A UAV-Based Urban Digital Twin Framework for Building-Resolving Urban Climate Modeling

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Abstract

Building-resolving urban climate models require high-resolution urban morphology datasets that are often labor-intensive to prepare from heterogeneous geospatial sources. Meanwhile, urban digital twins have emerged as promising platforms for integrating geospatial data, environmental observations, and numerical models to support climate-resilient urban planning. However, existing studies generally treat these components independently, with limited integration of UAV-based data acquisition, urban morphology preparation, climate-model preprocessing, and digital twin visualization within a unified geospatial workflow. This paper presents a UAV-based urban digital twin framework for building-resolving urban climate modeling that integrates UAV LiDAR data acquisition, three-dimensional city modeling, urban morphology generation, and web-based visualization into a systematic and reproducible workflow. The framework was implemented in the University of the Philippines Diliman Engineering Complex using UAV LiDAR and photogrammetric surveys. Point cloud processing generated Digital Terrain Models (DTMs), Digital Surface Models (DSMs), Canopy Height Models (CHMs), and LoD1 three-dimensional city models, while a Random Forest classifier produced an initial classification of major surface classes to support subsequent urban morphology generation. An interactive web-based digital twin prototype was developed using deck.gl to visualize the generated three-dimensional urban models and geospatial datasets. The proposed framework establishes a common high-resolution geospatial foundation for integrating UAV-derived products with complementary thematic datasets required for building-resolving climate modeling. The framework provides a transferable methodology for integrating geospatial data acquisition, urban climate model preparation, and digital twin development, contributing toward the development of digital twins for climate resilience and evidence-based urban planning.

1. Introduction

Urban areas are becoming increasingly vulnerable to the impacts of climate change due to their high population densities, concentration of critical infrastructure, and complex interactions between natural and built environments. These factors intensify urban environmental challenges such as the Urban Heat Island (UHI) effect, deteriorating air quality, reduced thermal comfort, and increased exposure to climate-related hazards. The Intergovernmental Panel on Climate Change (IPCC, 2022) recognizes cities as highly climate-sensitive environments where urban morphology and land cover strongly influence local atmospheric processes. Addressing these challenges requires high-resolution information to support climate adaptation, disaster risk reduction, and sustainable urban planning.

Building-resolving urban climate models have become essential for simulating urban microclimates by explicitly representing buildings, vegetation, and terrain. Unlike mesoscale numerical weather prediction models such as the Weather Research and Forecasting (WRF) model, building-resolving models such as the Parallelized Large-Eddy Simulation Model for Urban Applications (PALM-4U) simulate airflow, thermal conditions, and pollutant dispersion at meter-scale resolution (Chen et al., 2011; Maronga et al., 2020). However, their implementation requires detailed three-dimensional urban morphology datasets, including accurate representations of buildings, terrain, vegetation, and land cover.

Recent advances in UAV-based LiDAR and geospatial technologies have enabled efficient acquisition of high-resolution three-dimensional urban datasets suitable for city modeling. Combined with GIS and semantic city modeling standards, these datasets provide an effective basis for developing digital representations of urban environments. At the same time, urban digital twins have emerged as an important paradigm for smart cities by integrating three-dimensional city models with sensor observations and simulation models into dynamic virtual representations that support visualization, analysis, and decision-making (Batty, 2018; Biljecki et al., 2021; Mazzetto, 2024).

Despite these developments, the integration of UAV-derived three-dimensional city models, building-resolving urban climate models, and digital twin technologies remains limited. Existing digital twin implementations primarily emphasize visualization and asset management, while urban climate studies often focus on numerical simulations without providing an integrated geospatial workflow. Furthermore, preparing the urban morphology datasets required for building-resolving climate models remains a labor-intensive process that involves integrating multiple heterogeneous geospatial datasets, including terrain, buildings, vegetation, land cover, and surface characteristics, through extensive preprocessing across several software platforms (Maronga et al., 2020).

This paper presents a UAV-based urban digital twin framework for building-resolving urban climate modeling that integrates UAV LiDAR data acquisition, three-dimensional city modeling,

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urban morphology generation, PALM-4U climate model preparation, and web-based visualization into a unified geospatial workflow. The proposed workflow systematizes the generation of climate-model-ready 3D urban morphology datasets from UAV observations while providing an interoperable framework that links geospatial data acquisition, climate-model preprocessing, and digital twin visualization. The framework is demonstrated through its implementation in the University of the Philippines Diliman Engineering Complex and is designed to be transferable to other urban environments requiring high-resolution climate assessment and digital twin development.

2. Related Work

2.1 Urban Digital Twins

Urban digital twins have emerged as a key enabling technology for smart cities by integrating three-dimensional city models, sensor observations, and simulation models into dynamic virtual representations that support monitoring, analysis, and decision-making (Batty, 2018). Unlike conventional 3D city models, digital twins continuously synchronize static geospatial data with dynamic information, enabling applications in urban planning, infrastructure management, environmental monitoring, and climate resilience (Biljecki et al., 2021; Mazzetto, 2024).

Recent developments have expanded urban digital twins to incorporate Internet of Things (IoT), artificial intelligence (AI), and cloud computing for predictive analytics and adaptive urban management (Sacoto-Cabrera et al., 2025). Emerging applications include heat exposure assessment, green-blue infrastructure planning, and LiDAR-based city-scale digital twins. However, most implementations emphasize visualization and asset management, with relatively limited integration of building-resolving urban climate models.

2.2 UAV-Based 3D Urban Modeling

High-resolution three-dimensional city models form the geometric foundation of urban digital twins and building-resolving climate simulations. Advances in UAV-based LiDAR have enabled rapid acquisition of dense point clouds suitable for reconstructing buildings, terrain, and vegetation at neighborhood scales. Compared with conventional airborne surveys, UAV platforms provide higher point densities, lower operational costs, and greater flexibility for repeated data acquisition.

Following acquisition, point cloud registration, filtering, and classification produce Digital Terrain Models (DTMs), Digital Surface Models (DSMs), and Canopy Height Models (CHMs), which support three-dimensional reconstruction and environmental analyses. LoD1 building models are commonly used in neighborhood-scale urban applications because they strike a balance between geometric detail and computational efficiency (Biljecki et al., 2015). Although UAV-derived LiDAR has become increasingly common for city modeling, relatively few studies have developed integrated workflows that directly transform UAV observations into climate-model-ready datasets while supporting digital twin development.

2.3 Building-Resolving Urban Climate Modeling

Building-resolving urban climate models explicitly represent buildings, terrain, and vegetation to simulate airflow, thermal conditions, radiation exchange, and pollutant dispersion at meter-scale resolutions. Compared with mesoscale models such as WRF, models based on Computational Fluid Dynamics (CFD), including PALM-4U, provide more realistic simulations of neighborhood-scale atmospheric processes (Maronga et al., 2020).

These simulations require detailed urban morphology datasets, including building heights, terrain elevation, vegetation, pavement, and Local Climate Zones (LCZs), which are often compiled from multiple heterogeneous geospatial sources. Recent studies have applied machine learning techniques to automate land-cover and LCZ classification using remote sensing datasets, improving the efficiency of generating PALM-ready inputs. Nevertheless, relatively few studies integrate these preprocessing workflows within urban digital twin platforms, resulting in fragmented workflows between geospatial data acquisition, climate modeling, and visualization.

2.4 Research Gap and Contributions

Urban digital twins and building-resolving urban climate models have matured considerably over the past decade, yet they have largely evolved as independent research domains. Digital twin research has primarily emphasized data integration, visualization, Internet of Things (IoT) applications, and smart city management, whereas urban climate research has concentrated on improving numerical simulations of atmospheric processes using increasingly sophisticated CFD models. Consequently, there remains a lack of comprehensive geospatial frameworks that integrate high-resolution data acquisition, three-dimensional city modeling, climate model preparation, numerical simulation, and interactive visualization within a unified workflow.

This gap is particularly evident in tropical urban environments, where rapidly changing urban morphology, dense development, and limited availability of detailed three-dimensional datasets present significant challenges for urban climate modeling. Existing workflows frequently rely on multiple software platforms and extensive manual preprocessing to generate the urban morphology datasets required by building-resolving climate models, reducing reproducibility and limiting wider adoption by urban planners and local governments.

The framework proposed in this study addresses these challenges by integrating UAV-based LiDAR acquisition, three-dimensional city modeling, urban morphology generation, climate model preprocessing, and digital twin visualization into a unified geospatial workflow. Rather than treating these components as independent processes, the proposed framework establishes a systematic and reproducible methodology that combines UAV-derived geospatial products with complementary thematic datasets to prepare the urban morphology inputs required for building-resolving climate models such as PALM-4U. This integrated approach streamlines the preparation of urban morphology datasets for building-resolving climate modeling while providing a common geospatial foundation for digital twin development and the future integration of environmental observations and simulation outputs.

Although demonstrated using a pilot site within the University of the Philippines Diliman, the proposed framework is designed to be transferable to other urban environments. The methodology contributes not only to the development of urban digital twins but also to the growing field of climate-resilient geospatial infrastructures that support evidence-based urban planning, environmental management, and smart city development.

3. Methodology

3.1 Framework Overview

The proposed framework integrates UAV-based geospatial data acquisition, three-dimensional city modeling, urban morphology generation, numerical urban climate modeling, and digital twin visualization into a unified workflow for building-resolving urban climate applications. Figure 1 illustrates the overall framework.

The workflow consists of five major components: (1) UAV-based data acquisition, (2) three-dimensional urban model generation, (3) preparation of urban morphology datasets for climate modeling, (4) building-resolving urban climate simulation, and (5) digital twin development. Unlike conventional workflows where these processes are performed independently, the proposed framework establishes a continuous geospatial pipeline that transforms remotely sensed observations into a digital twin framework capable of supporting climate simulations and future real-time environmental monitoring.

The framework was developed as part of the KLIMA Project, which aims to establish an integrated urban digital twin for climate resilience by combining remote sensing, Internet of Things (IoT) sensing platforms, numerical climate modeling, and web-based visualization. While the complete digital twin architecture incorporates multiple sensing modalities and simulation components, this paper focuses on the development of the geospatial framework that enables high-resolution urban climate modeling.

3.2 Study Area and Data Acquisition

The proposed framework was implemented within the University of the Philippines Diliman Engineering Complex, which served as the pilot area for the initial development and testing of the methodology. The Engineering Complex consists of a heterogeneous urban landscape characterized by academic buildings of varying heights, open spaces, road networks, paved surfaces, and vegetation. The diversity of land cover and urban morphology makes the area suitable for evaluating workflows intended for building-resolving urban climate simulations.

High-resolution spatial datasets were acquired using UAV-based LiDAR and photogrammetric surveys. Airborne data collection was conducted using a DJI Matrice platform equipped with a DJI Zenmuse L2 LiDAR sensor. The flight mission was planned using predefined flight boundaries and optimized acquisition parameters, including flight altitude, overlap, scan frequency, and pulse repetition rate, to ensure complete coverage of the study area while maintaining sufficient point density for urban reconstruction.

Ground control was established using Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS) observations to improve the geometric accuracy of the generated products. The resulting datasets included dense LiDAR point clouds, aerial imagery, and accurately surveyed ground control points that served as the primary inputs for three-dimensional modeling.

In addition to primary UAV observations, ancillary geospatial datasets including building footprints, orthomosaics, and elevation products were incorporated into the workflow to support feature extraction and model generation. These datasets also facilitate interoperability with subsequent climate modeling and visualization components.

3.3 UAV-Based Three-Dimensional Urban Modeling

The development of the digital twin begins with the generation of a high-resolution three-dimensional representation of the urban environment from UAV-derived LiDAR observations.

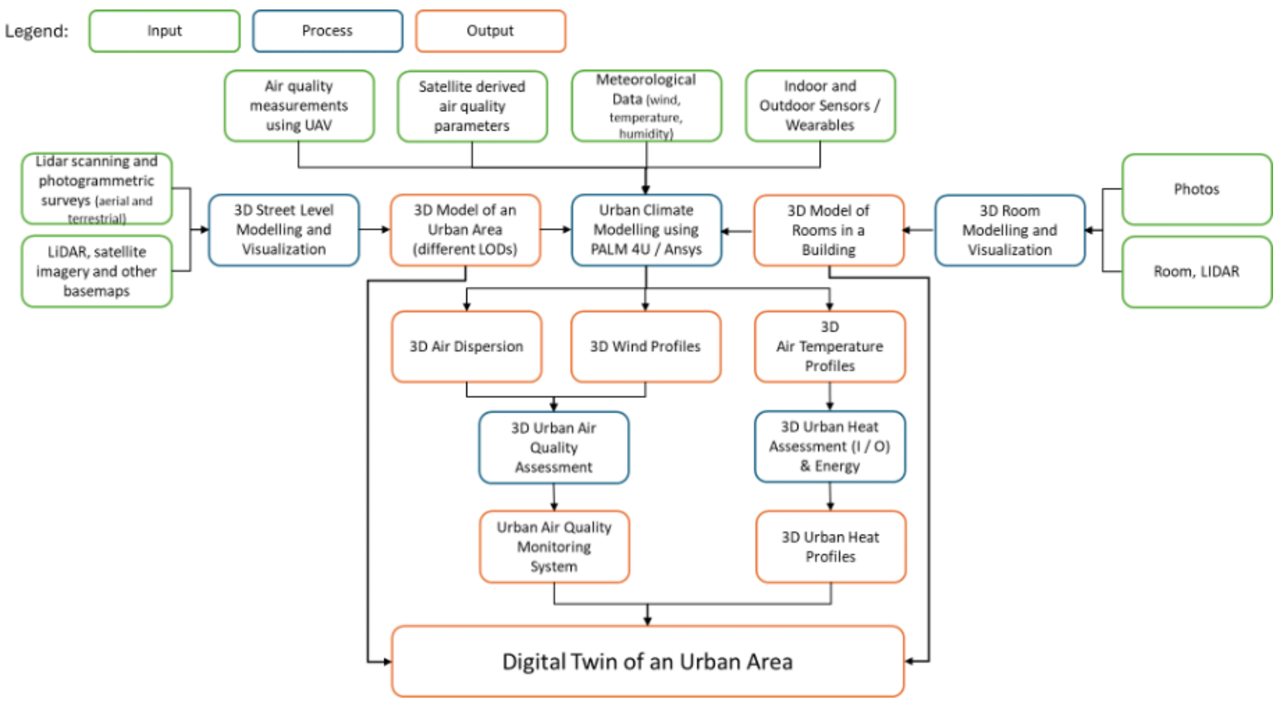

Figure 1. Overall methodological framework.

The acquired point cloud was first subjected to preprocessing procedures consisting of coordinate verification, point cloud registration, and noise removal. Initial point classification was performed using the automated classification tools available in ArcGIS Pro, separating the point cloud into ground, buildings, vegetation, and noise classes. Semi-automatic editing was subsequently applied to improve classification accuracy by removing remaining outliers and correcting obvious misclassifications.

Following point classification, DTMs and DSMs were generated through point cloud interpolation. The CHM was then derived by subtracting the DTM from the DSM, producing normalized elevation values that represent the heights of above-ground features relative to the local terrain.

Building footprints were digitized from the orthomosaic and combined with the CHM using zonal statistics to estimate representative building heights. These height attributes were subsequently used to extrude individual building footprints and generate a Level of Detail 1 (LoD1) three-dimensional city model. The resulting model preserves the spatial distribution and heights of buildings while maintaining a relatively lightweight geometry suitable for visualization and numerical simulations.

To investigate higher-fidelity representations, additional LoD2 models were generated directly from classified point clouds using multipatch reconstruction techniques. However, the LoD1 representation was selected as the primary geometric model because it provides an effective balance between computational efficiency and geometric detail required for neighborhood-scale climate simulations.

3.4 Urban Morphology Generation for Building-Resolving Climate Modeling

Building-resolving urban climate models require substantially more information than conventional three-dimensional city models. In addition to building geometry, numerical simulations require detailed representations of terrain, vegetation, pavement, water bodies, and other surface characteristics. Accordingly, the proposed framework includes an intermediate stage that prepares the urban morphology datasets required for climate-model preprocessing by integrating UAV-derived products with complementary thematic datasets.

Digital elevation products derived from UAV observations formed the primary geometric basis for the workflow. DTMs, DSMs, CHMs, and building footprints generated during the three-dimensional modeling stage were used to derive height layers that define the geometric characteristics of the urban environment.

An initial land-cover classification was performed using a Random Forest classifier implemented in Google Earth Engine. The classifier utilized UAV-derived orthomosaics together with DTMs and DSMs to classify the study area into major surface classes, including buildings, trees, vegetation, and paved surfaces. These classified products provide the initial thematic dataset for subsequent urban morphology generation.

Additional preprocessing is required to derive the thematic layers specified by the PALM Input Data Standard (PIDS). In particular, the vegetation and paved surface classes must be further refined into the corresponding PALM-4U subclasses and assigned the physical surface properties required for building-resolving simulations. This refinement may incorporate supplementary datasets, such as the TESSERA land-surface classification or other appropriate land-cover inventories, together with the UAV-derived products. The resulting datasets collectively describe the terrain, buildings, vegetation, pavement, water bodies, and other surface characteristics required by PALM-4U.
Meteorological boundary conditions are intended to be provided by mesoscale numerical weather prediction models through a domain-nesting approach. Regional atmospheric conditions simulated by the Weather Research and Forecasting (WRF) model provide the boundary conditions for PALM-4U, enabling neighborhood-scale building-resolving simulations that remain dynamically consistent with larger-scale atmospheric processes.

3.5 Digital Twin Framework

The proposed digital twin framework extends conventional three-dimensional city modeling by integrating spatial datasets, environmental observations, and numerical simulation outputs into a unified geospatial environment.

The framework consists of four interconnected layers:

1. **Physical Layer**, representing the real-world urban environment captured through UAV surveys, field observations, and environmental sensors;
2. **Geospatial Layer**, containing processed spatial datasets including point clouds, orthomosaics, Digital Terrain Models, Digital Surface Models, building footprints, and three-dimensional city models;
3. **Modeling Layer**, responsible for generating urban climate simulations through PALM-4U and incorporating regional meteorological conditions from WRF;
4. **Visualization Layer**, providing interactive access to three-dimensional city models, sensor observations, and simulation outputs through a web-based digital twin platform.

Information flows continuously between these layers. UAV observations provide updated representations of urban morphology, while future sensor deployments will enable continuous monitoring of environmental conditions including temperature, humidity, particulate matter, carbon dioxide concentration, and other air quality indicators. These observations will support calibration and validation of numerical simulations and allow the digital twin to evolve as a dynamic representation of the physical environment.

Although the current implementation primarily demonstrates the integration of three-dimensional city models and preliminary environmental datasets, the framework has been designed to support future incorporation of real-time sensing, predictive analytics, and scenario-based simulations for urban planning and climate adaptation.

3.6 System Implementation

An initial implementation of the proposed framework was developed using open-source and commercial geospatial software integrated through standardized data formats and interoperable workflows.

Point cloud preprocessing and classification were performed using ArcGIS Pro, CloudCompare, and Agisoft Metashape. Three-dimensional city models were generated using QGIS and ArcGIS Pro, while urban morphology preprocessing for PALM-4U utilized Python-based scripts together with Google Earth

Engine for land-cover classification. Building-resolving climate simulations were prepared using the PALM Input Data Standard (PIDS) and associated preprocessing tools.

The digital twin visualization platform was implemented using deck.gl, an open-source WebGL framework for large-scale geospatial visualization. The web interface integrates three-dimensional building models with orthomosaic imagery and environmental datasets, providing an interactive environment for exploring urban morphology and future climate simulation outputs. The architecture was designed to support interoperability with IoT sensor networks and external geospatial databases through web services and application programming interfaces (APIs), facilitating future expansion into a fully operational urban digital twin platform.

4. Results and Discussion

4.1 UAV-Based Three-Dimensional Urban Model

The proposed framework was successfully implemented within the Engineering Complex of the University of the Philippines Diliman. The UAV-based LiDAR survey produced a dense point cloud dataset (around 717 points/m^2) that captured the geometric characteristics of buildings, roads, vegetation, and other urban features with sufficient detail for neighborhood-scale three-dimensional reconstruction. Figure 2 shows the acquired point cloud data.

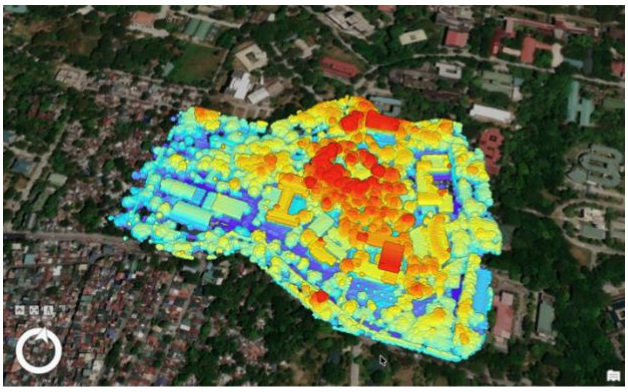

Figure 2. Engineering Complex point cloud data.

Automated point cloud classification in ArcGIS Pro successfully separated the acquired point cloud into ground, buildings, vegetation, and noise classes. Subsequent manual refinement removed remaining outliers and improved the consistency of feature classification. The classified point cloud enabled the generation of DTMs and DSMs, from which a CHM was derived through raster differencing. Figure 3 shows the results of the point cloud classification.

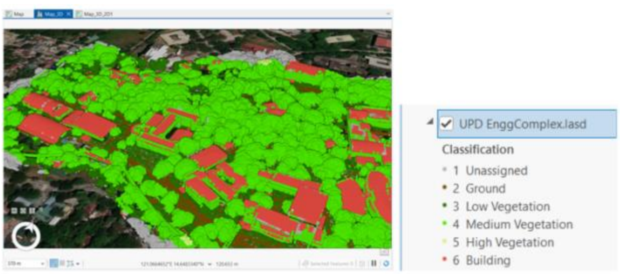

Figure 3. Resulting classified point clouds.

The generated CHM (Figure 4) effectively represented the height distribution of above-ground features throughout the study area and served as the primary input for estimating building heights. Integration of the CHM with manually digitized building footprints through zonal statistics produced representative building heights for each structure. These attributes were subsequently used to generate an LoD1 three-dimensional city model by vertically extruding individual building footprints.

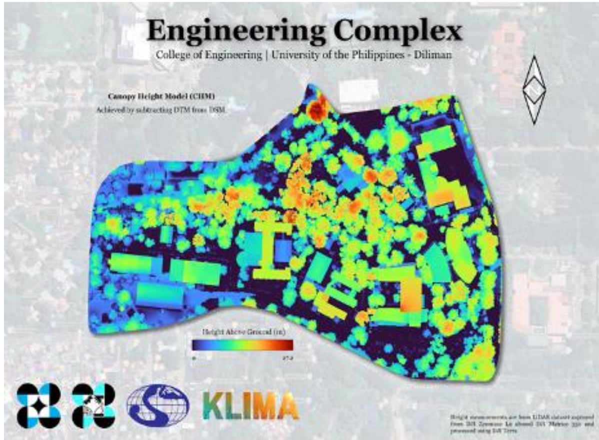

Figure 4. Canopy height model (CHM) of the Engineering Complex.

The resulting LoD1 model (Figure 5) represents the urban 3D model while maintaining relatively low geometric complexity. Compared with dense mesh reconstructions, the LoD1 representation substantially reduces computational requirements while preserving the geometric characteristics required by building-resolving urban climate models. This confirms previous observations that simplified semantic city models provide an appropriate compromise between geometric fidelity and computational efficiency for neighborhood-scale environmental simulations (Biljecki et al., 2015).

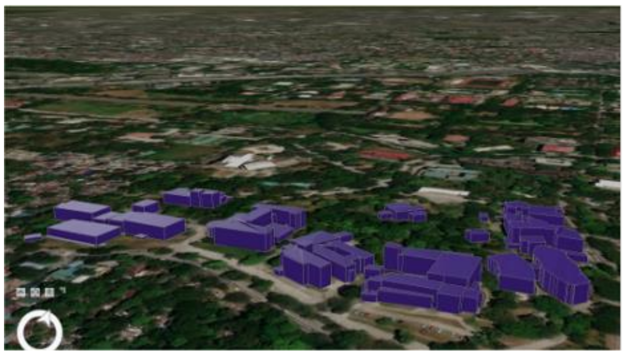

Figure 5. LOD 1 3D model of the Engineering Complex.

Although preliminary LoD2 models were generated using multipatch reconstruction techniques, the LoD1 model was selected as the primary representation for the proposed framework because of its compatibility with PALM-4U preprocessing requirements and interactive web visualization.

4.2 Generation of Urban Morphology Datasets

The proposed framework successfully generated the foundational urban morphology datasets required for subsequent building-resolving climate model preprocessing. These include high-resolution DTMs and DSMs, building height information, and an initial land-cover classification derived from the UAV observations, establishing a common geospatial foundation for subsequent thematic refinement.

The initial Random Forest (RF) classification identified the major surface classes of buildings, trees, vegetation, and paved surfaces with an overall accuracy of 96% and a Kappa coefficient of 0.94, demonstrating the suitability of the UAV-derived datasets for automated urban surface mapping. The resulting classification (Figure 6) provides the initial thematic representation of the study area from which additional PALM-4U input layers can be derived.

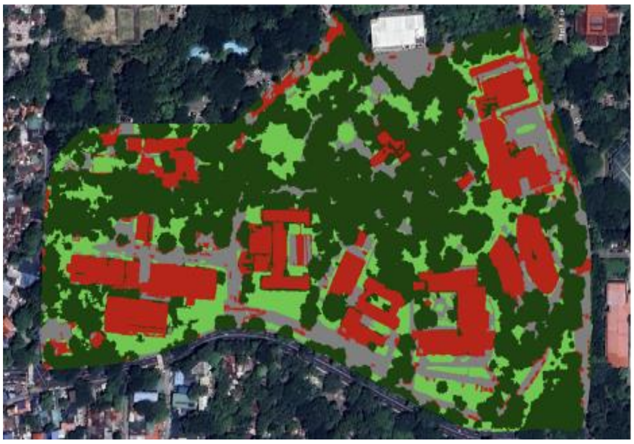

Figure 6. Resulting surface classes: Trees (green), Vegetation (light green), Buildings (red) and Pavement (grey).

Although the generated surface classes establish the primary thematic framework, additional refinement is required before they can be used for building-resolving climate simulations. In particular, the vegetation and paved surface classes must be further classified into the subclasses specified by the PALM Input Data Standard (PIDS), and the corresponding physical surface properties must be assigned. This refinement may incorporate supplementary datasets, such as the TESSERA land-surface classification or other appropriate land-cover dataset, together with the UAV-derived products.

4.3 Digital Twin Implementation

An initial implementation of the proposed digital twin was developed to demonstrate the integration of three-dimensional urban models with environmental information within an interactive web-based environment. The visualization platform was implemented using deck.gl, allowing efficient rendering of three-dimensional buildings together with orthomosaic imagery and geospatial datasets. Unlike conventional desktop visualization software, the web-based implementation enables interactive exploration of the study area directly through a web browser while maintaining compatibility with standard geospatial data formats.

The current prototype integrates the generated LoD1 building model with UAV-derived orthomosaics and preliminary environmental datasets (Figure 7). Although the present implementation utilizes sample environmental measurements, the system architecture has been designed to accommodate future integration of Internet of Things (IoT) sensor observations, including temperature, relative humidity, particulate matter, carbon dioxide concentration, and other air-quality parameters currently being developed under the KLIMA Project.

The digital twin architecture further supports the integration of building-resolving climate simulations generated using PALM-4U. Future simulation outputs, including wind fields, air temperature, pollutant dispersion, and thermal comfort indices, can be visualized in a single three-dimensional environment, enabling users to examine spatial relationships between urban morphology and atmospheric processes.

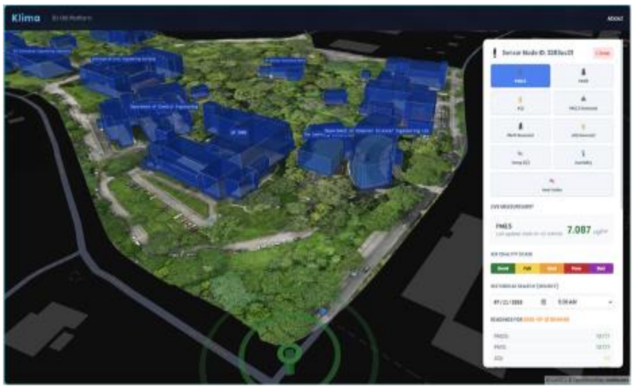

Figure 7. Initial prototype of the digital twin.

This integrated visualization environment offers a significant advantage over conventional GIS workflows by enabling static geospatial information, dynamic sensor observations, and numerical simulation outputs to coexist on a single interactive platform.

4.4 Readiness for Building-Resolving Urban Climate Modeling

The generated terrain models, building heights, and initial RF classification of major surface classes establish the primary geometric and thematic datasets required for PALM-4U preprocessing. These outputs provide the basis for generating the static drivers specified by the PALM Input Data Standard (PIDS). However, additional processing is required to refine vegetation and paved surfaces into the subclasses required by PALM-4U and to assign the corresponding physical surface properties. This refinement may incorporate supplementary datasets, such as the TESSERA land-surface classification or other appropriate land-cover inventories, to produce the complete set of climate-model-ready urban morphology inputs.

The modular architecture of the framework facilitates the integration of these heterogeneous datasets while maintaining a consistent, high-resolution spatial reference derived from UAV observations. It also supports multi-scale atmospheric modeling by enabling regional meteorological conditions from mesoscale numerical weather prediction models, such as WRF, to be incorporated through domain nesting. This allows PALM-4U to simulate neighborhood-scale atmospheric processes while maintaining consistency with larger-scale atmospheric conditions.

Several limitations remain. The current implementation utilizes an LoD1 representation of buildings, which simplifies roof geometry and façade details. While this level of detail is suitable for many neighborhood-scale climate applications, higher Levels of Detail may improve simulations involving solar radiation exchange, wind flow around complex roof structures, and pedestrian-scale airflow. Furthermore, the present work focuses on establishing the geospatial framework and preparing the prerequisite datasets for climate modeling. The generation of the complete set of PALM-4U static drivers, integration of real-time environmental sensor observations, and calibration and validation of PALM-4U simulations are ongoing as part of the broader KLIMA Project.

Overall, the results demonstrate the feasibility of the proposed framework as a foundation for developing operational urban digital twins for building-resolving urban climate modeling. By integrating high-resolution UAV-derived geospatial products with complementary thematic datasets, numerical climate modeling, and interactive visualization within a unified workflow, the framework reduces the complexity of urban morphology preparation while providing a scalable and reproducible pathway for developing digital twins that support climate resilience and evidence-based urban planning.

5. Conclusions

This paper presented a UAV-based urban digital twin framework for building-resolving urban climate modeling that integrates UAV LiDAR data acquisition, three-dimensional city modeling, urban morphology generation, and web-based visualization into a unified geospatial workflow. Rather than treating these processes as independent tasks, the proposed framework establishes a systematic and reproducible methodology that bridges geospatial data acquisition, urban morphology preparation, climate model preprocessing, and digital twin development. The framework provides a common high-resolution spatial foundation that can be integrated with complementary thematic datasets to support the preparation of urban morphology inputs for building-resolving climate models.

Implementation of the framework in the University of the Philippines Diliman Engineering Complex demonstrated its feasibility for generating the foundational datasets required for urban climate modeling applications from UAV-derived point clouds. These datasets, such as DTM, DSM, CHM, and LoD1 3D city model, form the basis for deriving the static drivers required by PALM-4U. The initial digital twin prototype demonstrated the ability to integrate three-dimensional urban models with geospatial datasets in an interactive web-based environment, laying the foundation for future integration of numerical simulations and real-time environmental observations.

The current implementation represents an initial stage toward a fully operational urban digital twin for climate applications. Future work will focus on refining vegetation and pavement subclasses using complementary thematic datasets, completing the generation of PALM-4U static drivers, integrating real-time environmental sensor observations, and calibrating and validating PALM-4U simulations using field measurements. The framework will also be applied to larger and more complex urban environments to evaluate its transferability to tropical cities. These developments are expected to strengthen the role of urban digital twins as decision-support tools for climate resilience, sustainable urban planning, and environmental management.

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