability.

Several critical considerations must be addressed during the conversion process. The most important is scaling the trees to ensure they are visualized at their actual heights. To achieve this, the height of the 3D model file used for tree visualization must first be measured. Subsequently, the ratio between the measured model height and the actual tree height, as derived from the shapefile, must be calculated. This ratio is then used to define a unique scale factor for each tree in the CZML file, based on its actual height. In the developed method, this scaling process is automated, ensuring that each tree is visualized at its true height. A representation of this visualization is provided in Figure 6.

Figure 6. Scaled tree models with 3D city model.

Clamping tree geometries to the terrain is essential for achieving a realistic and visually accurate representation of vegetation in CZML-based visualizations. By aligning the base of each tree model to the terrain's surface, discrepancies caused by elevation variations or mismatched ground levels are minimized. This ensures that trees appear naturally integrated into the landscape rather than floating above or sinking below it, which is crucial for maintaining visual credibility in urban and environmental models. Clamping also enhances the interpretability of the visualization, as it allows users to accurately assess spatial relationships between vegetation and other urban features, such as roads, buildings, and water bodies. Furthermore, this approach improves the realism of shading and shadow effects, which are highly dependent on precise terrain alignment.

High-resolution 3D tree models are highly valuable not only for visualization but also for advancing the understanding and simulation of vegetation interactions within urban climates. Detailed tree data, including precise geographic coordinates, height, and canopy dimensions, enables the development of models that accurately represent how vegetation shapes its environment. These models provide critical insights into the influence of trees on wind dynamics, shading, and evapotranspiration, which collectively impact urban temperatures and airflow patterns. By incorporating such detailed tree geometries, urban climate modeling tools like WRF and PALM can more accurately predict localized events, including the urban heat island effect, air quality changes, and thermal comfort levels. The availability of this detailed vegetation data enhances the reliability of climate simulations and equips urban planners with actionable insights for creating greener, more sustainable, and climate-resilient cities.

5. Façade Materials and Albedos

Information about buildings' façade materials, such as brick, concrete, and metal, can be incorporated into urban models as these materials significantly influence heat absorption, release, and reflectivity, closely tied to their albedo properties. To achieve this, street view imagery data from 1,039 buildings in the city center of Enschede were manually collected and classified into 10 common material categories used in the Netherlands. The classified materials were then matched to the corresponding building IDs and subsequently integrated into the CityJSON city model as attributes for each building, enriching the dataset. A visualization of the city model enriched with façade material classes is provided in Figure 7.

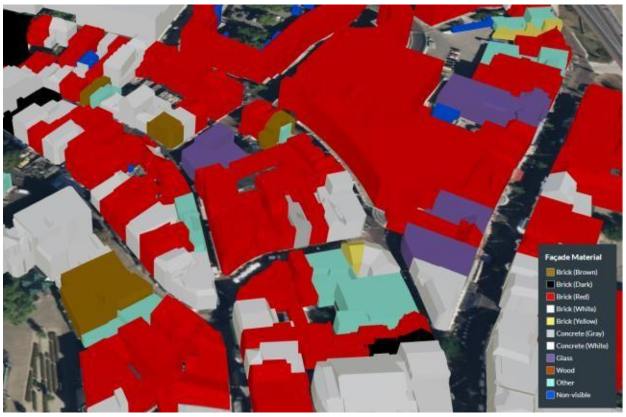

Figure 7. A view of buildings with different façade materials.

Although street view imagery serves as a valuable data source for façade material classification, several challenges arise during the data collection process. One significant limitation is that not all buildings are visible in the imagery, resulting in missing material data for those structures. Furthermore, inconsistencies in photographs taken at different times and seasons present additional complications. These variations can affect the accuracy and uniformity of material classification. While efforts were made to prioritize the use of the most recent images, there were instances where older images had to be utilized to extract necessary data due to a lack of updated imagery.

When generating the 3DBAG dataset, the two-dimensional BAG dataset was used as the building footprint. However, certain structures represented as a single building in the BAG dataset often include multiple individual buildings, each potentially having distinct façade materials. As a result, it became necessary to assign a single façade material to multiple structures, even when their materials varied. Moreover, individual façades of the same building can differ in both color and material, further complicating the classification process. These challenges, including discrepancies in building representation and variations in façade characteristics, were documented as significant obstacles during data collection and processing. Such limitations highlight the complexity of accurately capturing and classifying façade materials using street view imagery.

After the classification of street view imagery, albedo values for each material class need to be calculated and added to the CityJSON model as attributes for each building. Albedo values for materials can be obtained using various methods, such as spectrometer measurements or hyperspectral imaging. However, in this study, instead of these methods, existing albedo values from established material libraries were adapted and matched to each material class.

Albedo values of the façade materials are calculated based on the KLUM (Ilehag et al., 2019) library. KLUM includes 181 material samples categorized into 12 material classes and 33 subclasses. These classes encompass materials such as ceramics, concrete, asphalt, wood, plaster, and various types of stone (e.g., granite and sandstone). The spectral reflectances of these materials were measured using the high-resolution spectroradiometer in the Visible and Near-Infrared (VNIR) and Short-Wave Infrared (SWIR) spectral ranges (350–2500 nm). Each sample's spectra were recorded in under controlled conditions, with additional post-processing steps to correct for noise, solar irradiance variations, and signal clipping. This detailed spectral library focuses on capturing material variation in façade, ground, and roof materials.

The enrichment of the city model—incorporating façade materials and albedo values as attributes into the CityJSON file—is automated through the use of developed script. The implemented method requires the input of a folder containing classified materials and a text file specifying albedo values for each material class. The script generates an enriched version of the CityJSON file by assigning façade materials and corresponding albedo information to each building as attributes. A visualization of the 3D city model enriched with façade albedo values is presented in Figure 8.

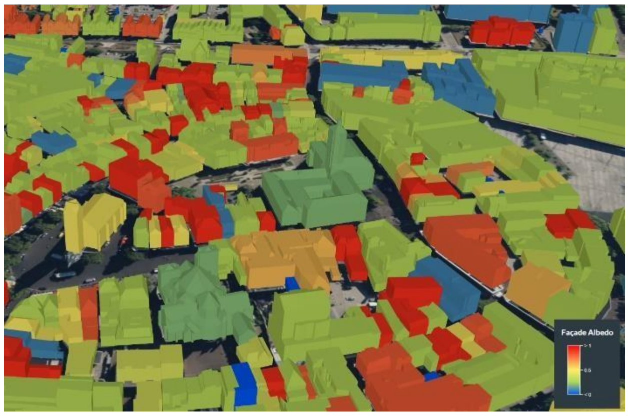

Figure 8. A view of buildings with different façade albedos.

6. Discussion

This study presents a comprehensive approach to enriching the Netherlands' 3D city model, 3DBAG, with energy-related attributes and vegetation data to enable precise urban climate modeling. By automating the integration of key features such as roof textures, façade materials, albedo values, roof slopes, and vegetation, this work addresses critical gaps in existing datasets, enhancing the realism and utility of urban digital twins for climate applications.

Several challenges were encountered during the enrichment process, particularly in texture mapping. A notable issue is the misalignment between the building footprints in the 3DBAG dataset and roof geometries visible in orthophotos, leading to potential mismatches. Manually correcting this misalignment for each building would require significant time and effort. To address this, building footprints and orthophotos should be overlaid in a GIS software for visual inspection prior to initiating the texturing process. True orthophotos, provided by PDOK in varying resolutions and from different years, are valuable resources. Selecting the most compatible orthophotos through comparative analysis ensures better alignment and improves the accuracy and quality of the textured models.

The results demonstrate the significant impact of these enrichments. Automated roof texture mapping enhances geometric accuracy and visual representation, aiding applications such as solar panel detection and energy balance studies. Accurate visualization of roof geometries and façade materials not only facilitates a better understanding of urban environments but also ensures more reliable simulations by reducing reliance on approximations. Similarly, the integration of roof slope attributes enhances the capacity to model radiation exchange and airflow patterns around buildings, contributing to more accurate urban heat island (UHI) analyses.

The inclusion of façade material and albedo data further refines simulations by enabling more precise predictions of heat absorption and reflection, which are critical for urban climate modeling. The incorporation of detailed vegetation data, such as tree height and crown diameter, adds another layer of accuracy, allowing realistic visualization of vegetation's impact on urban microclimates. These features support advanced analyses, including shadow mapping, thermal comfort studies, and pollutant dispersion modeling. Furthermore, the improved visualization capabilities facilitate effective communication and decision-making in urban planning, fostering collaboration among policymakers, researchers, and stakeholders through interactive tools like CesiumJS.

Despite these advancements, some challenges remain. The manual classification of façade materials, while valuable, is timeintensive and prone to inconsistencies due to image quality and temporal variations in street view imagery. Future work could explore deep learning techniques to automate material classification, improving efficiency and data consistency. Additionally, the workflows developed in this study may need adaptation to accommodate datasets from different regions, formats, and data availability. Addressing these challenges will further enhance the scalability and usability of the enrichment framework.

7. Conclusion and Future Works

The enriched 3D city model developed in this study provides a robust foundation for more precise urban climate simulations while enabling accurate and detailed visualization. By automating the integration of energy-related attributes and vegetation data, this work addresses key limitations in existing urban digital twins and enhances their scalability and usability. The results highlight the potential of these enriched models to improve energy efficiency, urban planning, and climate resilience by enabling more realistic simulations of urban microclimates. Moreover, the enhanced visualization capabilities serve as a powerful tool for communicating complex data to a wide audience, bridging the gap between technical analyses and actionable strategies.

Future works could focus on improving and expanding the framework in several ways. Automating material classification with deep learning could significantly enhance the accuracy and efficiency of façade material detection, addressing the challenges associated with manual processes. Calculating albedo values directly from hyperspectral imagery or spectrometer measurements instead of relying on static values from the KLUM library would allow for more precise and dynamic input data. Furthermore, integrating the energy-enriched 3D city model into the PALM-4U process could enable advanced urban climate simulations by leveraging the enriched datasets to model complex interactions within urban environments. Expanding the framework to account for dynamic attributes, such as seasonal vegetation changes or time-dependent albedo variations, and adapting workflows for broader geographic regions and datasets would further enhance its applicability. These advancements would ensure the scalability of this approach, supporting global efforts in sustainable urban development and climate adaptation.

Acknowledgements

This paper is part of the 4TU-programme HERITAGE (HEat Robustness In relation To AGEing cities). HERITAGE is funded by the 4TU-programme High Tech for a Sustainable Future (HTSF). 4TU is the federation of the four technical universities in The Netherlands (Delft University of Technology, DUT; Eindhoven University of Technology, TU/e; University of Twente, UT and Wageningen University and Research, WUR).

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