Precise Urban Green Volume-enabled Building and Environment Simulation: Sub-Meter Voxel Modeling of Airborne and Hand-held 3D Scans of Urban Trees

Qianyun Zhou[1]*, Jiajia Wang[2], Bin Chen[3], Fan Xue[4]

This is the authors' pre-print version of the paper: Zhou, Q., Wang, J., Chen, B., & Xue, F. (2022). Precise Urban Green Volume-enabled Building and Environment Simulation: Sub-Meter Voxel Modeling of Airborne and Hand-held 3D Scans of Urban Trees. Proceedings of the 27th International Symposium on Advancement of Construction Management and Real Estate (CRIOCM2022), Springer, in press.

Abstract: High-rise high-density cities around the world suffer from severe urban heat island effects. Greenery has the potential to heal urban microclimates, such as shading, lowered air temperatures, and increased humidity, apart from other benefits to urban health. Existing numerical simulation studies employing simplified, proxy greenery models have validated the potential at a macro level; However, the human-centric three-dimensional nature of greenery (e.g., tree crown volume, canopy density, and leaf area index) was ignored, leading to inaccurate results for buildings and blocks, especially in the high-rise high-density settings. This research proposes a precise voxel modeling of urban green volume for building and environment simulations. First, two scans, i.e., the airborne scan of tree canopies and hand-held LiDAR scan of lower parts, are registered and merged into a voxel model at 0.5-m resolution. Then, simulations and analysis of the voxelized green volume are conducted using Rhinoceros and Grasshopper. A preliminary experiment of shading on a university campus in Hong Kong proved the concept of this study. Future work will be directed to analysis of the voxel resolution and more types of simulations such as winds and urban thermal exposure.

Keywords: Urban green volume; Urban heat island; Building and environment simulation; LiDAR point cloud; Voxelization; Numerical simulation

[1] Qianyun Zhou
* Corresponding author, Department of Real Estate & Construction, The university of Hong Kong, China

[2] Jiajia Wang
Department of Real Estate & Construction, The university of Hong Kong, China

[3] Bin Chen
Division of Landscape Architecture, The University of Hong Kong, China

[4] Fan Xue
Department of Real Estate & Construction, The university of Hong Kong, China

1 Introduction

The intensive urbanization process and anthropogenic activities have increased the vulnerability of cities to climate change. The climate hazard is expected to trigger more frequent natural disasters, such as severe and protracted heat waves, which further harm economic, social, and environmental perspectives of the built environment [1]. For intensive land use and high-density cities, the increasing and long-term air temperatures are frequently associated with intense urban heat island (UHI) effects. UHI not only leads to heat stress among citizens but also raises urban energy consumption (e.g., air conditioning in buildings) and has a detrimental influence on the sustainability of the urban environment [1]. Thus, United Nations' Sustainable Development Goal-11 (SDG-11) calls for actions to resolve sustainability issues for cities and communities.

Existing studies in the literature have confirmed urban greenery's positive and negative effects on mitigating UHI. For example, the crown shape and leaf features have been shown to have cooling potential due to their influence on solar exposure, air humidity, and wind environment [2]. Morakinyo, et al. [2] found that dense foliage tall tree species play a significant role in cooling cities through field surveys and model validation, while Chen, et al. [3] extracted and mapped greening coverages with satellite remote sensing to analyze the multi-scale difference in greenspace exposure. Yet, Oshio, et al. [4] showed that urban greenery can significantly reduce wind speeds in streets, thus hindering the local microclimate. Therefore, holistic and accurate quantitative studies are demanded to assess three-dimensional greenery.

In recent years, 3D scanning, including airborne drone photogrammetry and mobile LiDAR, has been widely used for building and city information models [5]. The related remote sensing technologies obtain the coordinates (X, Y, Z), sometimes with the color (R, G, B) or laser intensity (I), from the points on the objects. Airborne 3D scan data was used to assess urban greening and its effects on mitigating UHI [4]. However, the airborne data that reflects the top parts of tree crowns cannot provide sufficient 3D vegetation features holistic and accurate quantitative studies.

This study presents a sub-meter voxel modeling method for integrating airborne and hand-held 3D scans of urban trees for building and environment simulation. The main contribution of this study is twofold. Firstly, the findings plot a technological pathway to integrate multi-source 3D scans of urban trees into computable voxels of 3D greenery; Secondly, it showed that the sub-meter green volume model could improve the accuracy of building and environment simulation at an ignorable cost of computational load.

2 Methodology

This study employs a point cloud-based scan registration for 3D greenery. First, photogrammetry of airborne scans generates high-resolution 3D color points composed of 18,431,241 points. Then, a total of 558,158 points of urban greenery can be collected from semantic analysis of urban models based on machine learning [5, 6] or by color filtering and segmentation, which separates target greenery from the surrounding environment, as shown in Figure 1. Then, handheld LiDAR scanning collects more of a human perspective on the three-dimensional greening features, with 18,146,233 colorful points. The collected information (e.g., the bottom of the tree crown, tree trunks, and ground shrubs) aptly complements the airborne scans. Similarly, the points of interest of 3D greenery can be collected using automatic or manual processing (e.g., functions in Cloud Compare). Figure 2 shows an example of pre-processed handheld laser-scanned greenery data. A complete 3D greenery data registers the airborne and handheld scans, as shown in Figure 3. The distance between the overlapping parts of the two source point clouds is calculated by the distance function in Cloud Compare, resulting in 0.3702m for average distance and 0.3104 for root-mean-square deviation (RMSD). The registered 3D greenery data is saved as a point cloud in the LASzip Compressed Lidar (*.las*) format, consisting of spatial coordinates (X, Y, and Z), source of points, and related variables.

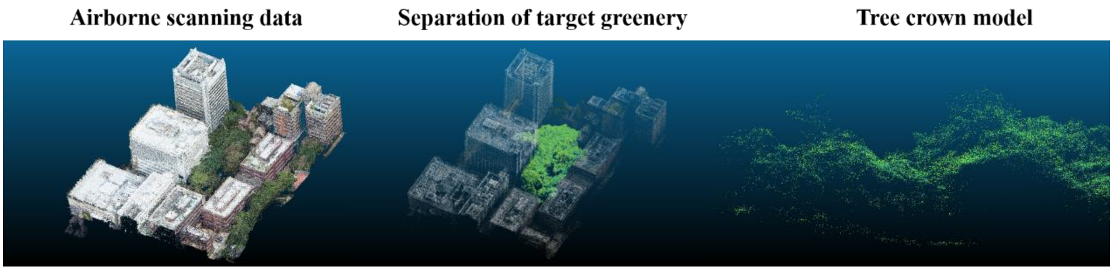


Figure 1. Pre-processing of airborne scanning data

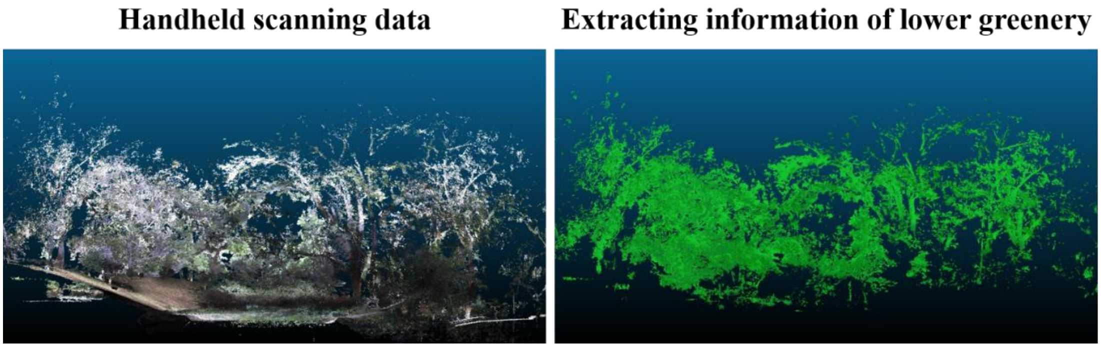


Figure 2. Pre-processing of handheld scanning data

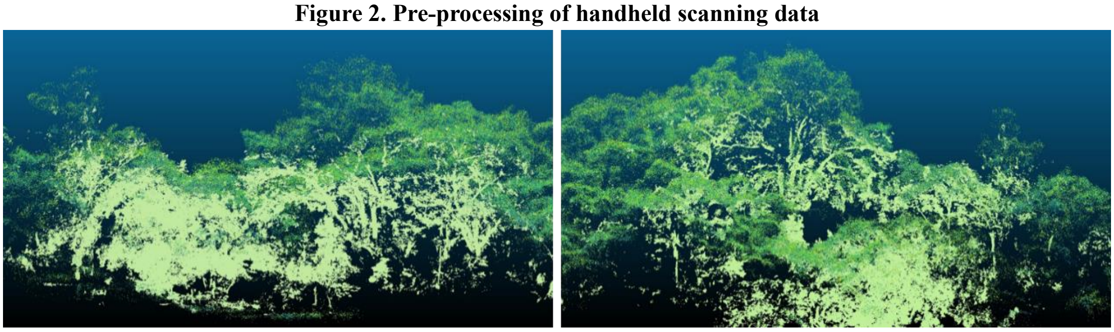
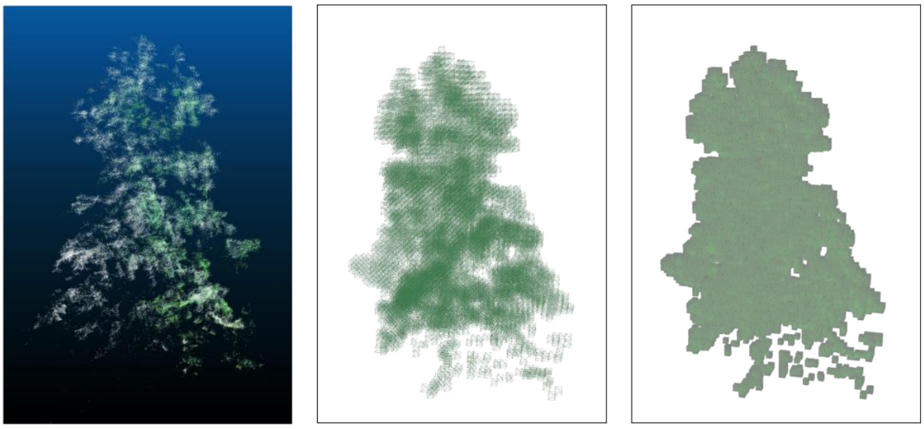


Figure 3. Registration results of airborne (in dark green) and handheld (in light green) 3D scans

Then, a voxelization modeling method for greening crown shapes is applied to crown volumes for measurement and visualization. A voxel is a 3D cubic representation of volume. Poux [7] presents an automation workflow for transforming point clouds into 3D voxels with Python codes. The voxelization process in this research is based on three Python (ver. 3.8) libraries: *laspy* (ver. 2.0.3), *open3d* (ver. 0.11.2), and *NumPy* (ver. 1.21.2). The voxels are assembled from the dataset's spatial bounding box, and the voxel location is generated as a relative value to the initial bounding box. The voxel model can be transformed into other 3D formats, such as *.obj* format, for further computation and simulation. Such transformations can be done through the *open3d* library. As a result, 3D greenery volume is calculated by voxel quantities, as shown in Figure 4.



a. Point cloud tree b. Voxel grid tree c. Voxel cube tree

Figure 4. Transforming the point cloud of a tree to voxel model

Numerical simulations can finally be conducted using the voxel model. Numerical simulation is often promising for assessing the influence of urban greening on the environment. Previous research has utilized environmental models to study the association between greening and urban air temperatures, local microclimate, and outdoor thermal comfort [2, 4]. Although parametric simulation tools are becoming increasingly well-established, the 3D features of greening in urban microclimate studies were generally replaced by theoretical, empirical values, or oversimplified (e.g., a conical-shaped tree crown). The complex characteristics of real greenery (e.g., the density of tree canopy, tree crown volume, and leaf area index) were seldom addressed in numerical simulations [8]. Therefore, it is essential to represent the urban environment via a high-precision vegetation modeling and simulation. In addition, the voxel-based approach allows for the numerical simulation of the urban thermal environment with changeable resolutions.

3 Preliminary experiment

3.1 Study area and settings

The preliminary study was established on a university campus (22°16'58.17" N, 114° 8'18.25" E) in sub-tropical Hong Kong, as shown in Figure 5. The city suffers from the severe UHI effect, while greenery significantly provides outdoor thermal comfort through shading [2]. Both the airborne and handheld scans were collected around Mong Kwok Ping Garden by the authors using a DJI Marvic 2 drone (with Pix4D Mapper) and a Paracosm PX-80 scanner, respectively. The scanned 3D point clouds were pre-processed in CloudCompare (including de-noising, filtering, and segmentation) and then the composite sources were registered and merged. The two types of point cloud data were then exported for simulations and further processing.

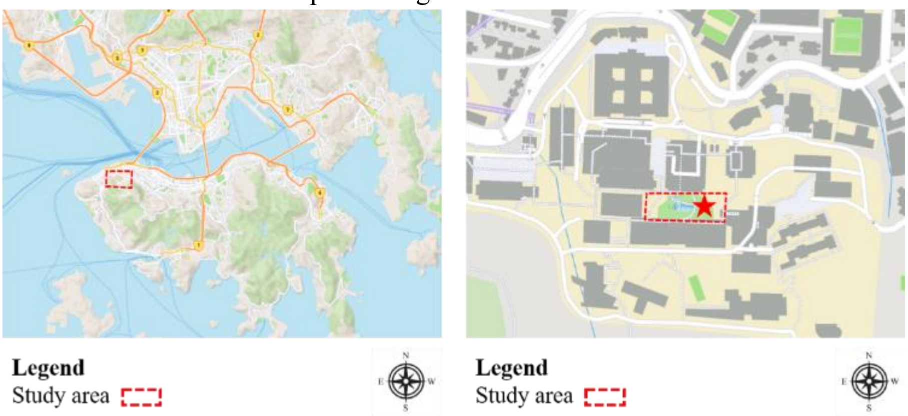


Figure 5. Location of study area

The voxelization process was coded on the *Spyder IDE* environment, which reads the full 3D greenery data (*.las* format). The selection of voxel size significantly impacts the spatial structure and volume of the vegetation (especially tree canopies). In general, larger voxels produce faster visualization results but only summarize the trees' structural information. In contrast, smaller voxels can convert more comprehensive vegetation information but require a longer time [8]. For this experiment, the transformed voxel model was set up at 0.5m resolution to balance computational time with the abundance of greenery information, as shown in Figure 6.

Lastly, simulations were based on *Rhino/Grasshopper3D*, with an open-source environmental plugin named *Ladybug V.1.5.0*. The daylighting engine in *Ladybug V.1.5.0* follows ray-tracing algorithm from *Radiance* and combines imported weather data files (*.epw*) to calculate readable plots as well as interactivity data. [9] In the ray-tracing algorithm for computing daylight, the following integral equation enables recursive evaluation for testing points on each surface [10]:

$$L_r(\theta_r, \emptyset_r) = L_e(\theta_r, \emptyset_r) + \int_0^{2\pi}\int_0^{\pi} L_i\,(\theta_i, \emptyset_i)\rho_{bd}(\theta_i, \emptyset_i; \theta_r, \emptyset_r)|\cos\theta_i|\sin\theta_i\, d\theta_i\, d\emptyset_i \quad (1)$$

Where:

θ means the surface normal polar angle;

$\emptyset$ means the surface normal azimuthal angle;

$L_e(\theta_r, \emptyset_r)$ is the emitted radiance;

$L_r(\theta_r, \emptyset_r)$ is the reflected radiance;

$L_i(\theta_i, \emptyset_i)$ is the incident radiance;

$\rho_{bd}(\theta_i, \emptyset_i; \theta_r, \emptyset_r)$ is the function for bidirectional reflectance-transmittance distribution.

The greening model was imported into Rhinoceros in *.obj* format, and the surrounding built environment was obtained from OpenStreetMap (https://www.openstreetmap.org) by blender. The daylight experiment started by importing both geometries and local meteorological data (https://www.ladybug.tools/epwmap/), and then simulated direct sunlight hours in Hong Kong during the summer (June to August). It also measured the total sunlight hours, single simulation time, and green volume under different greening model accuracy.

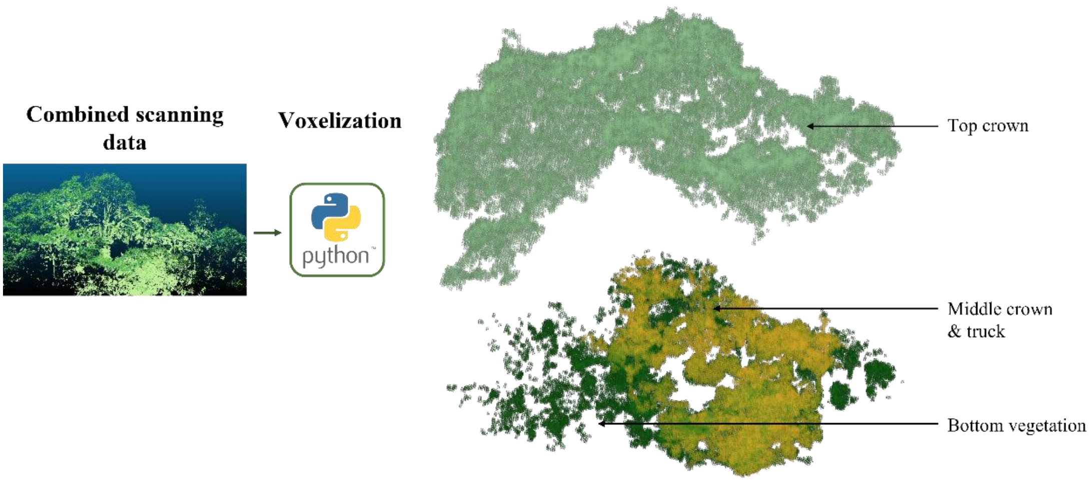


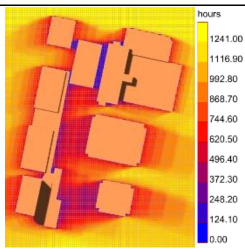
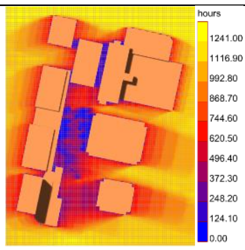
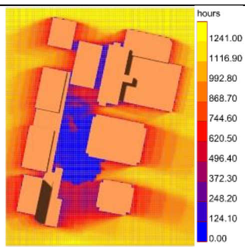
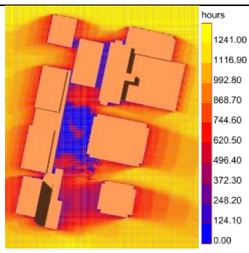
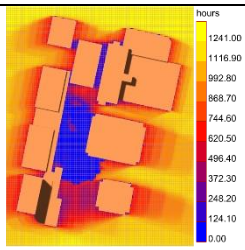
Figure 6. Voxelized 3D greenery model of the study area

3.2 Results

This experiment compares and analyses the results of five digital modeling simulations: the model of the built environment without greenery, the oversimplified proxy greenery model, the airborne/handheld scanned voxelized greenery model, and the hybrid voxelized greenery model.

The numerical simulations were compared with consistent *.epw* weather data, the target season (summer), and the surrounding built environment. Table 1 depicts the simulation results for the five greening precision models, as well as the greening volume, total sunshine duration, and simulation completion time. It can be observed that the integrated greenery voxel model demonstrates the lowest total solar exposure hours, which means that this model provides the largest area of shade.

Table 1. Comparison of radiation simulation results with varying accuracy models

Type	Experimental Subjects	Green Volume/m^3	Simulation Visualization	Total Radiation/h	Time/ s
1	No greenery model			596.63	40s
2	Conventional over-simplified proxy greenery model	3200		579.71	70s
3	The airborne scanned greenery model (no handheld, 0.5m resolution)	1841		561.46	75s
4	The handheld scanned greenery model (no airborne, 0.5m resolution)	3022.25		576.24	90s
5	The precise urban green volume model (This study, 0.5m resolution)	4863.25		560.38	100s

The experimental results indicated that registering two source point cloud data increased the overall volume of greenery by 34.2% over the traditional simplified version of the greening model. Moreover, with the increase of the projected area, the total radiation duration is correspondingly reduced by 3.33%. This sub-meter voxel model collects point cloud data from a multi-directional field of view, which complements airborne photogrammetry with handheld scanning data, and makes the numeric model more closely resemble real-world vegetation. This method boosts the precision of the digital simulation, contributing to further urban microclimate analysis. Furthermore, the voxelized greenery model offers an automated solution for quantifying greening volumes.

4 Discussion and future work

Urban greenery is commonly convinced to relieve urban heat, due to its function of providing shadows. [2] However, the quantity and density of urban forests can also impede the urban wind environment (especially in intensive development areas), causing an impact on the local microclimate [4]. The majority of computational simulations used for validation employ hypothetical greening models. These digital representations of vegetation are frequently replaced by empirical values or overly simple geometries, making the simulation results that do not accurately reflect the real urban environment [8]. This research proposes a technical solution for integrating scanned point cloud data from multiple sources, acting as the semantic enrichment of city information models. [5] Subsequently, a Python-based automated program efficiently converts the point cloud model into a sub-meter quantifiable voxel model. This voxel model can contribute to urban greening planning by raising the accuracy of numerical simulations without increasing the computational load considerably.

Nevertheless, this study also has some limitations. Firstly, the voxelized greening model was only presented at a resolution of 0.5m in the experiments, thus lacking comparative analysis of the impact of other resolution values of voxel models on environmental simulations. The optimal voxel resolution for specific urban morphologies (e.g., high density, low density, enclosed areas, semi-open areas, open areas) should be further investigated. Moreover, this study only employed point cloud processing software to align multi-source scanned data. A more intelligent and automated technique may be required for future experiments on complex urban environments to extend the model's applicability. Finally, the initial simulation validation in this test has focused on the shading effects of urban greenery, and future work will pay more attention to urban wind simulation (CFD) and outdoor thermal comfort studies.

5 Conclusion

Urban greenery has a positive impact on improving urban thermal comfort; however, the volume and density of the tree crown may also affect the urban microclimate. In recent years, numerical simulations have been frequently employed to validate and quantify the influence of greenery on urban outdoor comfort and environment, but lacking highly accurate vegetation models. In this study, the fusion of multi-source scanned greening point clouds (detailing the three-dimensional attributes of the top and middle crown layers, as well as the lower shrub vegetation) is proposed and automated to generate a sub-meter resolution voxelized greening model. This semi-automated technique enables the reconstruction of the urban forest from an actual physical environment at a low cost, thereby effectively boosting the accuracy and credibility of the environmental simulation. Future work includes optimal voxel resolution in urban environments with different densities and comprehensive urban microclimate simulations (e.g., CFD wind environment studies).

Acknowledgment

The work presented in this paper was supported by the Hong Kong Research Grants Council (RGC) (Grant No. T22-504/21-R).

References

[1] C. Rosenzweig, W. D. Solecki, S. A. Hammer, and S. Mehrotra, *Climate change and cities: First assessment report of the urban climate change research network*. Cambridge University Press, 2011.

[2] T. E. Morakinyo, K. K.-L. Lau, C. Ren, and E. Ng, "Performance of Hong Kong's common trees

species for outdoor temperature regulation, thermal comfort and energy saving," *Building and Environment,* vol. 137, pp. 157-170, 2018/06/01/ 2018, doi: https://doi.org/10.1016/j.buildenv.2018.04.012.

[3] B. Chen *et al.*, "Beyond green environments: Multi-scale difference in human exposure to greenspace in China," *Environment International,* vol. 166, p. 107348, 2022/08/01/ 2022, doi: https://doi.org/10.1016/j.envint.2022.107348.

[4] H. Oshio, T. Kiyono, and T. Asawa, "Numerical simulation of the nocturnal cooling effect of urban trees considering the leaf area density distribution," *Urban Forestry & Urban Greening,* vol. 66, p. 127391, 2021/12/01/ 2021, doi: https://doi.org/10.1016/j.ufug.2021.127391.

[5] F. Xue, L. Wu, and W. Lu, "Semantic enrichment of building and city information models: A ten-year review," *Advanced Engineering Informatics,* vol. 47, p. 101245, 2021/01/01/ 2021, doi: https://doi.org/10.1016/j.aei.2020.101245.

[6] M. Li, F. Xue, Y. Wu, and A. G. O. Yeh, "A room with a view: Automatic assessment of window views for high-rise high-density areas using City Information Models and deep transfer learning," *Landscape and Urban Planning,* vol. 226, p. 104505, 2022/10/01/ 2022, doi: https://doi.org/10.1016/j.landurbplan.2022.104505.

[7] F. Poux and R. Billen, "Voxel-based 3D Point Cloud Semantic Segmentation: Unsupervised Geometric and Relationship Featuring vs Deep Learning Methods," *ISPRS International Journal of Geo-Information,* vol. 8, no. 5, p. 213, 2019. [Online]. Available: https://www.mdpi.com/2220-9964/8/5/213.

[8] H. Xu, C. C. Wang, X. Shen, and S. Zlatanova, "3D tree reconstruction in support of urban microclimate simulation: A comprehensive literature review," *Buildings,* vol. 11, no. 9, p. 417, 2021.

[9] M. Pak, A. Smith, and G. Gill, "Ladybug: A Parametric Environmental Plugin For Grasshopper To Help Designers Create An Environmentally-conscious Design," *Building Simulation Conference Proceedings,* 2013.

[10] G. J. Ward, "The RADIANCE lighting simulation and rendering system," in *Proceedings of the 21st annual conference on Computer graphics and interactive techniques*, 1994, pp. 459-472.