3D Modelling of Vegetation from Optical and LiDAR Point Clouds for Inclusion in Basic Nationwide Built Environment Model

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Abstract

With the Czech Republic's impending "BIM Act" driving the creation of a basic built environment model, the study proposes a compliant workflow for incorporating 3D models of two key vegetation feature types from the fundamental geographic vector database: "Forest ground with trees" and "Significant or lonely tree, grove." Modelling relies on nationwide datasets, the digital terrain model, the digital surface model based on image matching of aerial imagery, and supplementary aerial laser scanning data.

For the forest features, the process comprised optical point cloud filtration and constrained Delaunay triangulation, resulting in height-extruded forest base polygons with canopy cover tops. The 3D representation uses *MultiSurface* geometry, recorded as a *PlantCover* object in CityGML/3DCityDB, and is in line with the LoD2 standard for buildings. For solitary trees, predefined prototypes were scaled and positioned based on individual tree detection and parameters extracted from point clouds. Features were mapped to the CityGML/3DCityDB *SolitaryVegetationObjects* class, utilizing *Implicit* geometry to optimize for data volume and visualization speed. While the digital surface model, generated from periodically acquired optical imagery, was sufficient for the forest features, aerial laser scanning data was superior in individual tree modelling. The number of extractable parameters increases with point density and is dependent on the platform used. However, the availability of such higher-density laser scanning data in Europe is limited and varies across countries and regions. The results demonstrate the generation of LoD2 compliant 3D models from nationwide datasets for both vegetation feature types, visually enriching the basic built environment model.

1. Introduction

The contemporary drive toward digital twins, smart cities, and building information models necessitates the existence of extensive built environment 3D geometric models. Vegetation in these models is often underrepresented and overshadowed by the focus on buildings (Ortega-Córdova, 2018). Although it is an integral component of the urban environment and provides elementary ecosystem services by regulating the microclimate through shading and evaporative cooling, mitigating air pollution, and reducing urban noise (Münzinger et al., 2022). Inclusion of vegetation in built environment models is functional, not merely for visual representation but for, e.g., environmental modelling – shade provisioning (Li and Ratti, 2018) and urban heat analysis (Beil and Kolber, 2024).

Aerial laser scanning (ALS) point clouds have been utilized in forestry applications for years, starting with height estimation at the stand level (Nelson et al., 1988), individual tree detection and metric extraction (Hyyppä and Inkinen, 1999). Over the past decade, the application of ALS in urban forestry has increased (Li et al., 2019). Recent work connected to the modelling of trees in the built environment from LiDAR (Light Detection and Ranging) data deals with the automatic construction of 3D tree models in multiple levels of detail (de Groot, 2022), the use of deep learning (Kippers et al., 2021), or data fusion methods (Münzinger et al., 2022).

For 3D models of buildings and other objects, it is a common practice to work with different Levels of Detail (LoD). A widely adopted standard defined by the Open Geospatial Consortium works with five LoDs increasing in their geometric and semantic complexity. While LoD0 represents 2D building footprints, LoD4 comprises detailed 3D models with indoor features (OGC, 2012). Futhermore, a refined set of 16 LoDs (in line with the LoDs of CityGML) focusing on the grade of the exterior geometry of buildings has been developed, providing a stricter specification and allowing less modelling freedom (Biljecki et al., 2016).

However, urban vegetation is usually blandly mentioned, and no common standard exists. CityGML 2.0 specifies five LoDs aligned to geographic extents, defining only the occurrence and minimal size. A more complex classification introduces four explicit LoDs generated from 3D tree models derived from aerial LiDAR and raster-based data (Chen, 2013). Higher LoDs build upon previous ones: LoD0 offers 2D location and crown projection. LoD1 extrudes the projection to acquired height. In LoD2, a tree is generalized with a volumetric form reflecting the real world’s crown shape and an acquired crown base height. LoD3 specifies a model with branches, leaf textures, and species. A review of all previously proposed standards suggests Single Vegetation Object (SVO) and root LoDs to meet different adherence requirements and scales (Ortega-Córdova, 2018)

Extensive geometric 3D models of the urban environment are becoming increasingly popular for visualization purposes and are part of building information models (BIM) and digital twins. National Mapping Agencies (NMA) have started to adopt this trend. Switzerland, namely swisstopo, the Federal Office of Topography, as one of the first countries, possesses a detailed 3D building model covering the whole country. Every building has been digitalized with realistic roof shapes and overhangs, along with bridges, cable cars, forests, and individual trees. To describe the topography, all these objects rest on a digital terrain model (swisstopo, 2025). Another example is the Netherlands with its

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3D land registry (3d.kadaster.nl). While the basic 3D model does not include vegetation, individual cities, such as The Municipality of Rotterdam have their own model freely available, including street furniture and, e.g., trees (3drotterdam.nl). The concepts of three-dimensional real property have been the subject of increased interest in land use management and research since the late ‘90s, and currently countries are at different stages of 3D cadastral implementation (FIG, 2018).

In the Czech Republic, in accordance with Act No. 330/2025 by the Ministry of Industry and Trade on the management of information on construction and the built environment and on amendments to certain other acts – abbreviated as the “BIM Act” – a unified legal framework for the effective management of information throughout the entire life cycle of a building must be developed.

Substantial preparatory work is required to achieve compliance with the new law before it takes effect on January 1, 2027. The NMA, Land Survey Office, has been entrusted with the creation and management of a basic nationwide model of the built environment, including the integration of existing geographic data in 3D. One output will comprise a 3D geometric model for building visualization, a digital representation of the physical and/or functional part of building design in a structured form. Regarding the LoD, national standards drawing inspiration from other European countries are/will be defined. However, it is expected that the basic 3D model will correspond to the standard LoD2 as defined by Bijlecki (2016). (Ministry of Industry and Trade, 2017)

While vegetation is not explicitly mentioned in the law, its inclusion in the basic 3D geometric model is envisioned mainly for visualization purposes, as inspired by built environment models from other countries/cities. Vegetation features are also part of the Fundamental Base of Geographic Data of the Czech Republic (ZABAGED®). In accordance with the aforementioned visions, the study's aims are as follows:

1. Forests: Propose a workflow for automated 3D modelling of the feature type “Forest ground with trees (categorized)” from optical and/or laser scanning point clouds at the national scale. While countrywide laser scanning was done once in 2010-13, new aerial survey imagery is acquired every other year for half of the Czech Republic, enabling the generation of an up-to-date digital surface model through image matching. The models should correspond with LoD2 to fit in the basic 3D built environment model and comply with the CityGML/CityJSON standards to be stored in a 3D City Database.

2. Solitary vegetation: Generate 3D models of the feature type “Significant or lonely tree, grove” and assess the suitability of point cloud data from different platforms for the automatic individual tree 3D reconstruction. Preferred is the use of implicit geometry, defining a database of parameterized prototype tree models, and transforming them based on identified dimensions of the individual trees. The LoD2 and CityGML/CityJSON standard requirements remain.

2. Area of Interest

The area of interest is the Czech Republic, a country in central Europe, covering an area of approximately 78 871 km². A smaller area in the eastern part of Bohemia, the Pardubice region, was chosen for testing purposes of the pipelines. However, the proposed methods should be applicable for the entire country, as they were developed on nationwide datasets from the Czech Office for Surveying, Land and Cadastre.

3. Methodology

3.1 Datasets

3.1.1 Digital Terrain Model (DMR 5G): The digital terrain model of the Czech Republic of the 5th generation represents the natural or human-modified earth's surface in the form of heights of discrete points in a triangulated irregular network (TIN) (ČÚZK, 2025a). It is based on aerial laser scanning data acquired in the years 2010 to 2013 with the LiteMapper 6800 system equipping the RIEGL LMS – Q680. Since 2016, the model has been updated locally with data from the Leica ALS80 scanner. Automatic robust filtration to separate the ground points was done in the SCOP++ software, followed by manual corrections in problematic areas. The average point density reaches 1.5 pts/m^2. In terms of accuracy, a complete mean height error of 0.18 m in exposed terrain and 0.3 m in forested terrain has been declared based on reference data. The data is distributed in the *.laz format free of charge through the ČÚZK geoportal under the Creative Commons CC BY 4.0 license. One can choose between the national bound coordinate system S-JTSK / Krovak East North (EPSG: 5514) and above sea level heights in the Balt height reference system after leveling (Bpv) and the ETRS89 / UTM zone 33N (N-E) coordinate system (EPSG: 25833) with normal heights EVRF2007. (ZÚ and VGHMÚř, 2016)

3.1.2 Digital Surface Model (DMP OK): The digital surface model of the Czech Republic based on image matching of aerial imagery represents the georelief, including all natural and human-made objects. It is a new product that will gradually replace the outdated digital surface model derived from laser scanning data. Currently data for the east half of the country is available, while the west part will be supplied in 2026 after the acquisition of new images for the periodically updated national orthoimagery. Image matching was done in the SURE Aerial software package, followed by point cloud filtration and classification processes in LAStools. The dataset is available in the form of a grid-like *.laz point cloud with a GSD of 0.2 m. The coordinate systems and licensing of data correspond with the Digital Terrain Model (DMR 5G). Unlike laser scanning data, aerial imagery is primarily acquired during the growing season, capturing the entire forest canopy. One of the main benefits lies in the possibility of regular updates based on an even/odd year acquisition scheme.
(ZÚ, 2025)

3.1.3 Aerial Laser Scanning Point Cloud: For the project of the Digital technical map, ALS data with a higher mean point density of 10.2 pts/m^2, was acquired over the Pardubice region. At the turn of 2021 and 2023, during the leaf-off season, the Riegl VQ-780ii-S LiDAR sensor was flown mounted on a Tecnam P2006T aircraft approximately 1700 meters above terrain. According to the data supplier, after relative strip alignment and absolute orientation, the average height mismatch was 0.08 and 0.02 m, respectively. The point cloud was processed in the TerraScan software package, harnessing both the automatic filtration of low and high noise points and user-adjustable parameters as well. Manual corrections were applied in problematic areas. Files were supplied in the *.laz format in the S-JTSK / Krovak East North coordinate system and Bpv heights.

3.1.4 Planimetric ZABAGED® Features: ZABAGED® is a vector geographic digital model of the territory of the Czech Republic comprising a wide range of features from different thematic classes, such as land cover, buildings, transport, hydrology, energy, environmental protection, etc. The abovementioned digital terrain and surface models also form a part of it. Planimetric features are represented by 2D vector components and a descriptive component containing qualitative and quantitative information about features (ČÚZK, 2025b). Of interest were two feature types (Table 1), namely “Forest ground with trees (categorized)” and “Significant or lonely tree, grove”. The dataset was provided as a *.shp, however, multiple export and service formats are openly accessible through the geoportal. (Land Survey Office, 2025)

Forest ground with trees (categorized)	
Definition	Soil covered by a plant community, the determining component of which are forest trees forming cover. (Categorized according to the height and type of vegetation.)
Geometric determination	area centroid (area)
Positional accuracy	$m_p = 5.0$ m
Geometric data source	aerial survey photos, ortophoto, field recognition, (NLI)
Attributes	unique identifier, (height category, species category, date of NLI categorization)
Size restrictions	area ≥ 500 m^2, width > 10 m
Significant or lonely tree, grove	
Definition	a (group of) tree(s) growing outside the forest land, visible from afar, with orientation significance
Geometric determination	point
Positional accuracy	$m_p = 2.0$ m
Geometric data source	aerial survey photos, ortophoto, field recognition
Attributes	vegetation subtype, name, unique identifier
Size restrictions	area < 500 m^2

Table 1. Description of selected vegetation features (ZABAGED®).

3.2 Forest Ground with Trees

The methodology for the “Forest ground with trees (categorized)” feature type comprises three successive steps (Figure 1). Initially, the Digital Surface Model (DMP OK) point cloud is filtered and thinned, followed by 3D geometric reconstruction of the forest canopy in a TIN form and integration into a 3D built environment model through the open data scheme CityGML (3D City Database adoption).

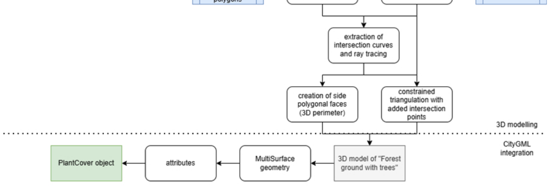

Figure 1. Schematic overview of the proposed workflow.

Point clouds were processed in the LAStools software package, and scripting was done in Python 3.11 with PyVista as the main 3D library.

3.2.1 Point Cloud Filtration and Thinning: From the Digital Surface Model (DMP OK) only points being classified as high vegetation (ASPRS standard class: 5) were extracted. Outliers and noise were removed, and the point cloud was thinned to obtain only the canopy cover/tops (Figure 2) – points representing the 95th height percentile in a 1 x 1 m grid. Subsampling using adaptive thinning took place, i.e., removal of points that do not cause deviation of the TIN a set distance (0.1 m) from the original. To reduce data volume even further but still maintain sufficient detail, only the highest point in a 2 m grid was subsequently extracted. The optional parameters can be adjusted based on the required amount of detail of the canopy cover.

Figure 2. Canopy cover point cloud – result of filtration and thinning of the Digital Surface Model (DMP OK).

The output canopy cloud was clipped with the “Forest ground with trees” polygons, which were previously converted from multipart to single part and buffered by 10 m in GIS. Each forest feature was then saved as a separate *.txt file with X, Y, and Z coordinates of points falling into its polygon. The name of the file corresponded to the unique identifier attribute.

3.2.2 3D Modelling: For the process of 3D modelling (Figure 3) of the forest features, the canopy cover points were triangulated along with a new input, the Digital Terrain Model (DMR 5G) point cloud. The “Forest ground with trees” polygon was extruded and capped to create a watertight surface for clipping. In an ideal case, both TIN layers would now be trimmed based on the intersecting extruded body; however, this proved to be difficult, as it wasn’t possible to clip the triangle ’s midsection.

Therefore, intersection curves with each layer were derived, and points forming both curves were merged and ordered. When projected back into 2D, they formed a continuous boundary line string of the same shape as the forest polygon, but with added edge points. Now, the common boundary line string could be ray traced back to the canopy cover and digital terrain TINs, and intersection curves were recalculated. The coordinates of points forming the intersection curves were used as vertices to create edges between adjacent points and faces between individual edges.

This procedure resulted in an extruded forest polygon (3D perimeter) trimmed by the canopy cover and digital terrain model from above and below, respectively. The last step comprised constrained Delaunay triangulation of the original canopy cover point cloud with added intersection points and using the top intersection curve as the boundary. This layer was combined with the 3D perimeter to create the final model of the “Forest ground ground with trees”.

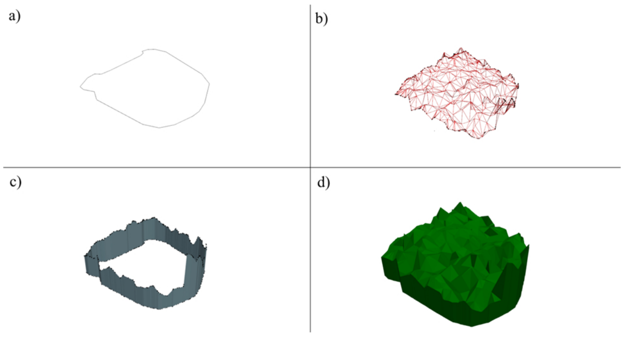

Figure 3. Simplified illustration of the 3D modelling process – a) forest base polygon; b) forest canopy point cloud and constrained TIN; c) polygonal faces and intersection points; d) resulting PlantCover object.

3.2.3 CityGML/3D City Database Compliance: CityGML defines a conceptual model and exchange format for the representation, storage and exchange of virtual 3D city models (OGC, 2012). The 3D City Database (3DCityDB) maps the CityGML data model to a general database design while making a few simplifications and customizations. It offers a free and open-source package consisting of a database schema and a set of software tools to import, export, manage, analyze, and visualize virtual 3D city models (Yao et al., 2018). 3DCityDB v4, which works with the widespread CityGML 2.0 version, was utilized. (3DCityDB v5 with support for the current CityGML 3.0 standard was released in March 2025 after the completion of the presented methodology. V4 is still in function and available in maintenance mode for an extended time period (TUM, 2025).)

CityGML’s vegetation model makes a distinction between solitary vegetation objects like trees and vegetation areas such as forests (3DCityDB Team, 2024a). For modelling of the feature type “Forest ground with trees”, the specific vegetation class *PlantCover* was used. *PlantCover* is subject to the abstract *_CityObject,* inheriting all attributes and at the same time adding specific new: class (plant community), usage, function (e.g. national forest) and averageHeight. (3DCityDB Team, 2024a). The geometry types in 3DCityDB are handled in a simplified way; all surface-based geometries are stored as polygons, which are aggregated to *Multi** and *Composite** types. This representation corresponds to Boundary Representation (B-Rep) (3DCityDB Team, 2024b).

The base structure of a CityGML file respecting the requirements of 3DCityDB was created with the help of the Python library lxml and for each “Forest ground with trees” feature, a single *cityObjectMember* class *PlantCover* was inserted. Attributes were extracted and written from the feature shapefile and *.laz point cloud, namely object_id (unique identifier), height (vegetation height), type (species category), gps_time_min, and gps_time_max. The *MultiSurface* geometry type was employed in LoD2. Each TIN triangle is then written as *surfaceMember* -> *Polygon* -> *exterior* -> *Linear Ring* -> *posList* (i.e., the coordinates of the triangle vertices). For the CityGML dataset validation, the official Importer/Exporter 3DCityDB client was run in Docker.

3.3 Significant or Lonely Tree, Grove

The “Significant or lonely tree, grove” feature type had to be treated differently as it is defined in a point-wise matter in ZABAGED®. The aim of the reconstruction was to represent each tree as a separate 3D model, in a realistic form, but still conforming to LoD2. The individual steps comprise point cloud normalization, individual tree detection, crown segmentation, and tree parameter extraction. Several tree prototypes were manually modelled and, in compliance with CityGML/3DCityDB used as implicit geometry for scaling and placement (according to the extracted tree parameters) into the 3D built environment model. For point cloud processing, the R package LiDR, focused on manipulating and visualizing airborne laser scanning data for forestry applications, was utilized (Roussel et al., 2020).

3.3.1 Individual tree detection and parameter extraction: The existing classification of the Digital Surface Model (DMP OK) and Aerial Laser Scanning Point Cloud was leveraged, and all classes apart from high vegetation (ASPRS standard class: 5) were filtered out. Using the Digital Terrain Model (DMR 5G), the point clouds were normalized and rasterized to obtain a Canopy Height Model (CHM). The CHM was smoothed with a kernel to remove small-scale variations and enhance tree canopies.

For every “Significant or Lonely Tree, Grove” feature, a 20 m buffer was formed around the point coordinates. The buffer polygon was then used to clip the area of interest, on which the subsequent individual tree detection and segmentation was performed. CHM-based local maxima Voronoi tessellation (Silva et al., 2016) was applied to the CHM. First, treetops (local maxima) are detected by a moving window with a fixed window size. An initial buffer with a set diameter calculated by multiplying the tree height by 0.6 (default parameter which can be adjusted by the user) is formed around the detected treetops; the data is further split through Voronoi tessellation. After each tree polygon is isolated, pixels with an elevation lower than exclusion (0.3) multiplied by the tree height are removed. The crown delineation can then be projected back on the point cloud, segmenting the individual trees (Figure 4).

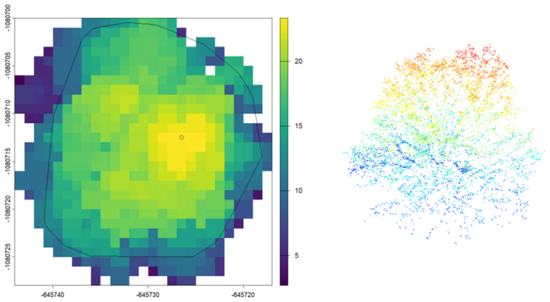

Figure 4. Detected treetop and delineated crown on a CHM; segmented individual tree point cloud.

From the 2D crown delineation and segmented individual tree point cloud, standardized geometric parameters were determined. Tree height was obtained as the length of the Z coordinate and the crown diameter as a minimum bounding geometry in the form of a circumscribed circle formed around the convex hull. The crown base height is equivalent to the stem height and was approximated as the 5th percentile of the z-values (Münzinger et al., 2022). The tree position was preserved from the corresponding ZABAGED® feature, however, the z coordinate of the tree base needed to be calculated. This was done by projecting the x and y coordinates on the Digital Terrain Model (DMR 5G) and extracting the relevant height.

3.3.2 CityGML/3D City Database Compliance: Trees are modelled by the class *SolitaryVegetationObject* which, as in the case of *PlantCover,* is subject to the abstract *_CityObject,* inheriting all attributes and at the same time adding specific new ones: class (e.g. tree, bush, grass), species, usage, and function, height, trunk and crown diameter. (3DCityDB Team, 2024a).

A *SolitaryVegetationObject* is associated with the *Geometry* class representing an arbitrary GML geometry (by the relation *lodXGeometry*), or it may be defined by implicit geometry. Instead of storing multiple recurring objects, a single prototype geometry in a local coordinate system is referenced, leading to space efficiency and accelerated visualization speeds. The prototype is scaled by a 4x4 transformation matrix (translation, rotation, and scaling), and its position is defined by the base point of the object in the world coordinate system. (3DCityDB Team, 2024b)

Inspired by Münziger et al. (2022), five tree prototypes of different crown-to-stem height ratios (from 0.9:0.1 m to 0.2:0.8 m) were modelled in SketchUp (Figure 5). All prototypes had a unit size of 1 x 1 x 1 m, which enabled direct scaling. The diameter of the stem was approximated to make the trees look natural.

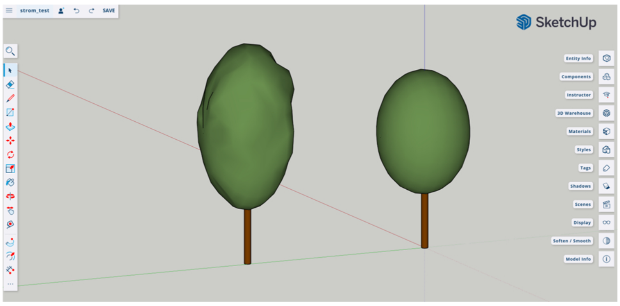

Figure 5. Tree prototype modelling in SketchUp.

Based on the determined parameters of the "Significant or lonely tree, grove" feature, the prototype with the closest matching crown-to-stem height ratio was referenced and scaled by tree height in the z direction and crown diameter in the x and y directions (Equation 1 - 4x4 transformation matrix). Additional parameters were stored as custom attributes. The prototype was then placed in the built environment model at the defined feature position.

$$\begin{bmatrix} S_x & 0 & 0 & 0 \\ 0 & S_y & 0 & 0 \\ 0 & 0 & S_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where S_x, S_y, S_z = scale factors in different dimensions

4. Results and Discussion

4.1 Forest Ground with Trees

A comprehensive approach for 3D modelling of the ZABAGED® feature type "Forest ground with trees (categorized)" from nationwide optical point clouds has been proposed. The resulting 3D model of multiple neighboring features is shown in Figure 6. TIN geometry represents the specific vegetation class *PlantCover* and is compliant with CityGML/3DCityDB. No CityGML extensions were implemented apart from the use of generic attributes.

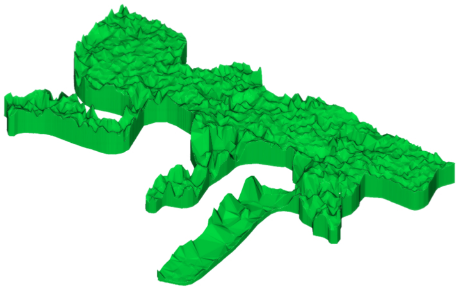

Figure 6. "Forest ground with trees" 3D TIN model.

The vegetation 3D models are mounted straight on the Digital Terrain Model (DMR 5G) without any gaps or overlaps. However, some features had a few missing triangles in the canopy cover TIN, which could potentially be fixed by a gap filling algorithm (Attene, 2010). Apart from manual inspection, no further accuracy assessment was carried out, as the main purpose was to visually supplement the built environment model with vegetation. If any of the 3D models were to be used in, e.g., microclimate modelling, proper validation would have to be undertaken.

4.2 Significant or Lonely Tree, Grove

3D models of the "Significant or Lonely Tree, Grove" feature type (Figure 7) were obtained by a different approach. As trees have similar shapes, they can benefit from the use of implicit modelling in terms of visualization speed and data volume. Individual trees were segmented from the point cloud; their parameters were extracted and used to scale and position a matching prototype. The 3D models were of existing class *SolitaryVegetationObject*, compliant with CityGML/3DCityDB.

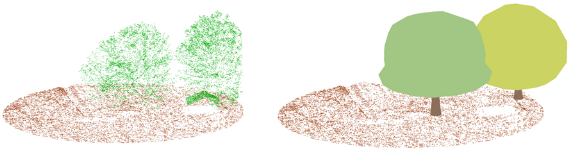

Figure 7. Original classified point cloud and resulting scaled tree prototypes according to the extracted parameters (height: 23 and 25 m; crown diameter: 22 and 20 m).

Prototypes with varying crown-to-stem height ratios were designed. All the crowns had a basic elliptical shape, not distinguishing between species, as the ZABAGED® database has no such attribute. Nevertheless, the majority of significant trees in the Czech Republic is deciduous (AOPK, 2025). Multiple other species prototypes can be simply modeled, or it is possible to exploit existing platforms offering low, high poly, and realistic 3D tree models (Sketchfab, free3D, xfrog, Globeplants*)*. A simple method of converting a tree point cloud into an accordingly shaped 3D model is slicing. The tree gets sliced at 0%, 25%, 50%, 75%, and 100% of its height and dimensions/ratios on each slice can be used to choose and scale the appropriate prototype (Kippers et al., 2021). Other tree parameters, which are not even measured in the field, can be computed using allometric equations (Coombes et al., 2019).

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4.3 Test area and scalability

The test area was approximately 144 km^2, but the workflow was developed on nationwide datasets only and can be upscaled to cover the entire country. Its usability is dependent on the availability of base vector data and optical/laser scanning point clouds. CityGML can be extended with additional generic *CityObject*s or an Application Domain Extension to meet the needs of various application purposes.

4.4 Level of Detail

The underway basic nationwide model of the built environment (for the Czech Republic) is supposed to be in LoD2, meaning the 3D models of vegetation features should adopt this direction. CityGML standard specifies five LoDs; LoD2 is for the city scale (OGC, 2012) and buildings are usually modelled as extruded polygons with simplified roof shapes, where the object’s parts can be modelled in multiple semantic classes (Biljecki et al., 2016).

PlantCover specification in LoD2 states only the minimum size of 5x5 m. The proposed 3D visualization of the “Forest Ground with Trees” feature is in line with the CityGML standard, exploiting and matching the regulations set for buildings. Forest polygons are extruded, and a generalized triangulated canopy cover is used for the top instead of a roof. The swisstopo 3D building model (swisstopo, 2025) uses individual tree models even in forested areas. The 3DCityDB scheme does not allow representing PlantCover by means of implicit geometry (3DCityDB Team, 2024a), hence, a *Multisolid* geometry would have to be used, resulting in large and complex datasets with high 3D graphics requirements.

For *SolitaryVegetationObjects* in LoD2, CityGML specifies the minimal height of 6 m and the use of prototypes. Others suggest (Figure 8) a generalized volumetric form reflecting the real-world’s crown shape (Chen, 2013); a 3D model of the main trunk and branches with known position, height, and diameter at breast height (Liang et al., 2016); minimal size specifications including nominal sizes based on standard ratios of tree components; a simple 3D solid with coarse morphology (Zhang et al., 2022). The “Significant or Lonely Tree, Grove” prototype models meet the requirements of most of the referenced standards.

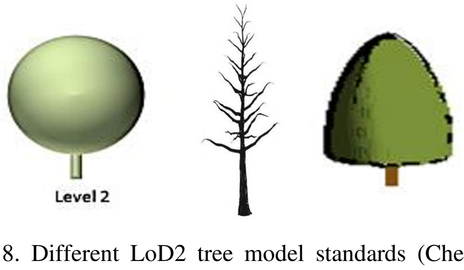

Figure 8. Different LoD2 tree model standards (Chen, 2013; Liang et al., 2016; unknown) in Ortega-Córdova (2018).

4.5 Optical vs. Laser Scanning Point Cloud

Modelling the “Forest Ground with Trees”, the optical point cloud was sufficient, as only the canopy cover/tops were of interest. Nevertheless, the Digital Terrain Model (DMR 5G) was still needed. DTM with sufficient spatial resolution and vertical accuracy, particularly in forested areas, is usually only available from laser scanning data (White et al., 2013). The methodology for 3D modelling of the “Significant or Lonely Tree, Grove” was tested on both the Digital Surface Model (DMP OK) and Aerial Laser Scanning Point Cloud. Comparable results were achieved in terms of individual tree segmentation for features that were isolated. If trees were clustered, the segmentation on the optical point cloud failed. In addition, the stem height could not be approximated from the Digital Surface Model

Optical remote sensing (e.g., stereophotogrammetry) primarily characterizes only the outer envelope of the forest canopy (Lindberg and Holmgren, 2017). While laser scanning has the capability to penetrate vegetation and record multiple returns, the reason why it is utilized in forest settings (Vosselman and Mass, 2010). Simultaneously, different sensors, platforms, and point densities enable the extraction of distinct individual tree parameters that may be applied to prototype scaling (Table 2).

Platform	**Aerial**		**UAV**	**Terrestrial**
Sensor	Optical	LiDAR	LiDAR	LiDAR
Point density	low	mid	mid/high	high
Tree parameters				
Tree height	Birdal (2017)	Gyawali (2022)	Chen (2022)	Srinivasan (2015)
Crown area/ diameter	-	Popescu (2003)	Panagiotidis (2017)	Srinivasan (2015)
Diameter at breast height	X	X	Calders (2015)	Srinivasan (2015)
Canopy base height	X	x	Zhou (2025)	Liang (2016)

Table 2. Overview of platforms/sensors and extracted individual tree parameters.

The availability of non-commercial nationwide laser scanning data in Europe varies across countries and regions (European Commission, 2021). In most cases, the point density falls below 5 pts/m^2 and data is not collected repeatedly due to high costs and time demands. Optical point clouds, on the other hand, can be generated from periodically acquired aerial survey images, making it possible to regularly update the models.

4.6 Individual Tree Detection Methods

CHM-based local maxima Voronoi tessellation (Silva et al., 2016) was utilized for individual tree detection and segmentation. The algorithm was chosen mainly due to its simplicity, ability to work with only the canopy cover, and existing availability in the open-source R package LiDR (Roussel et al., 2020). LiDR had implemented three other individual tree detection methods: Raster-based local maxima region growing (Dalponte and Comes, 2016), Point cloud level region growing (Li et al., 2012), and Marker controlled watershed algorithm (Chen et al., 2006). While the first two mentioned are image processing-based and require a rasterized CHM, the latter is statistical. Point clouds with higher point densities (under canopy ULS or TLS data) allow for the application of bottom-up individual tree detection (3DForest, TreeIso, 3DFin), where naturally separated trunks are identified first, based on their location, and the rest of the trees are segmented.

As mentioned above, the main purpose of the 3D models in this study is visual. For precise modelling, more attention would have to be paid to the segmentation of individual trees. Most of the algorithms are not robust and were primarily developed and tested for forests made of single or largely dominant species. For example, detection methods based on finding local maxima can be used for trees with a very evident pointed shape in the upper part of the canopy (conifers) but have lower performance for species that have a flat or irregular upper canopy (Balsi et al., 2018). The use of these methods on ALS data is still an unsolved research question, mainly due to their limited application in heterogeneous environments and the detection of lower layers of vegetation (Vandendaele et al., 2021).

5. Conclusions

The primary objective of the study was to 3D model two vegetation feature types, the “Forest Ground with Trees” and “Significant or Lonely Tree, Grove”, for inclusion in a newly emerging basic 3D geometric model of the built environment in the Czech Republic. The main purpose being visual supplementation of the nationwide building model. Existing datasets from the NMA, Czech Office for Surveying, Mapping and Cadastre, were leveraged, namely the digital terrain model and aerial laser scanning data. In addition, a new point cloud product, the Digital Surface Model (DMP OK) from image matching of aerial survey imagery, proved to be sufficient for modelling of the forests. One of the main benefits of the optical point cloud lies in the possibility of regular updates based on the aerial survey acquisition scheme; hence, overcoming the difficulties of repeating nationwide laser scanning due to high costs and time demands. For the forest features, an automated point cloud processing workflow was proposed, resulting in height-extruded forest base polygons with TIN canopy cover tops. The 3D representation uses *MultiSurface* geometry, recorded as a *PlantCover* object in CityGML/3DCityDB, and is in line with the LoD2 standard for buildings. Individual trees were modelled with implicit geometry as *SolitaryVegetationObjects* in CityGML/3DCityDB. Prototypes with varying crown-to-stem height ratios were transformed based on tree parameters (height, crown diameter) extracted from segmented point clouds. The usability of data from different sensors/platforms was assessed along with the application of individual tree detection methods. While the number of obtainable individual tree parameters increases with point density, the availability of usable, such high-density, nationwide datasets is still low and significantly varies across countries and regions.

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