MSc thesis in Geomatics for the Built Environment

Urban Vegetation Modeling 3D Levels of Detail

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URBAN VEGETATION MODELING 3D LEVELS OF DETAIL

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ABSTRACT

3D city models are now common planning and analysis tools. Urban vegetation as a feature in these models, however, is neglected overshadowed by the focus on buildings, so its inclusion in 3D city models is often symbolic. On the other hand, urban vegetation improves the comfort and social wellbeing of a city's inhabitants and is a resource for sustainable urban growth and an environmentally friendly resource for mitigating the negative effects of climate change, e.g., frequent heat waves, floods from storm downpours and extended dry periods. Trees also mitigate Urban Heat Island (UHI) effects. Urban vegetation's ecosystem services (ecoservices) as mitigation functions of pollution and negative effects of climate change have propelled research, studies, applications, and simulations that need data and 3D models of existing vegetation e.g., for spatial simulations, to assess the canopy cooling impact to surroundings or to identify areas prone to UHI. In view of these needs, urban vegetation in 3D city models is underrepresented. Guidelines for modelling vegetation are already provided in CityGML, the 3D city modelling standard, but they are insufficient for today's needs because it has vagueness and focuses mostly on built infrastructures.

In this research, 14 Single Vegetation Object (SVO) Levels of Details (LOD) and four root LODs are proposed. They target to meet different adherence requirements and scales. Their formulation is based on LOD specification approaches, and on a needs analysis that identified the vegetation models and data most commonly required in applications in the urban environment. Vegetation LOD description approaches include semantic 3D modelling standards, industry, and common practices of municipality users which are also GIS data providers.

Current vegetation LOD descriptions approaches fall into two different groups based on the geometry they adopted for their specifications: implicit or explicit, and no one approach fulfills identified needs. Acquisition techniques and demand in IT resources have influenced the definitions of vegetation LODs, the adoption of one geometry type or the other, and the wide use (or not) of certain LODs.

Refined SVO LODs specifications of this research combine the strengths of each group with descriptions that cover beyond geometric specifications. Refined LODs incorporate implicit components, underground representations and reconstruction LODs not defined by any approach. With them, most datasets can be represented by at least one LOD, and modelers can tell what LOD is possible to implement based on the data they already have. For acquisition, it is possible to tell what data is required for a particular LOD, and which LOD can be used to obtain data needed for an application. The broad spectrum of refined LOD allows them to meet different requirements.

A shadow analysis case study was done with implementations of refined SVO LOD specifications. Acquisition from aerial and mobile LiDAR data was done in a workflow that brought the 0D tree inventory of the municipality of Rotterdam to 3D models using mainstream and open source tools. The case study confirmed a quantitative impact in shadow duration and extent by each LOD indicating that each is independently differentiated. Volumetric and non-volumetric models had different shadow over and underestimation impacts. The study further highlighted the properties of the crown of the real-world object that help in choosing a LOD and gave insights offered by lower LOD models.

The implementation of the assorted LODs revealed that while much research has been done in acquiring vegetation parameters from LiDAR data, the many options, methods and algorithms are scattered necessitating a unifying process or tool.

ACKNOWLEDGEMENTS

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ACRONYMS

2.5D: 2D location with a height or elevation value

3D: Three Dimensional

ADE: Application Domain Extension

BHD Trunk diameter at Breast height diameter

Cd Crown diameter or dripline

CHM: Canopy Height Model

CO2: Carbon dioxide

DBH: Diameter at Breast Height of a tree trunk

DSM: Digital Surface Model

DTM: Digital Terrain Model

ESRI: Environmental Systems Research Institute

Hb: Baseline or elevation

Hc: Crown base height

Hf: First fork height

Hp: Height at crown perimeter

Ht: Tree top relative to Hb

LAI: Leaf Area Index

LIDAR: Light Detection and Ranging

LOD: Level of Detail

LSA: Leaf Surface Area

PC: Plant Cover

Rd: Root depth

Rsd: Root spread diameter

SVO: Single Vegetation Object

Td: Trunk diameter

TIN: Triangulated Irregular Network

UHI: Urban Heat Island

VOC: Volatile Organic Compound

1 INTRODUCTION

1.1 MOTIVATION

3D city models are used increasingly across multiple application domains (Biljecki et al., 2015). Similarly the demand for 3D data increases as realistic features of mountains, lakes, roads, etc. are included in 3D simulations and virtual settings (Smelik et al., 2014). Both are fueled by advances in computer graphics (CG) and remote sensing technologies as they allow the processing and capturing high quality 3D data. 3D city models are now planning and analysis tools, e.g., for mapping urban noise propagation, estimating potential solar energy (Hofierka et al., 2012; Stoter et al., 2008), or research platforms for 3D simulations, and as sensor devices are included, they turn into dynamic backbones for smart urban development (Kolbe, 2016; Schaller et al., 2016).

However, the evolution of 3D city model's usage has been for studies that focus on buildings. Urban vegetation in these models is often symbolic and limited for supporting 3D spatial analysis or for estimating impacts that canopy has on other objects. For example, in assessing the canopy shadow extent or duration as in this work's case study which results can be input to assessments in cooling surroundings and power consumption.

Urban vegetation is a resource for sustaining urban growth as cities expand and become denser from increasing population. Trees, parks and urban forests[1] make them livable. They bring psychological and medical benefits (Dzhambov et al., 2014; Ulrich, 1984; Woolner et al., 2010), improve social cohesion reducing crime (Kuo & Sullivan, 2001) and promote recreational and physical activities (Climate Proof Cities Consortium, 2014). However, as cities grow, hard surfaces increase diluting the benefits of existing vegetation (London et al., 2006; Rogers et al., 2015; Zhang et al., 2014). (2) Urban vegetation also provides ecosystem services (ecoservices) which aid in addressing pollution and negative effects of climate change. Climate change and urban vegetation ecoservices drive research, studies, and applications in need of existing urban vegetation 3D data, models, and simulations (Livesley et al., 2016; Rogers et al., 2015; Nowak et al., 2007). Many are reviewed in this work.

Currently urban vegetation in 3D city models is underrepresented. Potentially due to how vegetation features are specified for their inclusion. These specifications are referred to as Levels of Detail (LOD). Another potential reason is the different interpretations for the concept of LOD itself (Meng & Forberg, 2007).

In Computer Graphics (CG), LOD is a technique for balancing visualization quality with display performance. A LOD specifies the count of faces a model has. The same object is modeled at various LODs (Figure 1.1). For performance, the optimal LOD is chosen on the fly: objects closer to the viewer are rendered in more detail than those further away (Luebke et al., 2002). In 3D Geo-Information Systems (GIS), LOD relate to real-world objects and specify more than visualization. They can include semantics, object attributes, complexity, etc. The specifications do not include face counts. In GIS, typically a single LOD is chosen prior to modeling and is used as a procurement tool for acquisition requirements (Biljecki et al., 2015). In this work, a LOD communicates the degree of adherence to its corresponding reality so it can be used to specify data acquisition, modeling, generalization, and serve the exchange of spatial data in accordance with Biljecki et al. (2013).

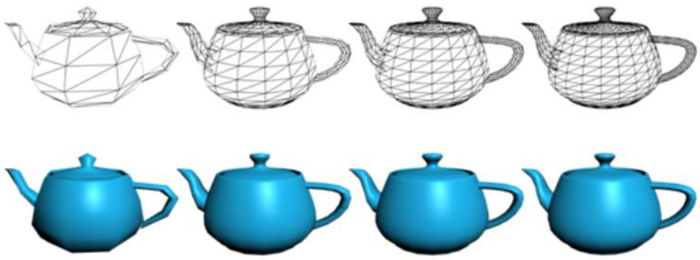


Figure 1.1: Four LODs of a teapot with respective polygon structures (Grant, 2016)

[1] An urban *forest* refers to ecosystems containing all trees, plants, and associated animals in an urban environment, both in and around a city (Sands, 2005).

1.2 PROBLEM STATEMENT

For representing and storing real-world objects in 3D city models, the de facto international standard of 3D Geo-Information is CityGML from the Open Geospatial Consortium (OGC). CityGML's LOD descriptions aim to serve multiple application domains with differing requirements. CityGML v2.0 specifies five levels aligned to geographic extents: LOD0 for a regional landscape, LOD1 for a city or region, LOD2 for a city district, LOD3 for an architectural project, and LOD4 for a landmark or architectural project (OGC, 2012).

When seeking to represent a tree, for example, the LOD specifications specify *None* for LOD0 (no specifications), *important* for LOD1, *prototype if taller than 6 m* for LOD2*, prototype if taller than 2 m* for LOD3, and *real form* for LOD4 (OGC, 2012). In a very probable interpretation of these specifications (Figure 1.2), one can observe that these specifications are limited. The example shows LODs that are hardly differentiated. They are adequate for visualization but not for quantitative analysis because adherence to the real-world object is limited despite the realistic appearance (shows leaves and branches) of LOD4's. CityGML is further described in Chapter 2.

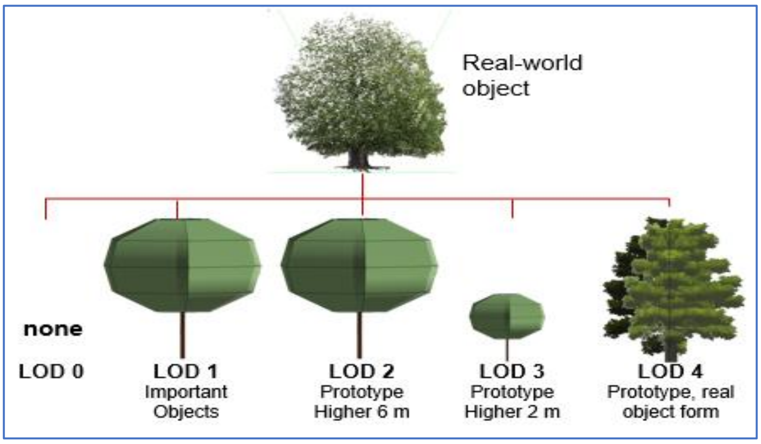


Figure 1.2: Example of an interpretation of CityGML LOD descriptions for trees.

LOD4 model is from ESRI-LumenRT (2014) vegetation model library

1.3 RESEARCH QUESTION AND METHODOLOGY

The inclusion of urban vegetation in 3D city models for purposes beyond visualization is hindered by vague and limited LOD descriptions. They should support the rising demand for spatial analysis, operations, or quantitate assessments concerning vegetation in the urban environment. The descriptions should also be an efficient platform for communicating requirements by providing consistent specifications, semantics and standardized terminology enabling information exchange among the different stakeholders and disciplines, and desirable compatible and integrable data, thus reducing the need for proprietary specifications which perpetuate data fragmentation hampering reusability and exchangeability of urban vegetation data.

The goal of this research is to provide improved vegetation LOD descriptions in more than geometric aspects to meet demands of current use cases. This research seeks to answer the following question:

What is the best approach for modeling 3D vegetation features for their use in the built urban environment?

In refining urban vegetation LOD specifications, the following sub-questions are relevant:

- How are current LOD specifications of urban vegetation being described?
  What are the driving factors that define vegetation LODs? What considerations (acquisition technique, requirements, practices, etc.) are taken in account?
- Which applications require 3D vegetation?
- What impact do LODs have in analysis in a practical implementation?

A shadow analysis case study is done with implementations of refined LOD specifications. Quantitative impacts in shadow duration and extent of different LODs are assessed.

This thesis work is relevant to landscapes where parameters of each vegetation object are acquired even if in a plant community, and to other regions and countries as further elaborated in the scope section.

Research was done for conceptualizing refined vegetation LODs and for their practical implementation for a shadow analysis case study (Figure 3.1).

The research approach for the formulation of refined vegetation LODs was mixed involving literature review, interviews and direct inquiries. Review was conducted of vegetation LOD descriptions developed with different perspectives such as international and national semantic 3D modeling standards, i.e., CityGML and IMGeo-CityGML, proposed vegetation LODs, descriptions from private modeling companies. Interviews and direct inquiries were conducted on vegetation LOD specifications from academia and proprietary entities. For the shadow analysis case study research was conducted for vegetation parameter extraction from LiDAR data, 3D modeling, and shadow assessments of vegetation. The realization consisted in bringing a 0D tree dataset to a 3D dataset targeting automation as much as possible.

For applicability, use cases that utilize 3D vegetation data and models including simulation packages were reviewed. Many in sustainable urban growth and climate change mitigation applications where urban planning, GIS and remote sensing meet with other domains, e.g., environmental studies, urban ecology, and forestry given that many concepts and needs overlap. Inquiries were done into common practices for incorporating vegetation objects in 3D city models, and for data used in managing city vegetation to GIS advisors, modeling practitioners, data and vegetation asset managers, urban planners, and underground asset managers of the municipality of Rotterdam and with officials of the Dutch tree registry. Through analysis of use cases and common practices, common needs of vegetation LODs were identified. Through analysis of current vegetation LOD description approaches, specifications that aid in meeting applications needs were identified. These findings served in identifying CityGML vegetation LOD shortcomings which were considered in the formulation of refined LODs. Other aspects considered in the formulation were geographic extents, accuracy, data availability, acquisition and vegetation models in publicly available datasets.

A summary of the methodology in this research in shown in Figure 3.1.

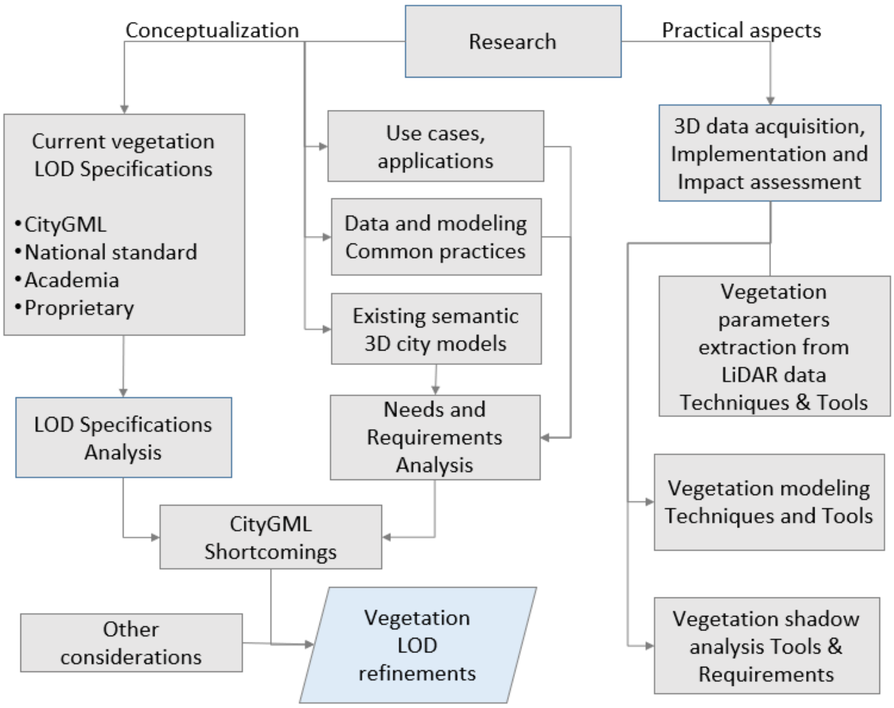


Figure 1.3: Overall research methodology

1.4 SCOPE AND THESIS STRUCTURE

Since definitions for a tree vary by domain, this work adopts i-Tree, (2018) definition. A tree can be ground cover or a shrub depending on the life stage. Some woody shrubs become trees when they mature. Others remain shrubs based on their species. A woody species is a young tree if its Diameter at Breast Height (DBH) is less than 2.54 cm and are taller than 30.5 cm. Shorter than 30.5 cm in height are considered herbaceous cover. Two main tree types are a deciduous and conifers. The former loses leaves in Winter and the latter is referred to as evergreen. There are variations (e.g., semi-deciduous and semi-evergreens) but in this research the distinctions are not made. A hedge is a tree class that is commonly grouped with others and trimmed similarly to shrubs. A bush is a generic term for shrubs and multi-stem plants.

This work targets to refine LOD specifications of stand-alone vegetation objects (SVO), i.e., a single tree, bush, shrub, or plant that is not in a group even though a SVO is equated to trees in many LOD description approaches, and most use cases focus on trees. This is because trees have the highest impact in the urban environment. The applicability and relevance of refined specifications are to landscapes with object-based vegetation data.

Groups of plants and forest stands which do not have individual data are out of the scope of this research but are discussed where appropriate; however, much of the initial realization workflow applies to the extraction of non-SVO vegetation features.

This research has been done in an internship with the 3D project team in the municipality of Rotterdam in the Netherlands. The data available for the case study is of trees managed and maintained by the municipality, yet this thesis work is applicable to other regions and countries despite the use of local data. In discussing canopy shapes to reflect the real-world object's species, one may wonder if they also reflect those of other regions, or countries. Canopy shapes are universal, and this is further elaborated in Chapter 4.2.

The realization of refined LODs aims to utilize existing mainstream software packages and open source tools as much as possible to facilitate further development of the workflow and integration with other 3D projects. Based on the municipality's data acquisition practices, LiDAR data is the 3D spatial data source.

This thesis is organized as follows:

- The present chapter introduces the motivation of this research and key theoretical aspects, the problem statement, the research question, the methodology and scope.
- Chapter 2 covers related work on LOD specifications, describes current vegetation LOD specifications and theoretical background on concepts used in the analysis.
- Chapter 3 overviews applications and common practices of urban vegetation models and data.
- Chapter 4 presents vegetation models and data needs in reviewed use cases, harmonizes terminology, analyzes current vegetation LOD approaches and identifies shortcomings.
- Chapter 5 introduces refined vegetation LODs, the approach taken in their formulation, requirements and recommendations.
- Chapter 6 presents the impact of refined LODs in a shadow analysis case study. It describes the data acquisition to realize each LOD, their integration into a 3D city, prior to presenting results.
- Chapter 7 answers the research question, discusses findings, and gives research questions and ideas for further investigation.

2 RELATED WORK

2.1 LOD DESCRIPTIONS AND FRAMEWORK FOR DEFINING LODS

There is abundant research in building LODs. Because in CityGML LOD descriptions of different models can be considered of the same LOD, some consider CityGML LOD descriptions as groups of LOD sub-levels. As the LOD variances proposed for LOD1 buildings by He et.al. (2012)**,** for LOD3 buildings by Besuievsky et al. (2014)**,** and for LOD0 to LOD3 buildings by Biljecki et al. (2016). The concept of expanding CityGML LODs with sub-levels is adopted in this research. Other city objects such as tunnels have benefited from an extended LOD specifications to create consistent multi-scale models (Borrmann et al., 2014). Few have focused on vegetation features LODs. Current specification approaches are described in this chapter.

Other LOD research has focused on aspects that impact building's LODs such as acquisition techniques (Wate et al., 2013), compatibility issues for integrating buildings from different sources (Döllner et al., 2005), or in separating exterior and indoor geometry with multiple semantic LODs (Benner et al., 2013)**.** Recently, in light of new applications in indoor navigation and energy performance estimation, extended geometric and semantic LODs for interior and exterior of buildings are proposed (Löwner & Gröger, 2016). Some acquisition techniques form LiDAR data are similar for both buildings and vegetation features such as extracting total heights from normalized Digital Surface Models (nDSM), but many are not given their different morphologies. Acquisition techniques and alternatives are briefly discussed within the case study chapter. Compatibility aspects for vegetation LODs are addressed in the definition of refined LODs. While there is no vegetation LOD equivalent to a building's interior, applications in outdoor navigation have prompted the use of certain vegetation representations. Further, use cases and applications have targeted to assess the impact of tree canopy shadow in energy consumption. Both are described and considered in the definition of refined LODs.

LOD description aspects not bonded to specific city objects relate to spatio-semantic coherence in 3D city models (Stadler & Kolbe, 2007), and in balancing economical aspects of multi-LOD data between cognitive and online bandwidth in the generation of LOD (Coltekin et al., 2011)**.** Lately, entire models of different LODs have been linked to derive a lower LOD while keeping relevant information (Arroyo Ohori, 2016). Currently, research for multi-object LODs generalization, i.e., buildings and roads is being conducted (Labetski, 2017). Spatio-semantic coherence and balancing economical and practical aspects are important considerations in the definition of refined vegetation LODs and they are discussed in Chapter 5. How balancing economical and practical aspects when choosing vegetation LODs are also aspects described within common practices in Chapter 3.

LOD specifications and concepts of LOD in GIS were analyzed by Biljecki et al. (2013) resulting in the formal definition of the concept of LOD adopted in this research. A framework for defining LODs of city objects was offered by F. Biljecki et al. (2014). It provides six metrics by which LODs of geo-datasets can be specified. They are described below, and their use is observed in the analysis of the different vegetation LOD descriptions:

- **Presence** (or not) to indicate if objects and their parts or components are modeled.
- **Complexity** of object in magnitudes (minimal sizes or lengths) at which objects are to be acquired while targeting to be as close to the real objects as possible.
- **Dimensionality** of objects or component's representation in terms of geometrical primitives (0D point, 1D for lines, 2D for surfaces, or 3D for volumetric objects), e.g., 3D buildings with 2D windows.
- **Appearance** may add features that are not acquired geometrically and semantically, e.g., windows on textured buildings can still be useful for rough measurements
- **Spatio-semantic coherence** attaches real world identities (window, door, etc.) to respective geometric entities (surface, points, etc.) of an object and its components in a one-on-one basis.
- **Attribute** or additional information at a dataset, object, or component level like wall material that is important to the application.

2.2 CURRENT VEGETATION LOD SPECIFICATIONS

Few approaches define vegetation LODs or target to improve CityGML's vegetation LOD descriptions. They are described below to provide background for their analysis in Chapter 4.

City Geography Markup Language Standard (CityGML) v.2 is an open geospatial information data model for urban landscapes. CityGML targets to represent relevant 3D urban objects in models that can be shared, integrated and re-used making them cost effective. It aims to describe objects, so virtual 3D city models support analytical tasks in diverse applications like simulations, urban data mining, facility management, and thematic inquiries. Semantic and geometric descriptions have separate hierarchies to support full spatio-semantic coherence to allow combining geospatial data from multiple sources (Stadler & Kolbe, 2007).

Vegetation objects are defined in the *Vegetation* thematic module as *Solitary Vegetation Object* (SVO) for standalone vegetation, and as *Plant Cover* (PC) for vegetation communities, e.g., a forest or grass (Figure 2.1).

- The geometric representation of SVOs can be with absolute coordinates as *explicit geometry*, or with *implicit geometry* which is a prototypical shape referenced and inserted on location points within a city model. PC objects are represented with *MultiSolid*/*Multisurface* or *solid* geometries.
- Appearance, e.g. material or textures are minimally specified for a SVO. PC can have surface-based appearance properties (Figure 2.1).
- Attributes of a SVO include *Total relative height*, *trunk diamete*r, *crown diameter*, vegetation *class* and *species*. The PC *averageHeight* attribute is used for its generalized representation.
- Other attributes are temporal and topological, e.g., *CreationDate, TerminationDate, relativeToTerrain and relativeToWater*, and *usage* (actual use) and *function* (intended or planned purpose of object).
- Attribute values can be added via code lists which can be linked externally.

The specifications above are not included in CityGML LOD descriptions in Table 2.1. LOD accuracy specification suggestions are applicable to all objects within the model and are considered as classifications by which the quality of a 3D city model dataset can be assessed, integrated, and compared.

Level of Tree-detail (LOT) -- Chen (2013) introduces four explicit SVO LODs and parameters generated from 3D tree models from aerial LiDAR and raster based data. Higher LODs build from 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. LOD4 specifies a model with branches, leaf textures, and species (Figure 2.2). PC is not described.

Single tree reconstruction -- Liang et al. (2016) review the use of terrestrial laser scanning for capturing 3D tree data and the use of reconstructed tree models for estimating attributes that are otherwise not measurable. This approach reconstructs trees and bushes underneath in five LODs starting with simple height and the trunk's Diameter at Breast Height (DBH) at LOD1. LOD2 adds position and a 3D model of the main trunk. LOD3 and LOD4 add branches, and 2nd and 3rd level branches, as well as, bushes below a tree. LOD5 adds leaves, and more detail in branches and surrounding bushes (Figure 2.3).

LOD of Trees, Alterra, Wageningen University -- Clement (2013) proposes explicit SVO descriptions with a parametrical SILVI-STAR tree model (Koop, 1989). Specifically, LOD0 includes tree crown projections. LOD1 adds the vertical height of the crown base. LOD2 is as LOD1 but reflecting the crown shape property. LOD3 switches from volumetric to 1st, 2nd and 3rd grade stem and branch structures, and LOD4 supplements LOD3 with textures of bark and leaves. PC is not described (Figure 2.3). Other characteristics that can be part of LOD descriptions are mentioned, i.e., levels of accuracy, time-based, physical/botanical information, geometry such as volume, influenced area (useful for micro-climate or shadow effect), underground space requirements, anticipated growth and seasonal visualization, etc. The approach further observes that while accuracy is not critical for visualizations, the realism of library models give the illusion of accuracy.

LOD and Trees, Wageningen University -- Rip (2013) argues that CityGML's vegetation LOD descriptions can include complex tree shapes and growth from which useful calculations are possible, e.g., tree canopy volume. Proposed vegetation LOD descriptions provide min. size specifications including nominal sizes based on standard ratios of tree components. PC is included in descriptions. SVO is excluded from LOD0 and LOD4. Only parametrical representations are described in LOD3. In LOD2, height classes are used in accordance to Dutch tree maintenance categories (Figure 2.4 and Table 2.2).

IMGeo is the Geography Information Model used as the Dutch national standard for storing, exchanging, maintaining, and using object oriented geographic information. Referred to as *BGT* in Dutch, it describes geographic objects in 2D in large-scale topography (1:500 to 1:5000). IMGeo-CityGML is the optional 3D implementation combining 2D, 2.5D and 3D geometries modeled as a CityGML Application Domain Extension (ADE) (Van den Brink et al., 2013).

Vegetation objects are included in LOD0 but excluded in LOD4 because the standard focuses on LODs that can be automatically generated or need little manual intervention (Blaauboer et al., 2013).

The SVO definition is expanded in contrast to CityGML's: a solitary object (SVO-tree), and those that form a single entity as hedges (SVO-hedge) are differentiated with a new *type* attribute (Geonovum, 2013). Other expansions include the addition of a SVO with explicit geometry descriptions using the SILVI-STAR's tree model (Koop, 1989). The standard also adds tree condition attributes (Table 2.4) to support data exchangeability with other Dutch public space data platforms (Rip & Bulens, 2013). SVO-tree is specified in two LODs: LOD2 which is based on 2D symbols or prototypical library models and LOD3 which is based on parametric models. PC attributes are also expanded, and PC and SVO-hedge are described in LOD0, LOD1 and LOD2 (Table 2.3).

Full spatio-semantic correspondence with class objects, elements, parts, components, attribute, and properties is required. Timeliness and accuracy descriptions require SVO data to be updated every 24 months with a 3D point coordinate position accuracy of 60 cm. Further, the accuracy for terrain heights can be set by users and by object. Temporal changes are supported, e.g., growth models for trees by species and for 3D models to portray realistic properties and parameters. Planned changes to existing objects in data and geometry are tracked, and the topography of future or historical objects is tracked with *plan* and *history* status. The topology of the 2.5D terrain requires integrating all 2D IMGeo objects (e.g., PC, and SVO-hedge) placed at ground level, above (e.g., a bridge) or below ground level (Geonovum 2017a).

Vertex Modeling (vertexmodelling.co.uk) offers 3D city models at LODs varying in accuracy and extents. Tree data is acquired alongside buildings during photogrammetric acquisition and added to city models as basic volumetric forms scaled to acquired dimensions, or with realistic forms using SpeedTree (speedtree.com) library models. Generic SVOs models are included with LOD2 buildings with an accuracy in height of 50 cm. City models with LOD3 buildings use LOD2 vegetation. City models with LOD4 buildings use realistic SVO models with the same accuracy of LOD3, and a fifth *Textured* LOD adds realistic vegetation which includes PC but not as an object rather as additional detail. LODs have preset geographic extent and accuracy levels defined as std. deviation in all three axes, but LODs can be tailored to client requirements (Figure 2.6).

Blom ASA (www.blomasa.com) is a GIS and data provider based in Norway with presence in 13 countries. Via proprietary technology, Blom 3D models offer five LODs and balance display and performance requirements for online consumption. LOD1 to LOD4 and Landmark LODs focus strictly on 3D buildings. Vegetation is part of the terrain even if added as a 3D object. The terrain in all LODs is an orthographic photograph draped over the ground surface. Location points for placing trees are optionally added to cartographic datasets optimized for outdoor navigation devices so they can be added to 3D city models. Realistic implicit vegetation models are included in interactive and virtual products (Figure 2.7).

ESRI or Environmental Systems Research Institute supplies GIS software and geodatabase management software. ESRI offers 3D vegetation models of different geometric complexity for different geographic extents (Figure 2.8):

- Large to medium geographic extents: low polycount model, e.g., billboard or 'fan'.
- Medium to small geographic extents: generalized or volumetric models or 'analytical'
- Small to single vegetation representation: detailed realistic models with leaves or 'model'

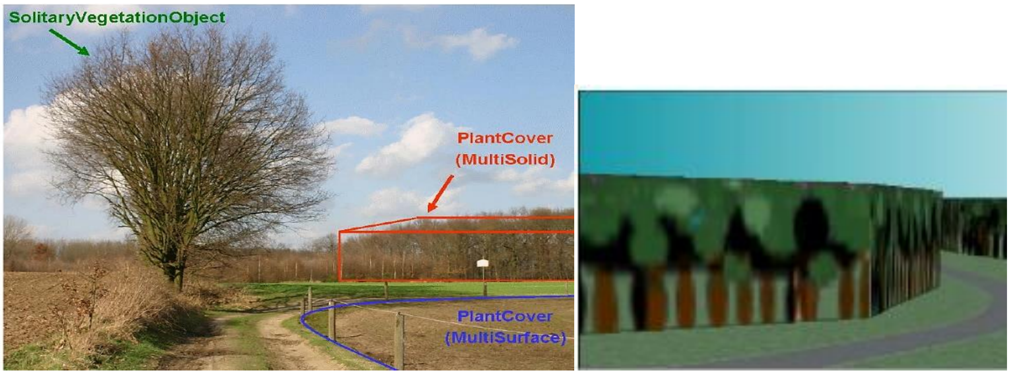


Figure 2.1: Left: CityGML vegetation classes Right*:* PC visualization of a forest (OGC, 2012)

Table 2.1: LOD 0-4 of CityGML with proposed accuracy as of 2003 (OGC, 2012)

	LOD0	LOD1	LOD2	LOD3	LOD4
Model scale description	regional, landscape	city, region	city, city districts, projects	city districts, architectural models (exterior), landmark	architectural models (interior), landmark
Class of accuracy	lowest	low	middle	high	very high
Absolute 3D point accuracy (position / height)	lower than LOD1	5/5m	2/2m	0.5/0.5m	0.2/0.2m
Generalisation	maximal generalisation	object blocks as generalised features; > 6*6m/3m	objects as generalised features; > 4*4m/2m	object as real features; > 2*2m/1m	constructive elements and openings are represented
Building installations	no	no	yes	representative exterior features	real object form
Roof structure/representation	yes	flat	differentiated roof structures	real object form	real object form
Roof overhanging parts	yes	no	yes, if known	yes	yes
CityFurniture	no	important objects	prototypes, generalized objects	real object form	real object form
SolitaryVegetationObject	no	important objects	prototypes, higher 6m	prototypes, higher 2m	prototypes, real object form
PlantCover	no	>50*50m	>5*5m	< LOD2	<LOD2
…to be continued for the other feature themes					

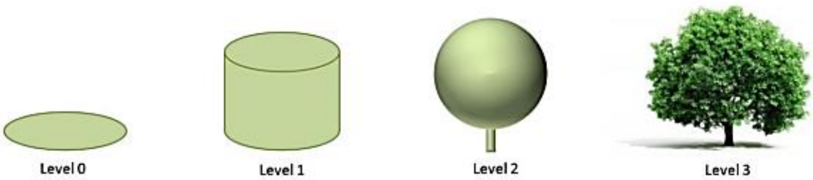


Figure 2.2: Level of Tree-detail (LOT) by Chen (2013)

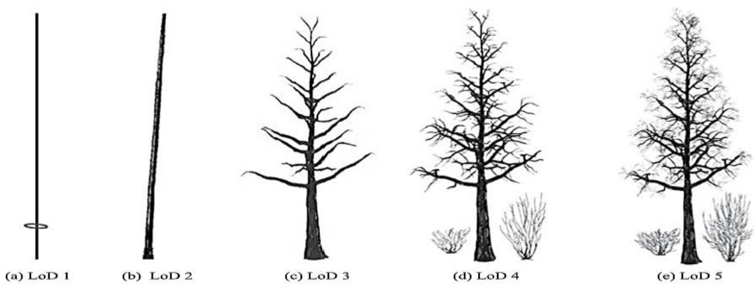


Figure 2.3: Single tree reconstruction LODs by Liang et al. (2016)

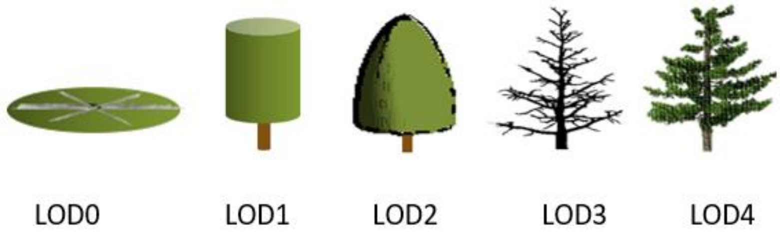


Figure 2.4: LOD of Trees examples

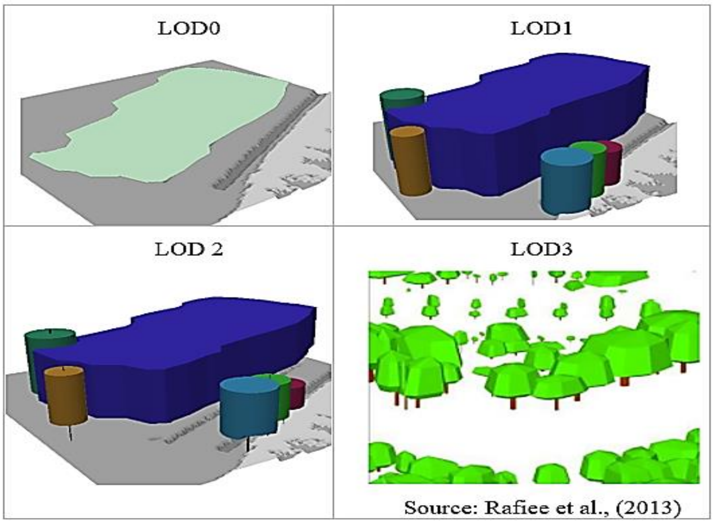


Figure 2.5: LOD and Trees LODs by Rip (2013)

Table 2.2: LOD and Trees vegetation LOD descriptions by F. Rip (2013).

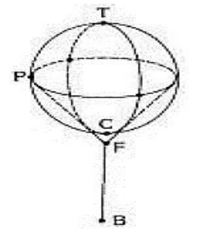
LOD0	SVO	• Points are not applicable to represent
	PC	• Min. size: >250 m in at least one direction • Footprint polygon of vegetation land use type
LOD1	SVO	• Min. size: > 3m. Measured height • Circle as tree crown projection, extruded to avg. height of 10m with avg. radius 5m.
	PC	• Min. size: CityGML 50x50m is to coarse for windbreaks or shelterbelts—Instead, use Dutch land use resolution of 25m in one direction • Polygons outlining tree groups and forest stands extruded to 10 m.
LOD2	Distinguish Individual vertical components and extent: trunk, crown, height and diameters.	
	SVO	• Using measured crown radius and height • Crown radius assigned to 1, 5 or 10 m • Crown: extruded circle to measured height from 3m above ground up to height class ranges*. Extrude from the ground up to 3m. • Trunk: circle radius of 1/20 of crown radius.
	PC	• Min. size: Polygons > 5*5m outlining tree groups and forest stands • Extrude from 1m height to avg. group/stand height
LOD3	SVO	• Detailed crown shapes: top height, horizontal extent, underside crown height. • Attribute deciduous or coniferous. • Tree model according to SILVI-STAR (Table 2.4).
	PC	• Polygons outlining tree groups and forest stands extruded from 1m height to individual heights of trees in group or stand.

* CROW tree maintenance height classes: 6 -9 - 12 – 15 – 18 – 24, > 24 m (Van Dijk, 2007)

Table 2.3: IMGeo-CityGML expansions to CityGML vegetation objects LODs

	PC	SVO
Attribute additions	• Location on slope (yes/no) • Classification by physical appearance and sub-classes.	• SVO type: Tree/Hedge • Explicit geometry parameters (Table 2.4) • Condition assessment (Table 2.4)
LOD 0	Extended: footprint polygon in 2.5D	Extended: SVO-hedge as line, or footprint polygon in 2.5D
LOD 1	No change, extrusion of LOD0 surface to avg. height	SVO-hedge: same as PC LOD1.
LOD 2	Extended: extrusion height can vary by area segments or within area	Extended: SVO-hedge as PC LOD2.
LOD 3	No extension or change.	Extended with explicit geometry

Table 2.4: SVO parametrical tree model, condition, and risk assessment (Rip & Bulens, 2013)

	ADE- SILVI-STAR	ADE-Assessed Tree
	• Height **T**op • Height **C**rown Base • Height **F**ork • Trunk **B**ase • Crown **P**eriphery • Tree base (not shown)	• Tree ID • Tree Height • Tree Position • Tree Assessed • Tree Safety Value • Tree Safety Measure

LOD2 (.1, .3, 1 Km sq.) LOD3 (.1 Km sq.) LOD4 (custom extent) Textured LOD (custom extent)

Figure 2.6: LODs that include vegetation (Vertex Modelling, 2017)

LOD1 LOD2 LOD3 LOD4 Navigation and Pedestrian LOD

Figure 2.7: Vegetation as terrain and SVO in a navigation and pedestrian LOD (Blom ASA, 2011)

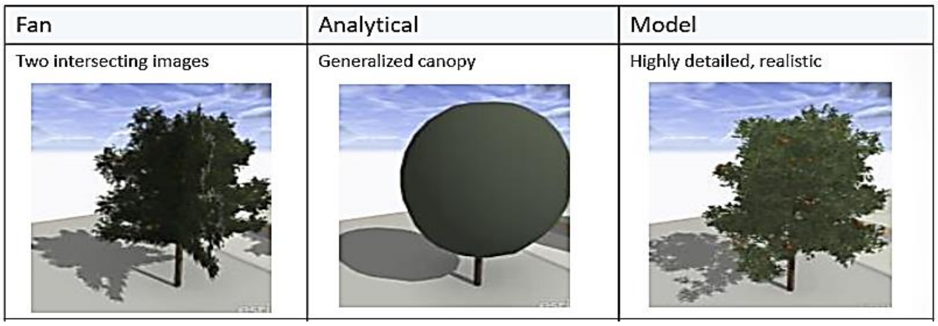


Figure 2.8: ESRI 3D SVO models (ESRI, 2014)

3 USE CASES AND COMMON PRACTICES

This chapter overviews applications and common practices in using urban vegetation models and data.

3.1 USE CASES AND APPLICATIONS

2D, 2.5D and 3D urban vegetation models and data are used in many applications, e.g., in managing and sustaining existing urban vegetation while ensuring that public space remains safe, in urban and landscape planning concerned with current and future aspects of urban growth, and in establishing environmental policies. Urban planning and policy making target to address the sustainability of continuous urban growth with negative effects brought by climate change at different scales. Policy making is further concerned with assessments and in setting goals that leverage and preserve urban vegetation ecoservices and, therefore, maintain the livelihood of their cities. These interrelated applications and the concepts in which urban vegetation plays a role are shown in Figure 3.1. Use cases within these applications are listed in Table 3.1.

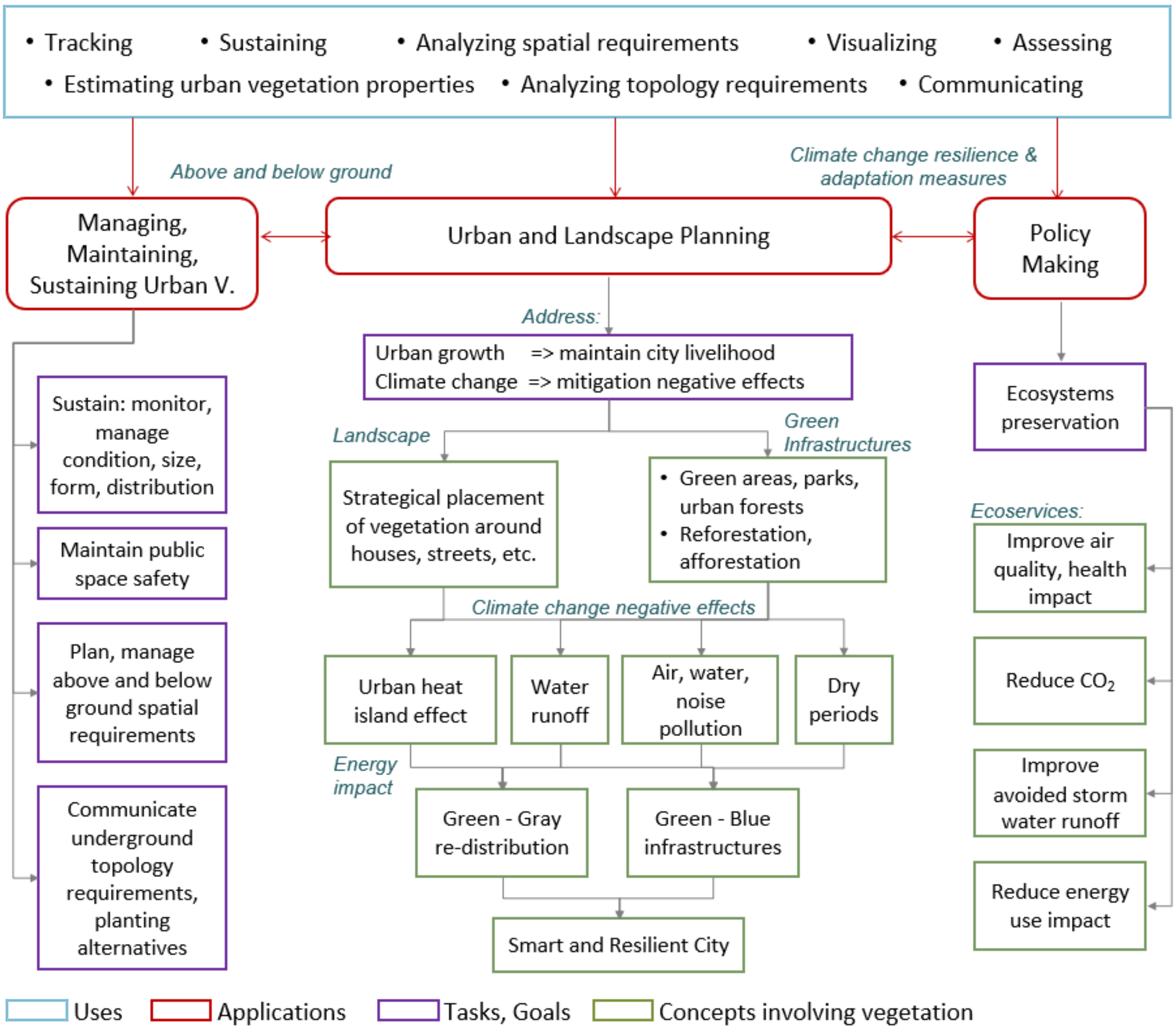


Figure 3.1: Applications and use urban vegetation models and data

In Table 3.1, use cases listed under *Models* require a 3D model of the vegetation to carry out spatial operations or for conveying information. An overview follows. Individual descriptions are available in the Appendix A.

Table 3.1: Applications in need of urban vegetation models and data

Application example	**Use case**
Urban Vegetation Management, Maintenance and Sustainability	1. Track street tree condition, progress and properties 2. Determine the ideal location of cell towers 3. Overhead rail maintenance Models for communication and analysis 4. Plan public work above and below ground 5. Communicate above, below ground topology regulations 6. Analyze tree diversity and distribution
Urban Planning and Landscaping	7. Streetscape spatial requirement estimation 8. Tree root spatial requirement estimation Models for communication 9. Promote sites and projects 10. Solicit collaboration and participation 11. Design alternatives decision making 12. Communicate site renovation /current-future changes Models in simulations 13. Mitigation of UHI from cooling effects of tree canopy 14. Urban vegetation avoided runoff contribution 15. Vegetation morphology and placement for noise reduction 16. Tree placement optimization for cooling houses and parking lots Models for spatial analysis 17. Identification of UHI prone areas 18. Tree shadow impact on solar panels 19. Identification of vegetation and building vertical relationships for urban ecology 20. Underground open space, object distribution assessment
Environmental Policy Making	21. Structure and ecoservices analysis 22. Ecoservices benefits analysis 23. Growth forecast
Tree Properties Extraction	Models 24. Tree crown properties extraction 25. Urban tree allometric model's refinement 26. Tree reflectance and directional light/radiation transmission 27. Tree structure tolerance to storm winds 28. Tree crown evapotranspiration estimation
3D City Models	Models 29. Vegetation models for 3D datasets enrichment 30. Inventory tree properties and data query

To ensure safe and risk-free public spaces, tree inventories are used by municipalities to monitor tree structure and condition (Zwiep, 2016), by province administrator for maintaining trees along roads, and by communication and tram services for assessing cell towers placement and maintenance, respectively (Pol et al., 2016).

Because trees can topple from root damage due to underground repair work, and roots can damage pipes, models of different dimensionalities are used to manage the impact of underground work on trees and to communicate spatial topology of trees with the underground network (Berger et al., 2009; Zwiep, 2016). Topology regulations are based on tree height classifications, life stage, function, etc. Planning and communicating spatial requirements for planting trees on streets and along roads involve assessing spatial requirements with environmental implications, and because of the extensive underground network (cables and heating, water, and sewage pipes, etc.), knowing root space requirements aid in assessing planting feasibility (De Goederen, 2012; Slee et al., 2015).

Planning and landscaping with climate change adaptation and resiliency involves addressing the increase of impervious surfaces because they intensify the harmful effects of climate change, e.g., more heat waves, storm downpours, and extended dry periods. Heat waves and storms are worrisome for areas already prone to Urban Heat Island (UHI)[2] effects or flooding (Climate Proof Cities Consortium, 2014) which become worse where vegetation is absent (US EPA, 2008; Wang & Akbari, 2016). Heat mitigation occurs with cooler surfaces from tree canopy shadowing, cool air from canopy transpiration and air flow due to introduced temperature differences in spaces. Storm water runoff mitigation occurs as trees, shrubs, plants, and grass slow down the water or absorb it and make the soil more infiltrating (Rogers et al, 2015). Other ecoservices that urban trees and urban forests bring to a city include the removal fine dust, air pollutants, and reduction of noise pollution. Indirectly, tree canopy has an economic impact in energy savings from heat mitigation, from cold air protection in Winter, and by reducing air pollution health related expenses (London et al., 2006; Rogers et al., 2015; Zhang et al., 2014).

The demand for urban vegetation data and models with different degree of adherence for spatial analysis and for input to quantitative impact assessments increases when ecoservices are seen as mitigation functions of heat, water runoffs, air pollution, and energy consumption reduction. All are climate change resilience and adaptation measures (EC, 2013; Van Wesenbeeck et al., 2016), e.g., simulations for optimizing tree placement for cooling and for noise reduction use 3D vegetation models.

Smart city project opportunities link selected ecoservices to designs of green infrastructures (parks, open green areas, etc.) to reduce impervious surfaces with energy efficiency measures or to combine blue-green infrastructures where excess water is stored for use in dry periods. All requiring spatial data and 3D city models (Gehrels et al., 2016; Schaller et al., 2015). Vegetation data and models that allow projecting and visualizing future changes of vegetation for communicating plans are then needed.

To determine cost-benefit of such large infrastructures, the value of ecoservices needs to be understood, e.g., how much air quality improvement are we getting from our trees? For this, the structure of city's trees and/or urban forests needs to be analyzed and their benefits quantified, e.g., how much CO_2 is being captured to establish baselines to set goals and to manage ecoservices to new targets. The quantification assists in introducing policies and procuring funds for upgrading and sustainability (NYC DPR, 2015; Rogers et al, 2015).

SVO models have been consistently used to enrich 3D city models and increasingly for data sharing, however, current needs require tree parameters, properties, location, leaf area, species, canopy cover, etc. as input data to ecoservices assessment tools. Further, tree reconstructions are used to extract properties which are not measurable directly, e.g., to adjust species allometric models of urban vegetation for better estimation of ecoservices, to improve canopy impact assessments of radiation of surfaces including solar panels, to better understand tolerances to wind or to simulate micro-climate canopy cooling effects. Reconstructions offer an alternative for sampling urban trees where data extraction methods destroy sampling trees.

3.2 COMMON PRACTICES

DAILY USE OF TREE DATA

City trees are commonly represented as OD, 1D, 2D and 2.5D objects. At the municipality of Rotterdam, trees are often managed and visualized using their location coordinate points or 0D, especially when shared with other groups involved in pubic work (use case no. 4). Despite the availability of the municipality's 3D city model with 3D trees (use case no. 30) and the 3D point cloud data itself. The main reason for the preferences is the timeliness and setup of the data. Their 0D dataset is the most up to date version and is linked to other systems. Updating and maintaining the 3D counterpart is simply not as practical. Other representations of tree data are lines (1D) to represent rows of trees and 2D and 2.5D canopy projections in urban planning in the municipality of Rotterdam and by the Dutch tree registry boomregister.nl (2015) as seen in Figure 3.2.

[2] Warmer temperatures in urban areas compared to surrounding rural areas (Oke, 1987). The effect's strength depends on the urban structure, building density, canyon geometry, surface materials, vegetation coverage and water surfaces in the city (Klok, Zwart, Verhagen, & Mauri, 2012).

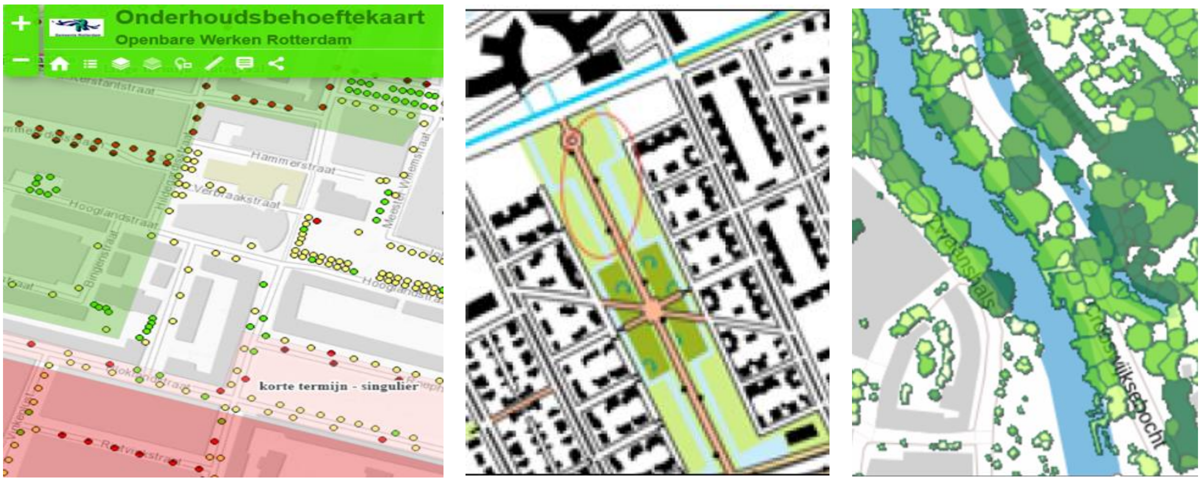


Figure 3.2: 0D, 1D and 2D tree representations used in common practices
Left: 0D data for location (Maintenance Public Work in Rotterdam, 2016); center: 1D data for rows of trees along roads (Clement et al., 2013); right: 2D tree crowns from Boomregister.nl

VEGETATION IN 3D CITY MODELS

Vegetation models are included in 3D city models mostly in three ways: not at all, as instances of implicit models (Figure 3.3) or with realistic CG models (Figure 3.4). Few include parametrical tree models (Figure 3.5) and PC.

A hindering aspect for the inclusion is the low availability of existing public vegetation data. In the Netherlands, much vegetation data is kept by municipalities and provinces for management. What data is included, its acquisition, update frequency, quality, etc. are defined by the keeper and not shared (Rip & Bulens, 2013). The Dutch tree registry boomregister.nl (2015) sells 2.5D tree data initially acquired from the public nationwide 2008-2013 LiDAR point cloud (www.ahn.nl). Outside the Netherlands, vegetation data collection involves communities and local agencies motivated to improve their urban forests ecoservices for which free guidelines and tools are found online and in literature, e.g., London & Ham (2006); US Environmental Protection Agency (2008), and i-Treetools.org, but collected data is not made available.

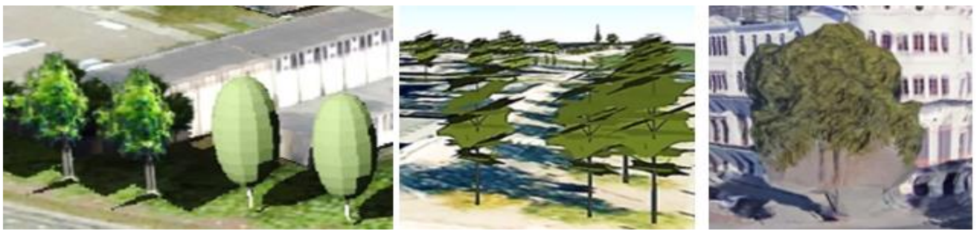


Figure 3.3: Implicit models of assorted geometry and appearance
Left: Rotterdam 3D Dashboard (2017); center: Kramer & Clement (2012); right: Google Earth.

Figure 3.4: CG realistic model (Pavel Dostal, 2011)

Figure 3.5: Parametric trees (Blaauboer et al., 2013)

Data acquisition costs, and IT resources for the implementation of a 3D city model with adequate viewing performance play a significant role in the incorporation of vegetation in such model.

A common practice for reducing computational costs is the use implicit tree models, billboard models, abstract symbols, or photo textured shapes as shown in Figure 3.4. These models are for visualization as those found in public Cities in the World Open Datasets (CityGML.org, 2017) and in Rotterdam's 3D v.2 (2017) city model. Their realization entails placing them at tree location coordinates. Using implicit models is automation-friendly and economical in storage because datasets only need to store location points. The prototypical shapes or models are stored once and reused many times.

Higher computing power is required to use realistic CG 3D vegetation models. This can hinder their use, e.g., a single high-end tree model can have thousands of polygons (Figure 3.5) which may exceed the number of polygons in an entire city model (Klooster, 2016). They can add visual adherence to existing vegetation if the models match in species, but this can be challenging. In tests for online viewing of the 3D model of the town of Hoogvliet in Rotterdam which had 1.2K trees of 300 species, acquiring models for all species was impractical. Due to technical limitations, after iterations, only models of the eight most common genera could be included.

Acquiring implicit models is fairly straight forward. Simple tree symbols or high-end CG models are found with unrestricted use (archive3d.net, cgtrader.com), in library collections of species, seasonal, age, geographical region, 3D formats (xfrog.com, Speedtree store), or by polygon count (turbosquid.com). 3D vegetation models are also included with GIS tools, e.g., ESRI 3D vegetation models, and in virtual reality and gaming tools.

Parametric 3D tree models are automation friendly in their generation and provide adherence to existing trees in their crown forms, but they require more resources. Acquiring needed parameters from LiDAR data, generating and storing the models require different expertise, tools, and data resources. The process is fully described by Meijer et al., (2015), and a simplified method is done in this thesis for the case study. Models with parametric trees are found in literature: Meijer et al. (2015) and Schouten et al. (2012), and in conference and national pilot programs: Kramer & Clement (2012) and Stoter et al. (2011).

In reviewing the benefits of vegetation modeling by the advent of Terrestrial Laser Scans (TLS) Liang et al. (2016) highlight the increasing availability of TLS and decrease in the cost of model construction make tree reconstruction from TLS a viable option to develop and update allometric models (establish a relationship between measurable tree attributes, e.g., height and DBH and non-measurable attributes, e.g., biomass). Tools for reconstructing trees from TLS such as *SimpleTree* by Hackenberg et al. (2015) are found in *Computree* a forestry open source processing platform for 3D point clouds. Different methods are described in *PlantGL* from Pradal et al. (2009).

4 ANALYSIS

This chapter identifies use cases' needs of vegetation models and data. It analyses how CityGML and other LOD specification approaches define their vegetation LODs and identifies the specifications that allow LODs to meet identified needs. This chapter also presents terminology harmonization of crown shapes and root parameters. Because roots are introduced for the first time in LOD specifications, recommendations in estimating and acquiring root data are given.

4.1 USE CASES NEEDS AND COMMON REQUIREMENTS

Most of the 30 reviewed use cases in Chapter 3 focus on trees since most of the benefits in an urban setting come from tree crowns. Other vegetation types are included in addition to trees mostly in the mitigation of storm water runoffs, noise reduction, and in canopy cover estimates.

After reviewing the 30 use cases presented in Chapter 3, based on the vegetation models and data mostly required, six main needs are identified.

Note: use case numbers are in parenthesis and Table 0.2 in Appendix A lists the needs of each use case:

A. 2D, 2.5D, 3D models and data are needed for visualizing or communicating designs and topology, sharing information, visual analysis, planning, and assessing space availability:
   a. Realistic models that reflect multiple aesthetic changes of life stage or seasonal for visualizing plans (9 -12)
   b. Models of multiple levels of adherence to visualize topology, visually analyze vertical and horizontal distributions of distances and tree types, and models with crowns that reflect spatial requirements and tree types (2-7, 19, 20, 29, 30)
   c. Data for planning, e.g., tree structure and appearance changes, tree types, and growth rates to project size changes (7-12)
   d. Data for assessing tree planting feasibility, e.g. above and below ground conditions, underground object topology, tree environmental pollution reduction properties and tolerances (4-8)

B. 2D, 2.5D, 3D models of varying degrees of adherence and component granularity to estimate impacts to surroundings:
   a. Models of multiple dimensionalities and levels of adherence in spatial aspects (not aesthetics) and granularity of components (7, 17 -20)
   b. Root as component and its parameters (5, 7, 8, 20) with tree species, type, and life stage.
   c. Crown as component and with adherence levels in forms (6, 7, 13, 16-18, 24) and properties, i.e., crown sparsity (case no. 7) and transparency (case no. 18)

C. 3D models and reconstructions to extract or estimate parameters and properties
   a. Detailed 3D crown models for estimating parameters of irregular crowns (24)
   b. Tree reconstructions to extract non-measurable properties, e.g., biomass, simulate and assess properties, e.g., mechanical tolerances, canopy evapotranspiration process (25-28)

D. Models and data as input to spatial impact simulations (13-16, 21-23)
   a. 3D models of multiple adherence levels and data: canopy cover (2D), vegetation type, bottom up tree data, or entire datasets as input to impact and assessment simulations.
   b. 3D models reflecting tree type forms for placement optimization simulations.

E. Vegetation attributes frequently needed (Table 4.1):
   a. For predicting size and appearance changes due to seasonal and life stage changes (7, 9-12), to describe types, and forms/shapes (6, 7, 15, 16).
   b. To assess impacts and spatial relationships to surroundings, e.g., crown properties, i.e., crown sparsity and transparency (7, 17, 18), and tree species, type, and life stage.

c. Related to maintenance and sustainability, condition, and risk, e.g., spatial requirements, tolerance properties, leaf area, species, aging stage (1, 3-7, 20, 21, 23).
d. Classifications (deciduous, coniferous, hedges) and roles (give shadow, mitigate runoff, noise reducing (1, 4-7, 9-12, 13-17, 21-23, 25-28).
e. Parameters and data for estimating other properties that are not measurable directly, as for:
   i. root depth and projected spread for calculating root volumes (8)
   ii. crown parameters and properties for calculating leaf area and biomass (21)
   iii. 2D canopy cover, vegetation parameters, crown properties for estimating carbon sequestration and storage (22)
   iv. Distance and angle to buildings for estimating energy consumption reduction (22)

F. Given the above, models and attributes are needed to support a broad range of scales: individual, street, project level, regions, detailed modeling of crowns, and reconstruction of individual trees.

Table 4.1 summarizes the parameters, attributes, and properties needed in use cases grouped by attribute types. CityGML attributes that also appeared are shown in italic. Other CityGML's attributes not included below are *function*, *CreationDate*, *TerminationDate*, *relativeToTerrain* and *relativeToWater* (OGC, 2012). Attributes marked with a '**+**' serve for assessing ecoservices (use case no. 22).

Table 4.1: Attribute extension for SVO LOD specifications refinement

Attribute Type	**Attribute**	**Description or value examples**
Classifications	Type	(Semi)Deciduous/(semi)Evergreen
	Class	Tree/Hedge
	Species+	Latin name
	Usage	Shadow/Erosion/Water run-off /Wind block…
Status	Condition	Excellent, good, fair, poor, dead, plagued
Parameters	*Total height+*	Tree top relative to terrain elevation
	Crown diameter +	or dripline contour diameter
	Td/BHD+	Trunk diameter/Breast height diam. (DBH)
	Crown base height +	Relative to terrain elevation
	Rd	Root depth (see Underground attributes)
	Rsd	Root spread diameter (max.)
Crown Properties	Crown shape	S1 – S15 shape numbers
	Crown light exposure+	sun exposure
	Percent crown missing+	crown volume missing
	Crown Condition/dieback+	estimate of dead branches
	Crown density	Open, semi-closed, closed
Topology	Distance to building+	
	Direction to building+	
Temporal Properties	Life stage	Seedling/Young/Adult/Mature/Ending
	Foliage fall/sprout/bloom	Month of year
Land related	*land use+*	
	Percent tree cover+	Percent to nearest 5%
Underground	Max. vertical distance limitation	e.g., underground water, rock bed level
	Max root volume	
Application specific	Maintenance -Class: height class	Tall, medium, small

1. **+** Data used by i-Tree Eco (2016) use case number 21, *Structure and ecoservices analysis*, in Table 3.1

4.2 HARMONIZATION OF CROWN SHAPES AND ROOTS

For the inclusion in vegetation LOD specifications, canopy shapes and root parameters need definition and harmonization. This also facilitates the exchange and integration of datasets as it increases their compatibility.

4.2.1 Crown Shapes

Crown structure and morphology were relevant in use cases where volumetric tree models with different crown shapes represent different tree and vegetation types, e.g., in displaying diversity of species, designing and selecting trees for streetscape, optimizing placement of trees near houses and in parking lots (use cases no. 6, 7, 15, 16 in Table 3.1). In these cases, regular crown shapes or naturally formed shapes were suitable. In estimating shadow or volume, shape adherence is proportional to desired accuracy of estimates (use case 16).

For LOD descriptions, harmonizing crowns-shape names is necessary as several names are used for the same shape in reviewed datasets, international urban tree care material, tree growers, and literature listed below. The pictorial compilation in Figure 4.1 shows the need for their harmonization.

- Standard tree crown shapes used in forestry, arboriculture, and ecology (Coder, 2000)
- Approved tree species for planting in New York City open dataset (Haywood-Samuel, 2003)
- Municipality of Rotterdam tree crown descriptions (Van de Vondervoort, 2016)
- The national Dutch tree registry tree crown descriptions (Cobra Adviseurs, 2017)
- European Tree Worker certification training material (Janson & Janssen, 2013)
- European tree nurseries Van den Berk B.V. (Van den Berk, 2015) and Ebben (Ebben, 2017)

13 shapes describe the most common shapes. Alphanumeric names were given to avoid language issues. S1 to S8 were introduced by Coder (2000) as standard shapes are used in forestry, arboriculture, and ecology for crown volume estimation. S11 to S15 were added based on the above.

Even though many use cases focused on trees because of the many services that they provide, the same shapes are applicable to other SVOs provided they grow in open spaces and their overall form is not altered by men. In general, trees of the same genus have the same shape with some exceptions. Predominance of native species is reflected with similar shapes. In large cities, tree species tend to be diverse as climate compatible species are brought-in throughout history or because of specific properties, e.g., out of the top 10 tree species in Rotterdam one is native to Canada and another to China: Canadian Poplar and the Callery Pear.

The adopted 13 shapes reflect a tree stump, topiary or hedges, and tree crowns and SVOs grown in open ground. S12 reflects trees with no clear main trunk. 3D models of S1 to S15 solids were created with Autodesk Maya and were used to create a model library for the case study implementation. See Appendix B for descriptions and link.

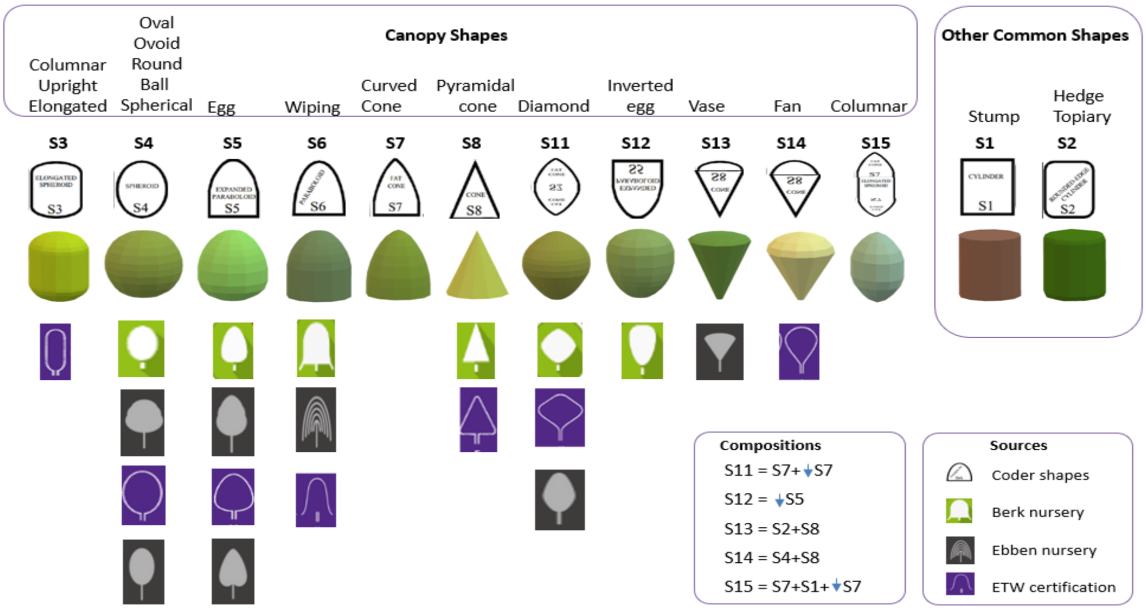


Figure 4.1: Compilation of crown shapes

4.2.2 Roots

For a basic root volume estimation, a root depth (Rd) and a root spread diameter (Rsd) are needed. Since there are no denominations for such parameters, Rd and Rsd are adopted as root parameters. For acquiring them, the following notions and approaches are useful:

For trees to live a full life adequate space is needed for their roots. Roots are mostly shallow systems with over 50% lying on the top 15 to 30 cm of the soil (ISU, 2012) to absorb water-and-mineral. A few inches/cm of soil added over the root system smothers fine roots and lead to death (International Society of Arboriculture, 2011). Roots search for fertile, moist, un-compacted soil. They spread further in dry or compacted soils, go deeper when planted close together, or wider when downward growth is restricted (Harris et al., 2004).

In Rotterdam, for example, surface soil is limited and covered near the roads, sidewalks, and bicycle paths. Soil condition and distance between trees vary, and roots only grow as deep as the underground water level (Zwiep, 2016). Rd under tree locations were estimated with extrapolated underground water level readings.

To estimate the Rd, knowledge is needed of species root habit, and the depth of impenetrable manmade structures, bedrock, underground water, etc. which prevent roots from going deeper. To estimate the Rsd, different approaches can be considered. They are expressed as multiples 'X' of a parameter:

- 2X to 4X the average crown diameter (Sillick and Jacobi, 2013)
- 4X to 7X crown surface area (Randall, 2018)
- 1.5X to 3X wider than foliage (Kourik, 1986)
- 4X to 8X wider than the dripline for irregular growth conditions (Kourik, 1986)
- 12X trunk diameter for protecting roots from underground work
- 1X to 3X the tree height (International Society of Arboriculture, 2011)

Where reliable DBH measurements are available, Day et al. (2010) work is helpful. They investigated the different approaches for predicting root spread in an urban environment using worldwide data of root systems from young, old, deciduous and coniferous trees: in urban settings, root depth and spread can be highly irregular. In minimal restrictions, root spread showed a strong relationship with trunk diameter for young trees (root to trunk diameter ratio is ~ 38:1) which slows down as trees mature.

All approaches agree in one aspect: using a root spread that equals the size of the crowns is a gross underestimation. Because the growing conditions in Rotterdam are not optimal, it is most likely that roots spread irregularly. Given that measures of tree heights and crown dimensions are available as acquired from their point cloud, these parameters can be used for estimating Rsd, but decisions have to be made in how conservative the estimation should be. A caution in estimating root spread is to consider canopy trimming. Roots do not match pruned canopy. Here trunk diameter and tree height are helpful.

For protecting trees during street work, the International Society of Arboriculture (2011), recommends to set a root protection zone of 12 to 1 ratio of distance from the trunk to trunk diameter. When using height, a tree's root system can extend horizontally a distance 1 to 3 times greater than the height of a tree. Root damage within the zone jeopardizes the wellbeing of the tree and outside the zone is tolerable. The protection zone size also depends on policy, age, and species of the tree (Day et al., 2010).

For representing roots, a cylindrical model was created for volume representation with AutoDesk Maya (Figure 4.2). Root models for aesthetic and volumetric visualizations including root types: Shallow, heart and deep, which vary by species, are free downloads from ESRI Germany (2015a).

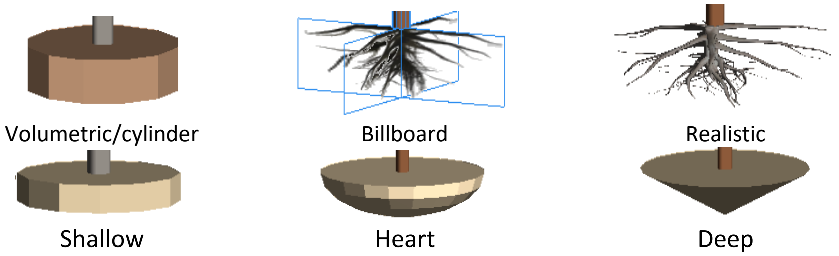


Figure 4.2: Root visualizations.
Non-cylindrical models are free downloads from ESRI Germany (2015a)

4.3 VEGETATION LOD SPECIFICATION APPROACHES ANALYSIS

This section analyzes how CityGML's and other vegetation LOD specification approaches specify their LODs to identify the factors that are key in defining LODs that meet most common use cases and practitioner's needs. These factors serve in determining CityGML's areas for improvement.

The vegetation LOD specifications (Chapter 2.2) are grouped by predominant focus to facilitate their reference:

1. Standardization-focused: *CityGML, IMGeo-CityGML, LOD and Trees.*

   They describe relevant topographic city objects for 3D city models to support analytical tasks in diverse applications like simulations, urban data mining, facility management, and thematic inquiries. The latter two include 2D, 2.5D object geometries and explicit specifications to satisfy multiple scale requirements.

2. Geometry-focused: *LOD of Trees, LOT, Single Tree*

   They focus in describing SVOs with explicit descriptions with parameters acquired from LiDAR data to either reconstruct trees for estimating attributes or for building parametrical models.

3. Proprietary: *Vertex, Blom ASA, and ESRI*

   They focus on 3D city buildings at LODs varying in accuracy and extents for which SVOs are incorporated mostly for visualization, and are concerned with online consumption, interactive and virtual products, and in multi-scale modeling.

For the analysis the specifications are mapped against the six LOD defining metrics described in Chapter 2, where *Presence* is expressed as *component granularity*, and *semantic granularity* for semantic specifications at component level. Other specifications used in CityGML LODs which also appear in other approaches are also mapped. Table 4.2 gives a high-level overview of the specifications used and an indication of the depth at which a concept is specified. The analysis focuses first on LOD specifications and requirements, and then on differentiating factors and relationships. Remarks are made on specification impacts.

4.3.1 Specifications and Requirements

Letters or numbers in parenthesis refer to items in the needs summary or to a use case in section 4.1.

1. Most of the approaches focus on SVO and do not describe PC except in the standards. Blom considers it part of the terrain, and if included, PC is not an object (Vertex and Blom).

   Not considering PC as objects prevents GIS data from being associated limiting its inclusion in quantitative analysis or scientific studies.

2. All descriptions are primarily geometric, and the type of geometry used divides them into two sets:
   a. Those that use implicit geometry, i.e., CityGML and Proprietary approaches. CityGML supports explicit geometry but specifies SVOs in four levels with only implicit geometry.
   b. Those that use explicit geometry, i.e., Geometry-focused approaches
   c. IMGeo-CityGML provides one SVO-tree LOD with each geometry type.

3. The LOD at which vegetation objects are introduced varies:
   a. Explicit modeling approaches mostly include SVOs in LOD0 as 2.5D projections.
   b. CityGML and implicit modeling approaches exclude SVOs are LOD0.
   c. In general, SVOs are introduced at different LODs. CityGML at LOD1, others at LOD2, or LOD5.

      Excluding SVOs at LOD0 is contrary to common practices of representing and using SVO data in 0D, 1D and 2D and 2.5D (use cases 1, 4, and 21). The exclusion also prevents incorporating these datasets in city models perpetuating their low availability as highlighted in Chapter3.2.

4. LOD-definition metrics are underutilized in all approaches.
   a. *Component granularity* and *dimensionality* specifications add adherence to their LODs as components are added in explicit LOD modeling. Other explicit approaches include SVOs as 2.5D crown projections (LOT, LOD of Trees, IMGeo-CityGML SVO-hedge).

      They increase of adherence as components are added result in multiple LODs applicable to different scales as also required in use cases**.** They further support adherence at component level needed for assessing impacts and extracting properties of crowns (B**, C**).

      CityGML and other implicit geometry modeling approaches offer no component granularity and remain as 0D throughout their LOD ranges.

   b. *Feature complexity* specifications which can complement *component granularity* specifications are minimally utilized: they are specified as min. SVO heights (CityGML), as standard ratios, e.g., trunk radius as 1/20 crown's (LOD and Trees), and absent in remaining approaches.

When defined, they determine min. size requirements for inclusion of SVOs at the particular LOD. When defined quantitatively, they avoid vagueness.

CityGML's geometric complexity specifications add adherence in SVO heights and are specified discretely. They do not include horizontal aspects nor are specified consistently across the LODs.

Providing standard component ratios (vertical and horizontal) for explicit modeling provides an alternative if minimal data is available, e.g., when SVOs locations are known.

c. Spatio-*semantic* correspondence is required in IMGeo-CityGML and optional in CityGML. Other approaches do not consider this specification.

   Not specifying semantic relationships with reduces the compatibility of datasets. In this case it would add compatibility at component level.

d. *Appearance* specifications are confined to highest LODs (realistic form). Lower LODs lack appearance and adherence in this respect regardless of the geometry used.

   Inconsistency adds vagueness and no guidelines for other appearance aspects are provided (A).

5. *Attributes* are specified in different ways. Some are discussed in many approaches but not specified.
   a. For parameter specifications, the same parametric tree model is adopted in many explicit modeling approaches

      It supports modeling SVOs at different degrees of adherence and a bottom up parameter acquisition in alignment to those required in environmental assessments (16, 17, 21-23).

   b. Classification specifications like *class* in the standards are limited. They do not support multiple and simultaneous classifications for the same object.

      CityGML's C*lass* attribute combines multiple, different classifications which need separation, and there is a limit of one *Class* attribute per object. In use cases, different classifications are associated to object and serves data input and mining. For example, in simulations of tree placement and noise *class* (delicious/coniferous) and *type* (tree, hedge) are used (9-12, 14, 15, 17), or in maintenance, combinations of *usage* and *height class* are used (1, 5).

   c. Root spatial requirements specifications are mentioned (LOD of Trees) and considered in daily practices and in use cases 5, 7, 8, 20. Root definitions as a component with respective parameters are absent in all approaches.
   d. Temporal specifications such as anticipated growth and seasonal visualization changes are mentioned (LOD of Trees) and some are described: growth rates, planning and changes tracking at object level are specified in IMGeo-CityGML; creation and termination dates (CityGML). Other basic temporal descriptions are in need of addition, e.g., life stage (1, 6, 9-12).
   e. Topological relationships are specified by the standards but not with respect to buildings, which are needed in spatial studies (17, 18, 22).
   f. Maintenance, risk and condition assessment attributes are specified in IMGeo-CityGML, and the Dutch tree maintenance categories are specified in LOD and Trees. These types of attributes are needed for overall sustainability (1, 6, 22).
6. CityGML and proprietary modeling approaches LOD which use implicit geometry modeling:
   a. Have minimal requirements and adherence, i.e. min. heights, and allow mixing LODs.
   b. Lack overall requirements towards higher adherence to real-world objects, e.g., in component granularity which can still be implicit, and do not consider explicit geometry specifications.
   c. Do not require/specify different prototypical representations (in geometry complexity, or in appearance) except at the highest level.
7. Explicit SVO modeling approaches LOD requirements:
   a. Mostly require the implementation of previous LOD.
   b. Require component granularity resulting into different levels of adherence
8. Geographic extents as defined by CityGML are found in many approaches in the ordinality of their LODs. In some approaches, the extents are specified discretely (Vertex) and related to their LOD accuracy descriptions (CityGML and Vertex).
9. Accuracy specifications that target vegetation objects are given by IMGeo-CityGML. It is specific in the accuracy of SVO's position and data timeliness, and it allows users to set footprint accuracy.

   CityGML associates optional accuracies to geographic extents applicable to all objects. Vertex associates geographic extent to offered accuracies and mixes SVOs of lower accuracy with higher accuracy buildings.

   Considering accuracy descriptions of a city model as a quality indication to facilitate comparison and integration as stated by CityGML seems adequate if the model has only one feature type. Instead of trying to fit all objects within a model to a single accuracy specification, it is more relevant to specify accuracy at object level. In this case the description provided by IMGeo-CityGML can be used as guidelines. Since accuracy descriptions are dependent on several aspects, e.g., use case requirements of component granularity, available data, acquisition processes, etc. they are best specified by the users.

Table 4.2: Vegetation LOD specifications comparison

	Standards			Geometry focus			Proprietary		
	CityGML	IMGeo-CityGML	LOD of Trees	LOD and Trees	LOT	Single Tree	Vertex	Blom ASA	ESRI
Veg. LODs / All LODs (36/40)	4/5	3/4	5/5	4/5	4/4	5/5	4/5*	4/5**	3/3
Veg. objects described:	2	3	1	2	1	1	1	1	1
Geometry type:	I	B	B	E	E	E	I	I	I
Dimensionality—of geometric primitives used in object representations	0D 2.5D 3D	0,1D 2D 2.5D 3D	2D 2.5D 3D	2.5D 3D	2D 2.5D3 D	2.5D 3D	0D	0D	0D
Feature Complexity	◑	◑	◑	●	-	-	-	-	-
Appearance	◔	◔	◔	◔	◔	◔	●	●	●
Component granularity	1-3	1-5	1-5	1-5	1-5	1-5	1	1	1
Semantic granularity	◑	●	-	-	-	●	-	-	-
Geographical extent	OR	-	-	-	-	-	expli cit	-	OR
Accuracy by LOD	◑	-	-	-	-	-	●	-	-
Accuracy by object	-	●	N	-	-	-	-	-	-
Vegetation data timeliness	-	●	-	-	-	-	-	-	-
Attributes									
Temporal	◔	◑	N	-	-	-	-	-	-
Underground	-	-	N	-	-	-	-	-	-
Topology	◑	◑	-	-	-	-	-	-	-
Maintenance: condition, risk	-	●	-	◔	-	-	-	-	-
Requirements									
Builds on previous LOD	n	n	y	n	y	y	n	n	n
Optional SVO in LOD0	-	◑	●	-	●	-	-	-	-
Optional additional LODs	n	n	n	n	n	n	y	y	–
Optional object components	y	y	-	-	-	-	y	y	–
Optional attributes	y	y	y	y	-	-	y	y	y
Can mix LODs	y	n	n	n	n	n	y	y	y

Legend: OR = Ordinal; N = Nominal. Fully described: ●; partially: ◑; minimally: ◔. n= no, y =yes implicit: I; explicit: E; both implicit and explicit: B; Component granularity: tree: 1; crown: 2; trunk:3; branch: 4; leaf: 5.
* includes a separate LOD for textured objects, PC included in fifth LOD only not as an object;
** includes SVO as an object in exclusive LOD for interactive models.

4.3.2 Differentiators and Relationships

To visualize comparisons, Figure 4.3 shows differentiating specifications. Each approach has SVO models that it specifies or allows. Close up examples of the SVO models are shown in Figure 4.2.

10. Both standards have limited differentiation. IMGeo-CityGML SVO-tree LODs are differentiated by their geometry type. Each can have multiple representations as seen in Figure 4.3, but there is no differentiation among them. CityGML LODs are differentiated by geometry complexity (total height) in LOD2 and LOD3, in appearance in the highest LOD, and by geographic extent. Similarly, multiple implicit representations are possible in LOD1 to LOD3. The specifications offer flexibility but have vagueness.
11. Explicit modeling approaches differentiate with component granularity and dimensionally (see item 4.a). They offer a wider range of LODs (Figure 4.3). Dimensionality differentiation is seen when a 2.5D crown projection in LOD0 changes to 3D or a combination of geometric primitives of different dimensions in LOD1.

12. Implicit modeling specifications (CityGML and proprietary) differentiate with appearance, which changes from unspecified to realistic for the highest LOD (see item 4.d), and secondly by geographic extent: Vertex specifies accuracy with geographic extents, ESRI's, it influences the type of model to be used, and in CityGML SVOs specifications change from None, Important, and Prototype in LOD1 – LOD3
13. Compared to building LODs, the realistic appearance as *realistic* coincides with the highest LODs. At lower levels, features can be of mixed/different LODs as in Vertex. Approaches that use explicit SVO models relate to buildings LODs with increasing component granularity. Examples of CityGML building LODs are shown on top of Figure 4.3 for comparison with vegetation's.

    There is no consistent alignment of SVO LODs with geographic extents/buildings as seen in Figure 4.3.

To appreciate relationships between LODs within an approach and across all approaches, LODs are charted connecting examples of respective LOD in Figure 4.4. The arbitrariness of CityGML's LODs' ordinality to those of SVO LODs' can be seen, as well as, the LOD in which SVOs are introduced:

14. Dependency between levels and adherence to the real-world object vary by geometry type:
    a. Implicit LOD specifications are independent from each other or unrelated. LODs progress to a high LOD not necessarily reflecting the real-world object's
    b. Explicit LOD specifications mostly build from lower LOD levels. Starting at LOD0 with 2D or 2.5D crown projections (LOT and LOD of Trees) or at LOD2 (Single Tree). They proceed to real-world object adherence as LODs increase.
15. IMGeo-CityGML is the only approach that starts with implicit and ends with explicit geometry in two distinct LODs. There are no intermediate levels.
16. There is no aggregation nor generalization relationships between LODs levels, nor a consistent quantified specification with either a systematic discrete pattern or continuous relationship.

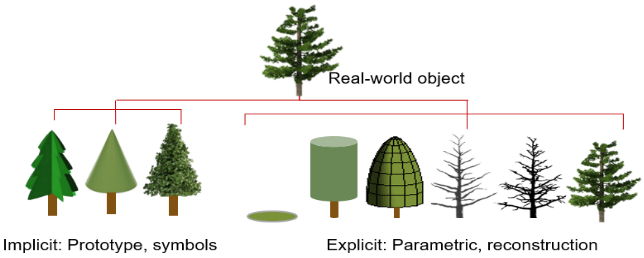


Figure 4.3: Examples of SVO representations in implicit and explicit geometries

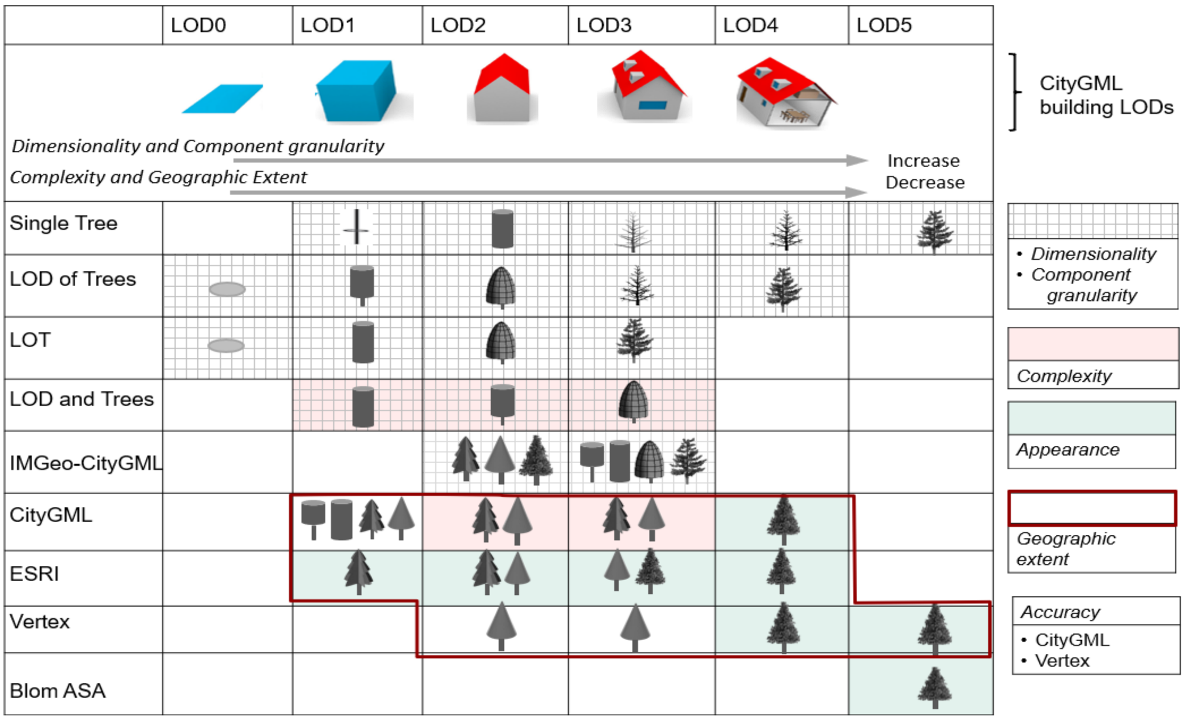


Figure 4.4: SVO LOD specifications' differentiation
Building LODs from Biljecki et al. (2016)

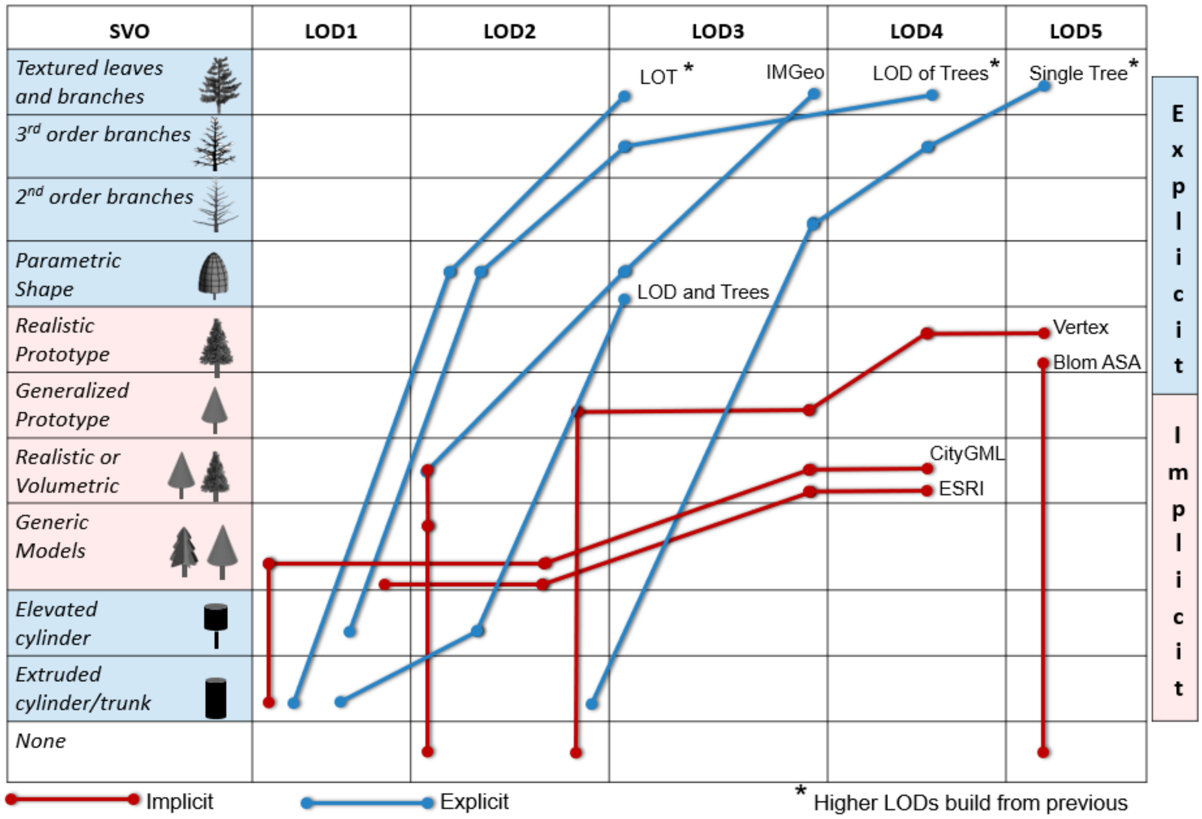


Figure 4.5: SVO LOD specifications'as explicit (blue) and implicit (red)

4.4 STRENGHTS AND WEAKNESESS

Based on the above analyses, vegetation LOD specifications can be considered as either implicit or explicit geometry modeling approaches which complement each other. The strengths of one set are the weaknesses of the other (Table 4.3). Many specifications in the explicit modeling approaches allow their LODs to meet many use cases needs identified in section 4.1 which is why such specifications are considered strengths.

Table 4.3: Vegetation LOD approaches comparison

Numbers in parenthesis refer to items in the analysis sections

CityGML and Implicit Modeling	Explicit Modeling
Weakness	Strengths
• Exclude SVO in the terrain or LOD0 (3)	• Include SVO at LOD0 or terrain level (3)
• Confined to 0D dimensionality • Lack of component in LODs (4.a)	• Support multiple dimensionalities (4.a, 11) • Support parametrical tree modeling (5.a)
• Adherence to real-world objects is limited to realistic models. It is weak at intermediate and high LODs (4.b, 4.b, 4.d, 6)	• Adherence is progressive (4.a, 7, 11) • Align better to buildings LODs (13)
• Differentiation is minimal LOD, i.e., it is mostly associated to appearance specification for the highest LOD, or in feature complexity in total height (10, 12)	• Differentiation is driven by component granularity, dimensionally and (standard feature complexity specifications if specified (11)
Strengths	Weakness:
• Minimal requirements therefore they have flexibility (6) • LODs are unrelated or not dependent from each other (14.a) • Relative low cost of acquisition, realization, computing and storage resources (Chapter 3.2)	• Requires implementing prior LODs (7) • LODs depend on previous (14) • Higher cost of acquisition, realization, computing and storage resources (Chapter 3.2)

In addition to targeting to meet identified needs for use cases (Section 4.1, items A-F) and common practices (Chapter 3.2), the following aspects are key to strengthen CityGML's vegetation LOD specifications applicability.

1. Add components, e.g., crowns and roots. As components are added, they differentiate a LOD and provide levels with increasing adherence and applicability for different scales.
2. Add geometric descriptions of other dimensionalities for the inclusion of SVO LOD LOD0 and support to common practices of representing SVOs in 0D, 1D and 2D and 2.5D.
3. Improve minimal feature complexity specifications and reduce inconsistencies. They are important since they define the inclusion of vegetation in a LOD:
    a. To support the inclusion of SVOs in LOD0, they need to also specify horizontal aspects
    b. They need to be applicable to components
    c. Ideally, they are defined quantitatively to avoid vagueness.
    d. Given the low availability of public vegetation datasets, providing standard component ratios as feature complexity guidelines gives an alternative if minimal data is available, i.e., position.
4. Specify consistent appearance descriptions to eliminate vagueness and inconsistency from their absence in levels lower than LOD4.
5. Add spatio-semantic relationship specifications to eliminate vagueness especially as components are introduced. Semantic specifications can apply to appearance descriptions, e. g. for displaying SVO temporal aspects (e.g., life stage) and different properties (e.g., type) using appearance changes.
6. Expand existing and add new attributes which are mostly specified by the standards or are suggested in other approaches. Compared to those commonly required in use cases:
    a. Attributes that can be expanded:
        i. Classifications: multiple classifications per object
        ii. Temporal specifications: growth rate, seasonal visualizations (foliage, bloom)
        iii. Maintenance: condition, height classifications
        iv. Topology: relationship to buildings
    b. Need to be added:
        i. Parametric tree model that supports a bottom up parameter acquisition
        ii. Root parameters

Ideally, the above are implemented while keeping CityGML's flexibility, low acquisition cost, and automation friendliness.

4.5 CITYGML'S SHORTCOMINGS AND UNCERTAINTIES

The weaknesses identified for CityGML in Table 4.3 with additional observations form the basis for CityGML's shortcoming and uncertainties. Addressing them allows CityGML vegetation LODs to be applicable in quantitative assessments, spatial analysis, urban studies, simulations, etc.:

1. Does not support practitioner's common practices and use cases with:
    a. SVO representations in LOD0 or terrain level (B.a, D, 3)
    b. Underground representation (B.b, 5.c)
2. Higher LODs provide insufficient degree of adherence to real-world objects at object level and component level (A-D, 6.b) mostly due to:
    a. Not providing explicit modeling specifications (2.a)
    b. Lack of SVO components definitions (4.a)
3. Weak LOD differentiation (10, 12) partly due to underutilized LOD definition concepts (4)
4. Limited in attribute specifications (F, 5)
5. Uncertainties rise from specifications gaps and their inconsistency in many aspects:
    a. Gaps: min**.** height for SVO LOD1 is missing. SVO LOD1, PC LOD3 and LOD4 have no explicit min. sizes specified as other of their levels.
    b. Inconsistent: SVO LODs are first described as *important*, then by complexity and geometry type, and then by appearance. PC LODs are first described with min. sizes and then ordinally. Further, there is no consistent progression in any of the categories.

c. Vagueness is introduced with ordinal descriptions like < LOD2 in adjacent LODs.
d. Practitioners are left to define their own LOD descriptions at the cost of homogeneity and compatibility w.r.t vegetation features

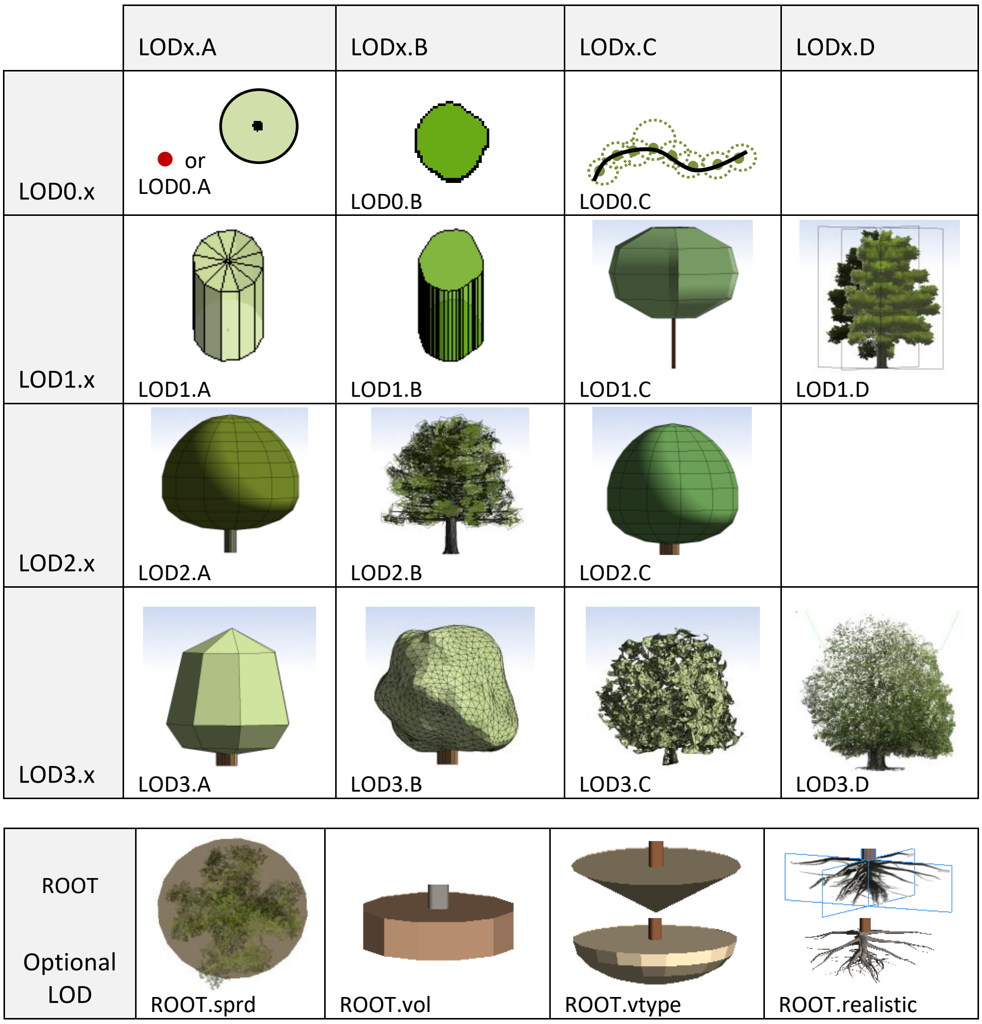
6. Uncertainties rise from *geographic extent*, *accuracy*, and *generalization* descriptions within CityGML's LOD scheme. These specifications seem to have no direct influence or apply to SVO LODs, rather to other objects:
   a. Geographic model extents--LOD0 to LOD4 set the ordinality of SVO LOD specifications, however the extents themselves are mostly arbitrary to vegetation objects (8, 13).
   b. Accuracy descriptions as guidelines lack horizontal descriptions and are not object specific (9)
   c. Generalization specifications (Table 2.1) are not specific to vegetation rather arbitrary: if meant for minimum footprint or heights, these specifications then relate inconsistently: when min. size specifications are missing as in SVO LOD1, the generalization specification of 3 m for min. height could apply, but in LOD2 the SVO min. height specified is 6 m.

5 REFINED VEGETATION LEVELS OF DETAIL

Because most vegetation LOD definitions omit PC as a feature and most use cases focus on SVOs, in particular trees, refined vegetation LOD specifications cover SVO LOD descriptions and not PC.

14 LOD specifications and four root LODs are provided covering above and below ground aspects. There are four groups, LOD0.x to LOD3.x, each with sub-LODs. Adherence increases as the levels increase by family and within sub-levels. Each family aligns to respective CityGML LODs. Roots are optional and not aligned to SVO LODs.

This chapter describes the considerations and definition approach in their formulation. Visual examples of proposed LODs are shown below in Figure 5.1. A LOD description matrix is found in Table 5.1, and the specifications in Table 5.2. Requirements and recommendations are available in Section 5.5. A list of extended attributes is found in Table 5.3, and a cross-check of attribute requirements and/or equivalent models found in use cases with refined LODs is found in Table 5.4.



LOD1.D, LOD2.A and LOD2.B and some roots are library models (ESRI)

Figure 5.1: Visual examples of refined SVO LOD descriptions

5.1 CONSIDERATIONS AND DEFINITION APPROACH

To formulate the refined LODs, the following was done:

1. Identified the needs, i.e., vegetation models or representations, data, and attributes that were commonly used by practitioners (Chapter 3.2), and mostly required in use cases and applications in spatial and quantitative analysis studies in the urban environment (items A to F in Chapter 4.1).
2. Used identified needs to determine CityGML's SVO LOD specification shortcomings:
    - Analyzed how CityGML's and other vegetation LOD specification approaches defined their LODs, i.e., how LOD specification metrics were used, requirements, their differentiation, and how they related to each other and to other objects (Chapter 4.3). Analyzed LOD description approaches covered different perspectives: national standards, researchers, and proprietary modelers which cover a wide range of users.
    - Identified the specifications that were key in defining LODs that allowed fulfilling identified needs. The strengths and weaknesses of the specifications were grouped based on the geometry type of the descriptions. Those that allowed LODs to meet the identified needs were considered strengths. Many coincided with explicit modeling specifications (Table 4.3).
    - CityGML's shortcomings coincided with many of the implicit geometry modeling specifications. They are described in Chapter 4.5 and are listed below as they are addressed in the formulation of the refined LODs.
3. The strengths that the two distinct modeling approaches offered were combined:

   One of CityGML's LOD specifications strength is the relative low cost of acquisition, realization, and friendliness for computing and storage resources from using implicit geometry. This aspect is preserved in lower LODs. Intermediate and higher LODs offer increasing adherence first with components, and then with explicit geometric specifications. The strengths of explicit modeling are adopted for high LODs at component level. Resulting LODs join both modeling approaches to meet different requirements.
4. Other aspects: vegetation data availability, acquisition and computational costs, and the vegetation models used in publicly available 3D city models (Chapter 3.2) were considered as follows:
    - Low vegetation data availability is addressed by providing standard parametrical specifications so LODs can still be implemented provided the positions of SVOs are known. These specifications are given in the Requirements and Recommendations section 5.5.
    - Acquisition and computational costs (Chapter 3.2) are addressed as strengths and weaknesses from the definition perspective (as explained in item 3, above). Higher costs are limited to LOD3.x. Notes regarding certain parameter's accuracy in relation to acquisition are given in the requirements section 5.5.
    - Widely used implicit SVO models in publicly available datasets are included and differentiated.
5. Requirements and guidelines for modeling SVOs besides trees are found in requirements section 5.5.

5.2 LOD FORMULATION

Refined SVO LODs address CityGML's main shortcomings for fulfilling identified needs. The specifics of each shortcoming are given in Chapter 4.5. Each shortcoming is addressed as follows:

1. *No SVO representation in LOD0 or terrain level, and no underground representation*
    - SVOs are incorporated in LOD0 with non-3D representations, i.e., 0D, 1.D, 2D and 2.5D as used by practitioners for managing and planning SVOs. These specifications form the LOD0.x family. They describe SVO locations, canopy projections, and representation of groups of SVOs. The needs for these representations are described in Chapter 3.2 and in use cases 1, 4 and 21 in Chapter 3.1., The addition of this family allows the exclusion of assorted datasets into city models which promotes data sharing and data mining if made publicly available.
    - The optional 2D/2.5D root spread representation allows underground depiction at terrain level.
2. *Higher LODs have insufficient degree of adherence to real-world objects at object level and component level*

   This is addressed in two ways:

   1. Based on the most needed SVO representations identified as needs (items A, B, C, D in Chapter 4.1) respective specifications are added:

a. The need for 2D, 2.5D, 3D models and data for visualizing or communicating designs, topology, sharing information, visual analysis, planning and assessing space availability:

- Realistic models for visualizing or communicating designs, to reflect multiple aesthetic changes, e.g., of life stage or seasons (use cases 9 -12)

  These are fulfilled with LOD2.B, the realistic implicit LOD which reflect leaves and branches (blooms, Winter, Autumn foliage, etc.) to visualize SVOs that do not yet exist or to reflect future aesthetic changes in new designs or renovation plans.

- Models of multiple levels of adherence to visualize vegetation topology, for visual analysis of distributions of vertical and horizontal of distances or of tree types, and crown forms to reflect spatial requirements and type (2, 3, 5-7, 20, 29, 30)

  LOD1.A extrusions, and LOD1.B (for irregular footprint adherence) provide basic dimensions for visualizing distributions vertically or horizontally (use cases 2, 3).

  LOD1.C (lollypop) and LOD1.D (billboard) which are more aesthetic in appearance add SVO presence in 3D city models and share data in interactive 3D city models (use case 30). LOD1.D which displays foliage is commonly used with textured buildings. It has slightly higher adherence in appearance than previous. These two LODs, differentiate and formalize the two most common SVO representations used in publicly available datasets and in 3D city models (use cases 29, and 30).

  The LOD2.X family provides higher adherence for visualizations and visual analysis of distributions of tree types differentiated by their forms (use cases 6), and for more meaningful spatial representation of crown types for streetscape designs (use cases 7). LOD2.A, the implicit volumetric, is a low-cost LOD option for matching SVO forms where regular canopy is suitable (use cases no. 6, 7, 15, 16).

b. The need for 2D, 2.5D, 3D models of varying degrees of adherence (not aesthetics), and component granularity to analyze spatial relationships or assess impacts to surroundings:

- LOD1.A/B, LOD2.A/C, LOD3.A, LOD3.B/C and Root LODs fulfil multiple levels of adherence in spatial aspects some with component granularity.
- Root LODs for the root spatial requirements and parameters (5, 7, 8, 20).
- LOD2.C, LOD3.A, LOD3.B, LOD3.C provide crowns as component with varying adherence levels in forms (6, 7, 13, 16-18, 24) and properties, i.e., crown sparsity (case no. 7) and transparency (case no. 18). Some for small extent, some for larger.

c. 3D models and reconstructions to extract or estimate parameters and properties

- LOD3.B models crowns for estimating parameters of irregular crowns (24)
- LOD3.D defines tree reconstructions to extract non-measurable properties, e.g., biomass, simulate and assess properties, e.g., mechanical tolerances, canopy evapotranspiration process (24-26)

d. Models and data as input to spatial impact simulations (13-16, 21-23)

- LOD0. x, LOD2.A/C, LOD3.C fulfill as models of multiple adherence levels and data--canopy cover (2D) and vegetation type i.e., LOD2.A/C, LOD3.C reflect tree type forms for placement optimization simulations.

2. Providing adherence requirements in appearance and semantics.

   Refined LODs specifications expand not only in geometric aspects, also in dimensionality, feature complexity, and appearance specifications for each level with semantical requirements.

3. Weak LOD differentiation, partly due to underutilized LOD definition concepts

The weak differentiation of CityGML's is because it is mostly based on geometry complexity specifications (total height) for a couple of LODs, and in an appearance change in the highest LOD. Specifications that address differentiation, which also allow fulfilling identified use cases' needs, leverage LOD definition metrics and contribute to the core of requirements and specifications of refined LODs:

- Components, e.g., crowns and roots, were specified which introduce component granularity differentiation and increase adherence.
- Discrete feature complexity specifications for each LOD are specified to define the inclusion of vegetation in LODs. Horizontal specifications are also specified, and standard component ratios are given as guidelines where only SVO locations are known.
- Consistent descriptions of appearance as well as spatio-semantic relationships are provided and required also at component level to increase datasets compatibility.

4. Limited in attribute specifications

- Apart from modeling parameters, attributes are needed in many use cases. In addition to the attributes identified in the use case analysis (Table 4.1), others were added based on the analysis of the LOD approaches producing a slightly longer list (Table 5.3). Only those that are in bold are required. The rest are optional. Chapter 5.5 describes and justices their inclusion.

5. *Uncertainties from specifications gaps and inconsistency*

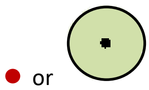
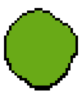
   This shortcoming relates to inconsistent specifications brought by gaps, and from vagueness of ordinal specifications. Uncertainties are also introduced by other specifications that do not seem to apply to vegetation objects as described in Chapter 4.5. Refined LOD specifications address this shortcoming with clear and consistent specifications and requirements for each LOD. At the same time, specifications allow to fulfil identified needs:

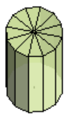
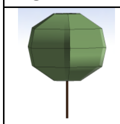
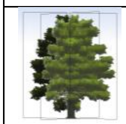
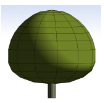
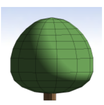
   - Components (crowns, trunk, roots, crown components) are specified for each LOD and increase progressively
   - Feature complexity specifications are required in all LODs and rules are provided.
   - Appearance specifications are provided and required in the form of material color at component level for each LOD.
     - Other uses of appearance are recommended, e.g., to reflect properties or status
     - Restricting the term *realistic* to appearance avoids its use to indicate solely a high LOD.
   - Semantics coherence is required at component level for each LOD. When appearance is used for denoting properties, it is also required to have a respective semantic description.

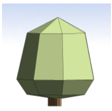
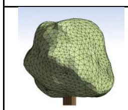
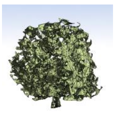
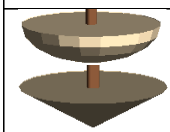
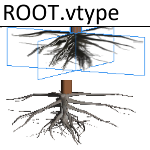
5.3 LOD DESCRIPTIONS

Each LOD is described independently in Table 5.1. The use cases that each LOD fulfills are listed, as well. For information on a particular use case, see Appendix A.

Table 5.1: LOD Descriptions Matrix

	Description	Need(s) fulfilled	See use case(s)
LOD0.x	• Incorporate SVO representations in 0D, 1D and 2D used in common practices (Chapter 3.2) • Brings extensive non-3D datasets into 3D city model's terrain • Represents most generalized form of SVO canopy at terrain level		
 LOD0.A	• Point (small filled circle) for location representation • 2D, 2.5D crown buffer based on Cd from SVO location	Visualize SVO distribution or locations of • Tree inventory in public space safety maintenance and planning • Tree assets for management and planning work above and below ground Rough estimation of canopy cover in • estimating avoided water runoff and green-grey relationships • for input to ecoservices estimate and benefits analysis	1, 4, 10, 21
 LOD0.B	• 2D, 2.5D crown projection from acquired canopy dripline • Projection reflects irregularities • Location often estimated from centroids • Higher acquisition cost than LOD0.A due to additional data, e.g., LiDAR	• Estimation of canopy cover where higher accuracy is desired given that it reflects canopy irregularity • Its acquisition often includes non-SVO vegetation expanding canopy cover estimation	10, 21
 LOD0.C	• Reflects consecutive relationship where individual trees/hedges are not discernable or fulfil a function	• Represent trees along roads, wind barriers, sound barriers, or green structures around buildings or areas	Common practices (Chapter 3.2)

	Description	Need(s) fulfilled	See use case(s)
LOD1.x	• Adds adherence to height (and width) to LOD0 canopy projections • Differentiates CityGML's LOD1 • Differentiates semantically popular vegetation symbols between volumetric and non-volumetric • (+) Least demanding LODs in terms of acquisition and resources • (-) Low adherence		
 LOD1.A	• Regular canopy extrusion • Scaled in height (and width)	• Visualize placement and height distribution • (+) For worst case or maximum volumetric scenarios • (-) Low adherence	2, 3, 19 Shadow analysis,
 LOD1.B	• Irregular canopy extrusion • Scaled in height and width	• Same as previous, but where canopy projection needs to be of higher adherence or is irregular	Same as previous in irregular versions
 LOD1.C	• Implicit tree symbol "Lollypop" • Generic volumetric SVO	• Add SVO presence in 3D city models • (-) Low adherence • (+) easy to acquire	29, 30
 LOD1.D	• Implicit "Billboard" • low polygon	• Same as previous. Popular because of low polygon count and foliage color matches textured buildings in aesthetically • (-) Low adherence • (+) Low IT resources demand	29, 30
LOD2.x	• Pre-made models (not acquired from real-world object) • Reflect genus or species form • Best adherence to real-world objects that have a regular shape or form • Scaled in height and width • (+) Implicit models leverage the flexibility to exchange, store, and reuse of models		
 LOD2.A	• Implicit volumetric SVO with S1 – S8 crowns	• Representing SVOs and reflecting type by form using S1 – S8 most common canopy/crowns, e.g., analyze tree diversity and distribution, streetscape, enrichment • Adherence depends on regularity of real-world's crown/canopy • (+) Low-cost LOD for matching SVO forms • (-) cannot scale separate components	6, 7, 16, 29, 30,
 LOD2.B	• Implicit realistic LOD: 3D leaves and branches (blooms, Winter, Fall foliage, etc.) • Standard representations of SVO by species or genus	• Visualizing and communicating designs, which reflect multiple aesthetic changes • (-) cannot scale separate components • (-) generic library model not acquired from real-world object • (-) high IT resources demand • (+) easy to acquire representations of the same species with different seasonal and life stage appearance	9 to 12, 29, 30
 LOD2.C	• Implicit crown (S1 – S15 crowns) and expandable • Implicit trunk • both scaled separately	• For higher adherence of crown by either using an expanded shape, and/or adjusting the crown base height to better match SVOs morphology, e.g., assess SVO optimal morphology based on street configuration, noise reduction • Adherence also depends on regularity of real-world's crown/canopy • (+) easy to acquire	13, 15, 16

	Description	Need(s) fulfilled	See use case(s)
LOD3.x	• Base on real-world objects • Point cloud based • Best adherence to real-world objects that have an irregular shape or form • Add adherence at component level • Varying adherence for extracting additional parameters or properties, e.g., volume, surface area as proxy of leaf area		
 LOD3.A	• Parametric • Explicit geometry tree model based on coordinates form the real-world object that it represents • Implementation can be of higher adherence if increasing crown points extrapolation	• To identify UHI prone areas • Can define sub-levels based on "layers" of Hp points • (+) Irregular crowns, enough adherence for extracting volume and surface area • (+) Crown acquired from real-world object • (+) Automated process • (+l supports large extents • (-) requires expertise	17, 27
 LOD3.B	• Convex hull •	• (+) higher adherence to irregular crown and entire SVO, e.g. crown properties extraction • (-) manual selection • (-) small extents	27
 LOD3.C	• Non-convex hull • Non-convex	• Where transparency of crown/canopy needs to be represented • Higher adherence to irregular crown and entire SVO, e.g., Urban vegetation, Tree shadow impact on solar panels avoided runoff contribution • (-) manual selection • (-) small extents	14, 18
 LOD3.D	• Reconstruction	• Where reconstruction is needed especially of trunk and branches, e.g., estimating biomass, • (-) manual selection • (-) small extents	24-26
Roots	• Optional LODs • Volumetric and aesthetical root representations • Not aligned to a particular SVO LOD		
 ROOT.sprd	• Root spread	• For visualization of root spread or projection	5, 7
 ROOT.vol	• Root volume	• Visualize and assess root space requirements and planting feasibility • Visualize root in underground 3D models for space distribution • Communicate topology requirements	7, 8 ,20
 ROOT.vtype	• Volumetric representation of root types	• Same as above with root type variants	Same as previous
 ROOT.realistic	• Billboard and realistic representations of roots	• Same as above with more aesthetical representations in billboard or realistic model variants	5

LOD0.X

This LOD family represents SVOs as 0D or position coordinates, 1D as lines for rows of trees/hedges, and 2D crown projections. They target to meet common practices uses (Chapter 3.2)

Required parameters are the SVO position and the crown diameter (Cd). A suggested min. crown size is 12 m for visibility, however, the size should be adjusted considering the model scale. SVO position coordinates and crown sizes can be acquired with watershed segmentation. In this case SVO positions can be estimated as the centroids of crown contours, and depending on the data used, their height can also be extracted which are useful for LOD1.x. Watershed segmentation was used for the case study with steps described in Appendix C.

Further, the attribute *Type* (deciduous/evergreen*)* is required. Distinguishing tree types allows considering seasonal differences in percent tree cover estimates. In combination with percent building cover, regional energy savings impact can be estimated, as well (Table 0.1 in Appendix A). Semantical description of the representation is required, e.g., *tree_ID* for a point location, *crown* for LOD0.A when the crown radius is used to buffer a tree position, *crown dripline* for LOD0.B when a polygon reflects extracted crown contour, *Tree/hedge row* for LOD0.C, and *root* to denote root spread projection. The *Root* component is optional. Visualization and appearance specifications are provided for each representation. Both target proper visibility. The optional root system representation is similar to the crown projection but with the root spread diameter (Rsd). LOD0.x sets up the base for the LOD1. Roots are described below.

LOD0.x LODs acquisition remarks:

- Acquiring the trunk position may not be possible with aerial LiDAR data with low point density in the underside of crowns
- Centroids of the crown projection are an alternative way for estimating the SVO position if suitable for the application at hand.
- In this case study, watershed segmentation was done with an ArcGIS workflow. It was lengthy but can be automated using the built-in model tool or scripting the process. It is a very well researched acquisition process. See watershed variations compassion by Amiri et al. (2014).

LOD1.X

LOD1.x are all scaled in height; therefore, require *total height* parameter. Acquiring tree heights for an area is commonly done with aerial LiDAR data in watershed segmentation, derived height models, or a combination with other data sources as covered in Appendix C.

This family has one component, *Tree*, and the optional *Root* component, both required to be semantically specified. Minimum sizes are required, and they can be set either in total height or crown diameter. The latter can be related to the size used in LOD0. In this case, a Cd of 6 m is suggested or half the size of LOD0's. If using a total height, the suggested height is 9 m, slightly lower than the standard height or 10 m. Required additional attributes are *Class*, *Usage* and S*ignificance*. *Class* and *Usage* are existing attributes in CityGML SVOs. *Class* values should reflect *Tree*, *Hedge,* or *Shrub,* and *Usage* values should reflect functional roles, e.g. shadow cooling or heat mitigation. S*ignificance* reflects current status e.g., endangered, monumental, etc., which serves for data mining as well as for visualization by role or status. Appearance specifications relate to material color for extrusions, volumetric symbols, primitive shapes, or realistic pattern for billboard models.

LOD1.A and LOD1.B LODs are coarse parametric extrusions of crown projections or contours to acquired total height (Ht). LOD1.A or cylinder is the equivalent to CityGML SVO LOD1.

LOD1.C and LOD1.D incorporate popular implicit tree symbols and billboard models. They are CityGML's LOD2 and LOD3 equivalent (height requirements are different).

LOD2.X

LOD2.A (volumetric) and LOD2.B (realistic) recognize popular implicit representations as separate LODs. Adherence is increased by scaling to acquired height and width, and the crown is required to reflect the SVO's species or genus, therefore, the *Species* attribute is required. it is recommended that LOD2.A volumetric implicit models reflect crowns that are not manually altered or that have a relative regular crown form. See Recommendations in Section 5.5.

LOD2.C separates the crown from the trunk allowing crown shapes to be expanded. This LOD requires a trunk diameter (Td) or DBH parameter, and the crown base height (Hc) attributes for scaling of each component. For SVO's whose crowns reach the ground or when there is no discernable trunk, the model reaches the terrain and has a trunk height of 0. See Recommendations in Section 5.5.

Implicit models can be acquired online using different selection criteria as described in Common Practices Chapter 3.2. Volumetric shapes can also be purchased or created with a 3D graphics tools to then incorporate into a model library as described in Chapter 6. Crown shapes S1 to S15 are provided (see Chapter 4.2).

Semantic and appearance specifications should correspond to components: for LOD2.A/B are *Tree*, and optionally, *Root*, and for LOD2.C, *Crown*, *Trunk* and optionally, *Root*. Additional required attributes are the *Life stage* and *Condition* for sustainability and data mining, or to analyze tree diversity and distribution which is possible when able to visualize vertical and horizontal distribution (NYC Parks, 2015). In the latter case, appearance changes can be used as mentioned in the recommendations in Section 5.5.

Notes:

- Relies on knowing species or genus of the tree or SVO
- Acquiring realistic models for each species can be a hinderance if numerous
- All species under the same genus have the same shape but there are some exceptions
- Provides no adherence to irregular crowns

LOD3.X

This set of LODs represent crowns or canopy of sufficient adherence to irregular crowns and for extracting additional parameters or properties, which otherwise are not possible. LOD3.A (parametric) and LOD3.B (convex hull) focus on the crown. LOD3.C (non-convex) and LOD3.D (reconstruction) focus on adherence to the entire tree. There are no equivalent in CityGML SVO LODs.

The parametric LOD3.A and convex hull crown LOD3.B require coordinates from a 3D data source, e.g., LiDAR or photogrammetry. LOD3.C and LOD3.D require LiDAR data with significant density to capture branches. The adherence of both LOD3.A and LOD3.B can be changed based on number of points forming the polygon or triangles, or on smoothness levels. A key difference is that LOD3.A is automation friendly for numerous SVOs than LOD3.B. Acquisition and realization workflows for these LODs are described in Appendix C.

LOD3.C models crown transparency but without reconstructing the components as with LOD3.D. Depending on their storage format, they can be inserted as implicit models once created.

In the SVO reconstruction LOD3.D, components include branches and leaves and further granularity related to branches, e.g., second and third levels of branches can be added by the user.

Resources demands:

- Storage needs to be thought out. The geometric primitives can be stored separately or if the object is saved as a single object which can then be inserted as implicit models but one for each SVO.
- Requires a learning curve for acquisition techniques, modeling tools, and tool related scripting
- Convex and non-convex required manual selection
- Parametric SVOs require manipulating each tree's LiDAR separately for coordinates acquisition.
- Reconstruction is a manual process although many objects can be worked on at the same time, but the tool used, SimpleTree, requires terrestrial LiDAR with discernable trunk and branches.

ROOT.X REQUIREMENTS

Different root LODs are defined and they are all optional. Root types descriptions are provided in Chapter 4.

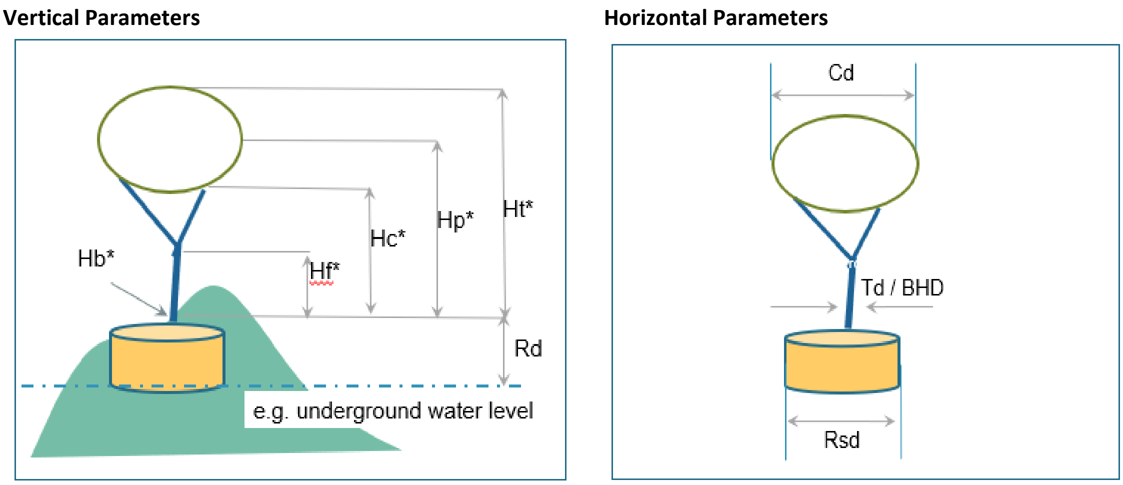
As a feature, a root is the underground extension of a SVO and an element of a tree, just like the crown, trunk, etc. Compared to a building, it is the equivalent of the foundation or basement. When included, a root is required to be attached to an above ground component trunk or canopy if it is alive. See requirements in Section 5.5.

As with other components, their minimum size specifications are required along with semantical and appearance specifications. Acquisition of root spread diameter and depth for volume estimations is described in Chapter 4.2.2. In general:

- There are many approaches for assessing the horizontal spread and is subjective in terms of how conservative the estimation can be.
- Vertical assessments require additional GIS data of a site's underground.

5.4 SPECIFICATIONS

Refined SVO LOD specifications are in Table 5.2. Parameters used in specifications provide explicit vertical, horizontal, and basic root parameters (Figure 5.2). Crown shapes are described in Chapter 4.2 (Figure 5.3). Attributes listed in the specifications are found in Table 5.3 and are described in section 5.6.



Ht*	Tree top relative to Hb		Cd	Crown or 2D dripline diameter
Hb*	Baseline or elevation		Cr	Crown radius
Hp*	Height at crown widest perimeter		Td	Trunk diameter/Breast height diam. (BHD)
Hc*	Crown base height		Rsd	Root spread diameter
Hf*	First fork height			
Rd	Root depth			

* SILVI-STAR tree model parameters (Koop, 1989)

Figure 5.2: Geometric parameters of refined SVO LOD descriptions

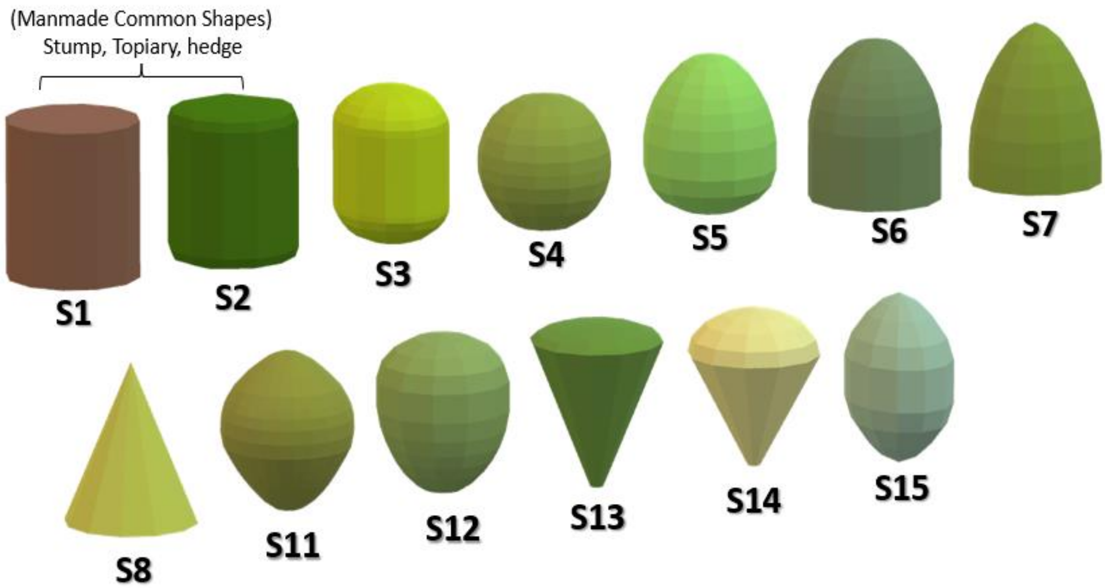


Figure 5.3: 13 most common SVO shapes

Table 5.2: Refined SVO LOD descriptions

Note: while each LOD has a minimum set of requirements, acquiring higher LODs parameters and attributes is encouraged.

	LOD0.x	LOD1.x	LOD2.x	LOD3.x
Dimensionality	0D, 1D, 2.5D	2.5D, 3D	3D, (4D temporal)	3D, (4D temporal)
Brief description	• Position • Canopy projection • Crown dripline contour • Trees/hedges row	Scaled in height: • Canopy extrusions • Implicit SVO symbol • Billboard SVO	Scaled in height and width, reflect genus or species: • Implicit volumetric or • Realistic • Crown and trunk scaled separately	Crowns: • Parametric • Convex hull • Non-convex SVO: • Reconstruction
Semantics	• Position • Crown projection • Crown dripline • Tree/hedge row • (Root projection)	• Coherent to components	• Coherent to components	• Coherent to components
Components	• Crown • (Root)	• Tree • (Root)	• Tree • Crown • Trunk • (Root)	• Crown, trunk • Branches • Leaves, (Root)
Min. geometric parameters	• Position (x, y, 0) or (x, y, z) where z=Hb • Cd/dripline contour	• Position (x, y, 0) or (x, y, z) • Cd/dripline contour • Ht	• Position (x, y, z) • Hb, Cd, Ht, Hc, Td/DBH	• Position (x, y, z) • Hb, Cd, Ht, Hc, Td/DBH, Hp
Min. size:	Cd ≥12 m	Ht ≥ 9 m or Cd: ≥ 6 m	Ht ≥ 3 m or Cd: ≥ 3 m	Ht > 0.3 m
Min. attributes	• Type • Application specific attributes	LOD0’s and … • Class • Usage • Significance • Application specific	LOD1’s and … • Species • Crown shape • Life stage • Condition • Application specific	• Same as LOD2 • *Application specific attributes*
Visualization Sub-levels: A, B, C or D	• Points as dots, spheres or crown circumferences • Top view of crown contour or dripline • Line segment	• Crown projection extrusion • Crown dripline extrusion • Tree primitive shape or symbol • Billboard tree	• Volumetric trees with S1 – S8 crowns of predominant genus/ species in dataset • Realistic tree model of predominant genus/ species in dataset • Volumetric crowns with S1 – S15 shapes	• Base on sub-level
Appearance	• Colored dots’ spheres • Filled or outlined polygons • Size, line thickness, and colored for clear visibility	• Material with natural color (MNC) for extrusions • Implicit tree symbols/billboard appearance with MNC or realistic pattern	A. Volume form reflects genus/species (S1-S15) B. Realistic leaves, branch reflects genus/species Optional: reflect 1 & 2 with A, or 1 and 3 with B. 1. Life stage 2. Condition 3. Seasonal foliage	• Crowns and trunk with MNC • Reconstructed components with MNC

Root system	Root A	Root B	Root C	Root D
Optional. Roots B, C and D are exchangeable	• Root projection • Rsd	• Implicit volumetric cylinder, or billboard • Rsd, Rd	• Implicit volumetric can reflect type • Rsd, Rd	• Implicit realistic • Rsd, Rd

5.5 REQUIREMENTS AND RECOMMENDATIONS

When the following requirements are met, descriptions can be considered a LOD:

Trunks

- Trunks have an attached crown if the real-world object is alive, not dead or is a stump
- One trunk or main branch to 0 or 1 crown relationship where trunk height is > 0 m.
- A trunk can be extended with branches as in a reconstructed tree
- Where no discernable trunk is found, trunk can be set to a 0 height and the SVO represented by the overall crown or canopy shape

Crowns

- No floating crowns. They require a trunk or main branch except when they reach the ground, when there is no discernable single trunk/stem, then the crown sits at terrain level.
- Dead trees or stumps do not have a crown

Roots

- Root components are optional
- No floating roots. For LOD1.x and higher, a root requires an attached above-ground component if the SVO is alive. For example, an implicit tree, a crown extrusion, canopy shape with no trunk, or a trunk in LOD1.C or greater. This is to maintain reference with above ground objects even when the root is the main object.

Feature complexity or minimum size specifications are required per LOD and at component level:

- Discrete values are suggested in specifications and can be vertical or horizontal linear distances.
- When tree parameters are not acquired, standards species dimensions can be used. If unknown, generic standard sizes can be used and components sizes can be based on typical ratios, i.e., standard tree height of 10 m., crown radius of 5m, trunk radius to crown is 1:20 m., and average crown base height of 3 m as suggested by Rip (2013).
- To include young trees, the total height or DBH can be used: DBH > 2.54 cm (1 in) and height > 30.5 cm or .3 m (1 ft) (i-Tree, 2018).
- Considerations: in defining total height and the crown base height of a SVO, the total height can be that of the top leaf or point, or the 99, 97 or 95 percentile heights. Each option impacts distribution analysis as seen in Figure 0.22 in Appendix C, and subsequent calculations. Similarly, the crown base height can be the height of the lowest leaf or point, or the 1 or 5 height percentiles. For ecoservices estimation, the total height is measured form the ground to the top of the tree even if the top part is dead, and the crown base height is up to the leaves at the base of the live crown. Branches with no foliage at the base of the crown are not included (i-Tree, 2018).
- When more than one LOD is planned, required minimum sizes should be set to change in similar proportion to preserve adherence progression. For example, the crown diameter min. length changes from 12 m to 6 m to 3 m for LOD0, LOD1 and LO2, respectively.
- There are different ways for estimating root spreads and depths. These are covered in Chapter 4.2.2. In general, maximum depth is usually determined by area's underground rock bed, water level, or other impenetrable or unhealthy surface. For spread estimation, available tree data can be used, e.g., crown diameter, total height or DBH. It is recommended to use whichever is considered more reliable.

Appearance specifications can be used to reflect properties, e.g., life stage, health, condition.

- Different material colors can be set. Textures and patterns are optional.
- Other uses of appearance are recommended. For example, changing the material color to reflect life stage, species, condition (sick, healthy), height class, etc. for assessing their distribution (use case 6).
- When appearance is used for denoting properties, it is also required to have a respective semantic description of the property, e.g., "Young", "Old", "Endangered", etc.,

Crown shapes

- Crowns are (1) a volumetric feature, (2) non-convex object, or (3) one to many crown components: leaves, fruits, flowers, buds, etc. that are not branches.
- When procuring for volumetric models to fulfil LOD2.A, it is recommended that the models contain S1 to S15 crown shapes, or at least S1 to S8 shapes as described in Chapter 4.2.1 which reflect the most common regular crowns and can be reused for different species and genera.

Attributes

- Some attributes are required by each LOD. These are specified in Table 5.1.
- Lower LODs can have other attributes and parameters, especially temporal attributes.

Ordinality of LODs and geographic extents

- Refined LODs align to CityGML's LODs but are not bonded to given geographic extents.
- The combination of refined SVO LODs and another object's is set by the user.

Accuracy

- These descriptions are not included in LOD descriptions; however, object-based specifications not associated to a particular LOD seems most appropriate.
- Separate accuracy descriptions for location, heights and widths are recommended. Given the different acquisition methods can be used to acquire heights from widths. For example, different accuracies can be set for the trunk's terrain elevation, since a change of more than 12 cm is detrimental to roots. Similarly, total heights, crown base heights, and crown diameters, can have separate accuracies because when acquiring them, it is common to use different acquisition processes as in the realization of LODs in this research.

5.6 ATTRIBUTES

Table 5.3 lists the attributes with adopted terminology. Those in bold font are in LOD descriptions as minimal requirements. The list includes crown and root parameters, and multiple classifications are no longer confined into a single *Class* attribute. The extended list also allows a dataset to be input to mainstream ecoservices assessment simulations and it supports the following:

1. Explicit parametrical tree specifications that facilitate SVO geometric complexity descriptions and explicit modeling to achieve higher adherence for quantitative analysis
2. Calculating properties which cannot be measured directly in addition to parametrical dimensions, e.g., crown properties for estimating leaf area and leaf biomass
3. Classification granularity: class (tree or hedge), type (deciduous or not), and botanical (species), and usage or roles, e.g. for cooling, or mitigation of noise, or water runoff., which support data mining, querying tasks, and combining datasets selectively
4. Assessments of ecoservices from simple attributes that describe tree structure
5. Temporal (growth, appearance changes)
6. Sustainability management and condition monitoring attributes, i.e., related to tree condition, risk, significance (endangered, historic, etc.), status, etc.
7. Assessments of underground space requirements
8. Topological descriptions of trees with respect to buildings

There is no restriction for acquiring additional attributes, e.g., LOD0.x can contain all extended attributes. In fact, this is encouraged since it can then be input to simulations, and when shared, allows datamining.

A cross-check of attribute requirements in the 30 use cases (Chapter 3) against those in the extended list in Table 5.3 is shown in Table 5.4, which illustrates the diverse applicability of refined LODs.

5.6.1 Extended List of SVO LOD Attributes

In the Table 5.3, required attributes are listed in bold font. There is no restriction acquiring additional data.

Table 5.3: Extended list of SVO LOD attributes

Type of attribute	Attribute	Description examples
Parameters	**Hb**	Baseline or elevation
	Ht+	Tree top relative to Hb
	Cd+	Crown diameter or dripline contour diameter
	Td/ BHD+	Trunk diameter/Breast height diam. (DBH)
	Hc+	Crown base height relative to terrain elevation
	Hp	Height at crown perimeter
	Hf	First fork height
	Rd	Root depth (see Underground attributes)
	Rsd	Root spread diameter (max.)
Crown Properties	**Shape**	S1 – S15 shape numbers
	Light exposure+	Sun exposure
	Percent missing+	Crown volume missing
	Condition/dieback+	Estimate of dead branches
	Density	Open, semi-closed, closed
Temporal Properties	**Life stage**	Seedling/Young/Adult/Mature/Ending
	Growth rate per Yr.	
	Foliage fall/sprout/bloom	Month of year
Status	**Significance/**importance	Endangered/monument/historic/none
	Condition	Excellent, good, fair, poor, dead, plagued
Classifications	**Type**	(Semi)Deciduous/(semi)Evergreen
	Class	Tree/Hedge/shrub
	Species+	Latin name
	Usage	Shadow/Erosion/Water run-off /Wind block
Underground	Vertical distance limitation	e.g., underground water, rock bed level, none
	Max root volume	
	Root type	Shallow, heart, deep
Topology	Distance to building+	
	Direction to building+	
Land related	land use+	
	Percent tree cover+	Percent to nearest 5%
Application specific	E.g.: Maintenance - height class	Tall, medium, small

+ Data used for estimating ecoservices. See use case 21 in Table 3.1.

5.6.2 Use Cases Attributes and SVO LODs

Table 5.4 maps refined LODs and attributes in the extended list against vegetation models and data that use cases in Chapter 3 mostly required.

Table 5.4: Use cases, type of vegetation attributes used, and LODX.x close matches

		Attributes in extended list in Table 5.3									
Use case		Parameters (additional)	Classifications	Crown prop.	Topology	Status	Land type	Temporal	Underground	App. specific	LODX.x model or attributes
1	City tree, progress and properties track	✔	✔	✔		✔		✔	✔	✔	LOD0/1/2.x
2	Determine of towers location	✔					✔	✔			LOD1.x
3	Overhead rail maintenance	✔		✔	✔						LOD1.x
4	Plan work above and below ground	✔			✔	✔		✔	✔	✔	LOD0/1/2.x
5	Communicate above, below ground topology regulations	✔	✔		✔	✔		✔	✔	✔	ROOT, LOD2.x,
6	Analyze tree diversity and distribution	✔	✔	✔			✔	✔		✔	LOD2.x,
7	Streetscape spatial req. estimate	✔	✔	✔	✔		✔	✔	✔		ROOT, LOD2.A
8	Tree root spatial requirement estimate	✔	✔		✔		✔	✔	✔	✔	ROOT, LOD2.A/B
9	Promote sites and projects	✔	✔	✔				✔		✔	LOD2.x
10	Solicit collaboration and participation	✔	✔	✔			✔	✔		✔	LOD2.x
11	Design alternatives decision making	✔	✔	✔	✔			✔		✔	LOD2.x
12	Communicate site renovation /current-future changes	✔	✔	✔			✔	✔		✔	LOD2.x
13	Mitigate negative effects of climate change - UHI	✔		✔	✔	✔				✔	LOD2/3.x
14	Urban vegetation avoided runoff contribution	✔	✔	✔	✔				✔	✔	LOD2/3.x
15	Vegetation morphology and placement for noise reduction	✔	✔	✔	✔					✔	LOD2.x
16	Tree placement for cooling houses and parking lots	✔	✔	✔	✔						LOD2.x
17	Identification of UHI prone areas	✔	✔	✔	✔					✔	LOD2/3.x
18	Tree shadow impact on solar panels	✔	✔		✔					✔	LOD3.D
19	Vegetation and building vertical relationships for urban ecology	✔			✔					✔	LOD1.x,
20	Underground open space, object distribution assessment	✔			✔				✔	✔	ROOT
21	Structure and ecoservices analysis	✔	✔	✔	✔		✔			✔	LOD0/3.x
22	Ecoservices benefits analysis	✔	✔	✔	✔	✔	✔	✔		✔	LOD3.x
23	Growth forecast	✔	✔	✔	✔	✔	✔	✔		✔	LOD3.x
24	Urban tree allometric equation	✔	✔	✔		✔	✔	✔		✔	LOD3.D
25	Tree reflectance, directional transmission	✔	✔	✔						✔	LOD3.D
26	Tree structure tolerance to storm winds	✔		✔						✔	LOD3.D
27	Tree crown properties extraction	✔	✔	✔						✔	LOD3.x
28	Tree crown evapotranspiration estimate	✔	✔	✔						✔	LOD3.D
29	Modeling for 3D datasets enrichment	✔									LOD1/2.x
30	Inventory tree properties, data query	✔								✔	LOD1/2.x

6 CASE STUDY: SHADOW ANALYSIS

IMPLEMENTATION OF LODS FOR SHADOW ANALYSIS

The cooling effect of tree canopy is one of the benefits that city trees offer. Quantifying the number of shadow-hours a surface experiences serves in estimating such cooling effect. These measurements can be input to other estimations with economic impact, e.g., energy savings from less air conditioning usage in the Summer. To assess the impact of using different LODs, a shadow analysis is done for each representation.

In this chapter, the following is covered:

- Chosen vegetation and test area
- LOD specifications of models to be realized for this analysis
- The acquisition, implementation, and integration of specified LODs in a 3D city model in a workflow that brings a 0D tree inventory dataset into a 3D dataset

6.1 AREA OF INTEREST

The area chosen of this analysis is in Noordereiland, an island in Rotterdam for which the municipality has both aerial and mobile LiDAR data. The shadow casted by a large old Aesculus hippocastanum (Tree ID: 70562) on a pedestrian paved area is measured for each specified LOD. The tree is located at the corner of Burgeester Hoffmanplein and Van der Takstraat. It was selected for many reasons: its size, its unobstructed location. A Google photo of the area is shown in Figure 6.1 alongside to its model. The surface for which the shadow is estimated is shown in blue.

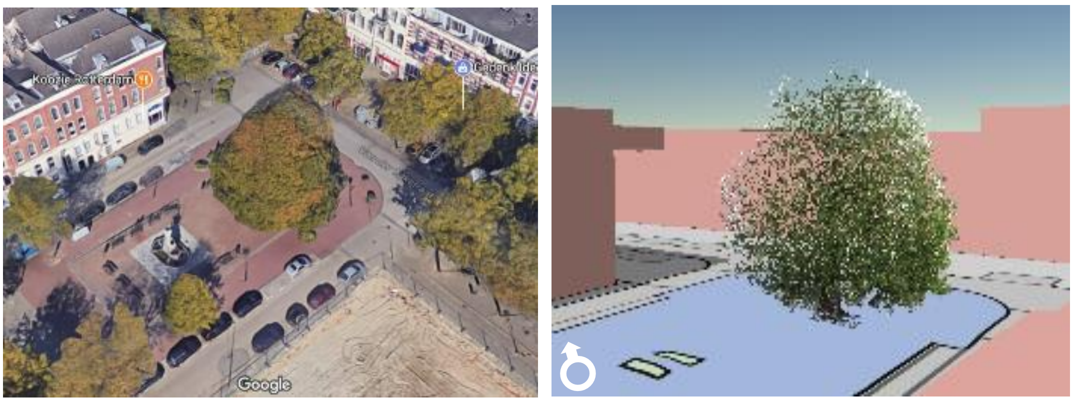


Figure 6.1: Shadow analysis case study area and test objects
Left: Aesculus hippocastanum with Tree ID: 70562 in Burgemeester Hoffmanplein and Van der Takstraat;
Right: 3D model of area.

6.2 LOD REQUIREMENTS FOR THE SHADOW ANALYSIS

Most of the refined LODs are required given the goal to observe their impact in the assessment. Nine out of the 14 LODs presented in Table 5.1 are required. The three LOD0.x representations are excluded. LOD1.B (crown contour projection extrusion) was excluded for two reasons: (1) the test tree's crown contour already resembles the crown diameter projection, LOD1.A, and (2) to include the 'worst case' scenario, LOD1.A. The reconstruction with branches as leaves, LOD3.D was not possible to realize due to insufficient trunk branches points.

6.3 IMPLEMENTATION WORKFLOW

The methodology for the case study was introduced in Chapter 1.3 with the research workflow shown in Figure 1.3. The implementation workflow is shown below in Figure 6.2. It also serves in establishing the degree of automation for generating models from the refined vegetation LODs when starting with a 0D vegetation dataset.

Upon determining required LODs, the implementation is done in four stages:

1. A fit-for-use examination of existing tree data against required LODs specifications is done to identify data in need of acquisition
2. Data acquisition is done within object-based parameter extraction methodologies
3. Realization of SVO models in specified LODs
4. Integration of realized SVO models into a 3D city model for input to a shadow analysis tools

To automate the workflow as much as possible, scripting and procedural modeling were used.

The aerial LiDAR data was primarily used so automated steps can be applied to new scans. The entire island was processed so shadow analysis with LODs up to LOD3.A (parametrical trees) can be done anywhere in the island. LOD3 models for the shadow analysis had parameters extracted from the mobile LiDAR data.

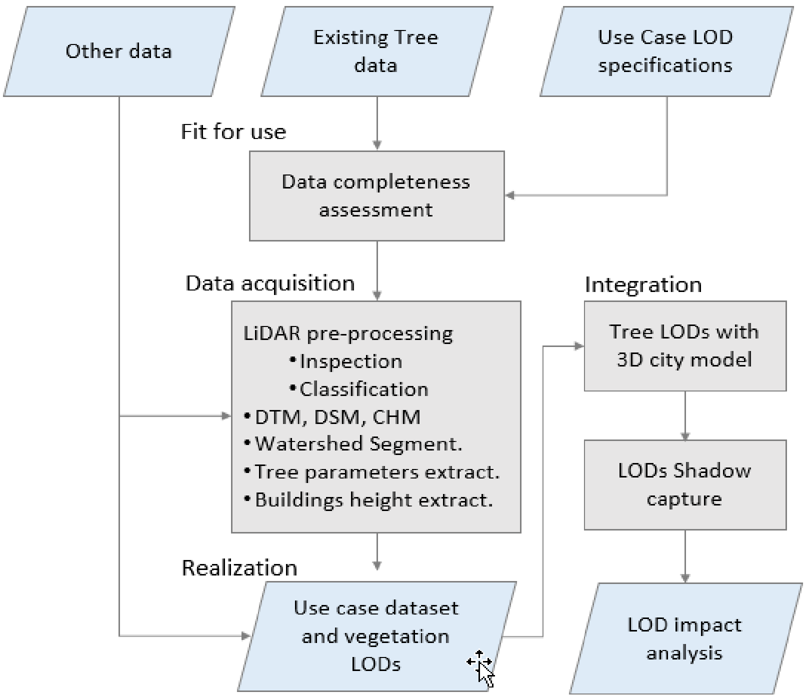


Figure 6.2: Implementation methodology

6.3.1 Tools

Tools already available in the municipality or open source tools, and techniques that were practical for municipality staff to utilize were chosen for the implementation of the models:

- LasTools, ArcGIS Pro, and Geomagic Studio 2014 for LiDAR data processing, visualization and for generating higher LODs, respectively.
- ESRI ArcGIS Desktop with for DSM, and CHM, and watershed segmentation
- Autodesk Maya for creating a 3D library of implicit components
- ESRI CityEngine for integrating datasets and for procedural LOD generation
- ESRI Local Government Shadow impact analysis package for ArcGIS Pro
- LasTools, CGA, and Python scripts for automation
- Excel for mapping model libraries to tree inventory dataset

6.3.2 Data

Rasters, and 0D, 2D vector data files were integrated in a 3D city model of the island and were also used for segmentation. Aerial and mobile LiDAR data were the sources of 3D parameters:

1. Digital terrain model (DTM) from the aerial LiDAR 2015-2016; 50 cm cell size
2. Vector 2D data of administrative boundaries for clipping areas
3. Topographic vector map (Basisregistratie Grootschalige Topografie-BGT) 1:1K for segmentation
4. Satellite photos: NEO bv Netherlands Space Office (2017) from 15/5/17 for segmentation verification
5. Aerial LiDAR data from 2015-2016 of 30 points m^2 in city areas
6. Mobile LiDAR data from 2014 of 358 points m^2
7. The municipality of Rotterdam tree inventory, ESRI shape file (Figure 6.3)
8. 3D vegetation models from ESRI-LumenRT

Figure 6.3: Municipality of Rotterdam vegetation data coverage of urban areas

The municipality vegetation inventory contains over 170K objects with 45 attributes including administrative codes. The objects are mostly individual trees owned and/or managed by the municipality of Rotterdam. Out of the 45 attributes, three are geometric parameters. Small, young trees are recorded with a crown radius of 0, but with a diameter of 1m. Other attributes are related to location, botanical genus, species, and forms. Temporal data covers the year a tree was planted and life stage. A list of the attributes can be found in Appendix C.

6.3.3 Fit-for-Use Analysis

The data required for implementing specified LODs for the shadow analysis was checked against the data available in the municipality's tree data. What is available is shown in Table 6.1.

Table 6.1: Available data in tree inventory to implement shadow analysis models

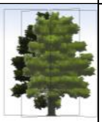
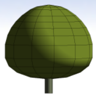
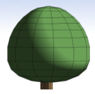
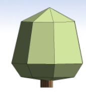
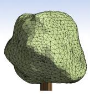
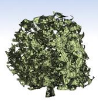
	Available in tree inventory data
LOD 1 A, C, D	Location coordinate point
LOD2 A, B, C	Crown diameter (Cd)
LOD3 A, B	Trunk diameter (Td)
LOD2 A, B, C	Tree species

6.3.4 Data Acquisition

The acquisition and realization including the data source used for of each LOD is summarized in Table 6.2. The entire acquisition process is further described in Appendix C and it consist of:

1. The LiDAR dataset pre-processing which entails the inspection of the point cloud to learn of existing classifications and of its point density. The inspection serves to establish needed re-classifications and raster's cell sizes.
2. The generation of DTM, DSM, and CHM rasters for height parameter extraction and segmentation
3. The segmentation of the point cloud using watershed delineation polygons
4. Extraction of other required SVO parameters

Table 6.2: Summary of LODs acquisition and realization

	Data used	Acquisition	Realization
 LOD1.B	• Tree inventory: • Tree ID • Location point coordinate • Aerial LiDAR	• 2D crowns dripline contours • Ht, total tree height Methodology: • Classified LiDAR vegetation data • Generated DSM, CHM, nCHM • Segmented: watershed delineation polygons LasTools scripts, ArcGIS	• Extrusion to Ht • Procedurally created • On demand generation • CE CGA scripts
 LOD1.C	In addition to previous: • Tree inventory: Cd, crown diam.	• Hb, tree base elevation • 3D generic tree model Methodology: • Hb extracted from DTM at location point coordinate • Manually created generic 3D model ArcGIS, Autodesk Maya	• Scaled model to Ht, Cd • Procedurally retrieved from created library • On demand insertion • CE CGA scripts
 LOD1.D	Same as previous	• Billboard tree model Methodology: • Acquired from ESRI vegetation library CityEngine	• Scaled model to Ht, Cd • Procedurally retrieved from ESRI library • On demand insertion • CE CGA scripts
 LOD2.A	In addition to previous: • Tree inventory: Tree species	• Volumetric tree model reflecting species or genus S1 – S8 crowns Methodology: • Researched species' crown shapes • Mapped inventory tree species crown to respective vol. tree model in ESRI library ArcGIS, CityEngine, Excel	Same as previous
 LOD2.B	Same as previous	• Species' realistic model Methodology: • Matched models to LOD2.A crowns ArcGIS, CityEngine, Excel	Same as previous
 LOD2.C	In addition to previous: (1) For case study tree: • mobile LiDAR (2) For Island trees: • tree inventory: Td, trunk diam.	• Td, trunk diameter • Hc, crown base height • Species' S1 – S15 crown models • Trunk model Methodology: • Td: (1) measured from point cloud's ISO curves • Hc: (1) extracted from point count at 50 cm height intervals; (2) extracted 1 and 5 percentile heights from 3, 4, and 5 pulse returns • Created S1 – S15 crowns and trunk models • Re-mapped crown shapes to tree inventory LasTools, ArcGIS, Maya, CityEngine, Excel	• Scaled crowns to Ht, Hc and Cd • Scaled trunk to Hc, Td • Components procedurally retrieved from created library • On demand insertion • CE CGA scripts
 LOD3.A	Same as previous	• Hp height at crown's widest perimeter • P1 to P4 perimeter crown points at Hp Methodology: • Hp: extracted for (1) and (2) from point-count at 1m height intervals from mobile and aerial LiDAR • P1-P4: extracted from segmentation bounds • Mapped parameters to tree inventory LasTools, ArcGIS, Excel	• Parametric trees • Scaled trunk to Hc, Td • Python script generation • Models stored for integration • ArcGIS
 LOD3.B	For shadow tree: • mobile LiDAR	• Convex hull of crown of case study tree Methodology: • Extracted point cloud slices at 1m height intervals for (1) from mobile LiDAR data • LasTools	• Convex hull of crown from thinned point cloud • Scaled trunk to Hc, Td • Geomagic
 LOD3.C	Same as previous	• Non-convex hull of case study tree Methodology: • Thinned mobile LiDAR data from case study tree • LasTools	• Non-convex hull of tree from thinned point cloud • Geomagic

6.3.5 Generation

The realization of the test SVO LODs and of the 3D city model consists of (1) the augmentation of the tree dataset. (2) The automated realization of LOD1.X, LOD2.X, LOD3.A, and of the 3D city model; (3) the non-automated realization of highest LOD3.B and LOD3.C, and the mapping of crown shapes to the inventory dataset.

Augmentation of the tree dataset (Table 6.3): Acquired data was added to the island's tree inventory dataset. A second dataset was created for generating parametric trees (LOD3.A) with coordinates for each crown. For LOD2.C and LOD3.A of the shadow analysis tree, values from Table 6.6 were used, many acquired from its mobile LiDAR. The bold values in Table 6.6 were used.

Table 6.3: Attributes added to datasets. (*) values as indicated in Table 6.4

Attribute	Field name aliases per dataset		
	Island trees	Parametric trees	Shadow tree
Hb	Z_terrain	X_ST, Y_ST, Z_ST,	Z_terrain*
Ht	HT_MAX_Z	HT	HT_MAX_Z
	HT_P99_1		HT_P99_1
Hc	HC_01P	HC	HC_01P *
	HC_05P		HC_05P *
Hp	H_P	HP	HP*
Cd	C_d	C_d	C_d*
Td/BHD	DIAMETER_S	n/a	Td*
P1 to P4		PX1, PY1, PX2, PY2, PX3, PY3, PX4, PY4	PX1, PY1, PX2, PY2,PX3, PY3, PX4, PY4*
Prototype	Prototype	n/a	Prototype
Cshape	Cshape	n/a	Cshape
CSHAPEX	CSHAPEX	n/a	CSHAPEX

Table 6.4: Parameters extracted for the shadow analysis tree from both LiDAR datasets.

	Mobile (2014)	Aerial (2016)
Hb		Segmentation Pol. centroid
Hc	**1.69** (HC_01P)	2.87
	2.02 (HC_05P)	3.77
Ht	19.51 (HT_MAX)	**19.45 m**
	17.83 m (Ht_99P)	**18.64 m**
Hp	**4 m**	14 m
P1, P2, P3, P4		PX1,PY1,PX2,PY2,PX3,PY3,PX4,PY4
Td/BHD	Avg. **1.55 m** from measures: West-E.: 1.9m; North-S.: 1.2m.	Unable to measured
Cd	Avg. **19.39** m from aerial and mobile extents	
Point cloud extent	West-E.: 19.41m; North-S.: 20.31 m	West-E.: 17.95 m; North-S.: 19.90 m

Automated Realization: LOD1-x, LOD2-x and the 3D city model with LOD1 buildings are automatically generated via procedural grammar rule scripts written in Computer Generated Architecture language for ESRI CE. The 3D geometry is created using attribute values or existing geometry within the datasets associated to script variables. LOD1 buildings were generated extruding footprints extracted from the BGT dataset to acquired 95 percentile heights. The LODs are generated on demand and can be changed without reloading any data.

LOD1.X and LOD2.X models were created or inserted from two model libraries. One containing s1 to S15 crown models and the second one was ESRI's vegetation library. The model mapping is explained below. LOD3.A or parametric trees were generated using a python script. It processed attributes listed in the *Parametric trees* column in Table 6.3. The script extrapolates and adds coordinate points above and below crown perimeter points to then create faces from the coordinates forming closed volumetric crowns. Crowns are stored in a text file which is imported into ArcScene or ArcGIS Pro using the *ASCII 3D to feature class* tool for conversion to multi-patch format as required by the shadow analysis tool. Trunks were procedurally added (Figure 6.4).

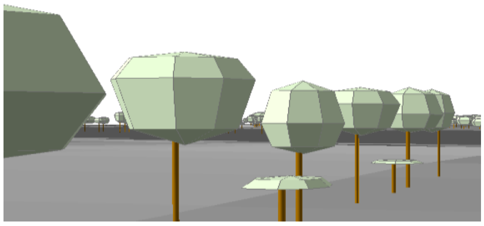


Figure 6.4: Parametrically created LOD3.A trees

Non-automated realization

Models and crown shapes mapping –3D models from two libraries were used: ESRI's with 80 species and a library created to store S1 to S15 crown models, a trunk, and root models.

ESRI's models were tabulated by genus and species with respective crown shapes to create a mapping table. The 47 species of the 513 segmented trees in the island were exported into a spreadsheet and their species mapped with those in ESRI's library and respective crown shapes. For those that did not match, a proxy species was used from the same genus. For LOD3.C (separate crown), the match was done with crown shapes S1 to S15. The proxy shapes were verified by checking online pictures of the species involved.

To match crown shapes to each of the 513 trees, the tree *ID* and the species, *Assortim*, attribute were exported into a spreadsheet. Their shapes were populated using Excel's Vlookup function and the mapping table as the look up table. Resulting spreadsheet was joined to the tree dataset via the ID field. The mapping is a one-time step. The already manual entry of newly planted trees would require the additional crown shape entry. For new species, the mapping table would need updating.

LOD3.B convex hull: Few point cloud processing tools are both open source and can create 3D meshes of vegetation, but libraries and tools, e.g., OpenAlea (2015), the CGAL Project (2018) and SimpleTree (Hackenberg et al., 2015) are available. With SimpleTree, trunk, branches, and convex hulls of different adherence can be reconstructed from high density terrestrial point clouds. VisionLiDAR works but requires a license for exporting meshes**.** Ultimately Geomagic Studio, another point cloud and modeling tool already available was used. To thin the mobile point cloud, wedges of points 10 cm thick were extracted from the mobile point cloud (LasTools script) and a convex hull was created (Figure 6.5).

LOD3.C not convex hull: A non-convex hull from the mobile LiDAR data was created with Geomagic's point wrap tool. The point cloud was imported, and the mesh exported in obj format as previous models (Figure 6.5).

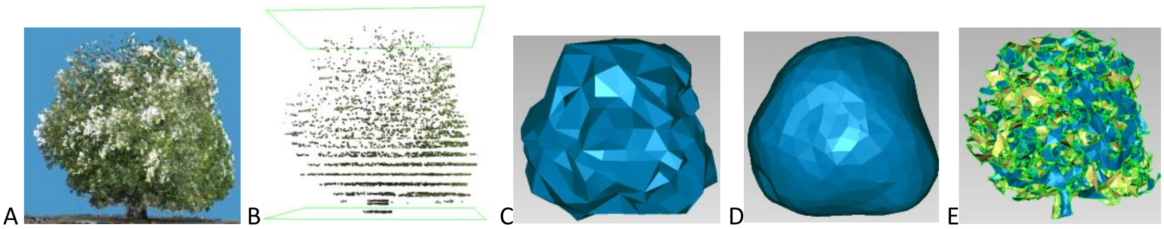


Figure 6.5: Shadow analysis LOD3.B and LOD3.C snapshots
A: mobile point cloud. B: point cloud wedges, C and D: convex hulls, E: non-convex hull

6.3.6 Integration

ESRI CityEngine was used for integrating datasets and models, and to automatically generate the 3D SVO LODs described above. LOD3.A, LOD3.B and LOD3.C models were imported. Integrated datasets include:

- Point tree dataset of the island from which LOD0.A, LOD1.A, LOD1.C, LOD1.D, LOD2.A, LOD2.B, and LOD2.C are generated
- 2D segmentation polygons from which LOD0.B, LOD1.B are generated
- Parametrical crowns imported in multi-patch format of LOD3.A with a separate trunk component
- Shadow analysis tree objects in LOD3.B and LOD3.C with a separate trunk component
- Building footprints for extrusion
- BGT topographic polygonal data with associated objects attributes
- Terrain elevation (DTM)

For generating the 3D city model and LODs (Figure 6.6), the CGA script is applied and run. Object attributes can be queried by selecting the object itself. New datasets can be linked and added for comparison. The model and LODs can be further refined. For example, for exploring vegetation distribution and underground space requirements.

Figure 6.6: Integrated 3D SVO LOD and datasets

6.4 IMPACT OF LODS IN A SHADOW ANALYSIS

Capturing the shadow from each LOD representation aims to assess their quantitative impact.

The shadow casted by each LOD was assessed with ArcGIS Pro Shadow Evaluator available as a free download from their *Local Government Solutions*. It records the hours of shadow a surface experiences given surrounding sun obstruction features. First, the sun motion was generated for the study area, then, the shadow from each LOD was quantified and stored in shadow maps. The tool captures straight shadow. Weather, ambient occlusion, canopy density, etc. are not factored in, and 3D objects are solids regardless of their surfaces transparencies. Validation was not done as the aim was to capture differences among the assessments. The setup of the test scene and sun motion are described below prior to shadow captures and analysis.

6.4.1 Sun Setup

The 3D city model of the study area in Noordereiland, Rotterdam (Figure 6.1) was set in ArcGIS Pro as a requirement for running the tool. The tool also required 3D objects in multi-patch format and ground surfaces with a DTM for the shadow capture to occur. Generated LODs for the selected Aesculus hippocastanum tree were exported from CE in multi-patch format so they can be set as *obstruction* surfaces. The recreational pedestrian area (85.68 m long and 29.5 m wide) under the tree was extracted from the BGT to be the *observation* surface. The LODs whose shadow were recorded are shown in Figure 6.7.

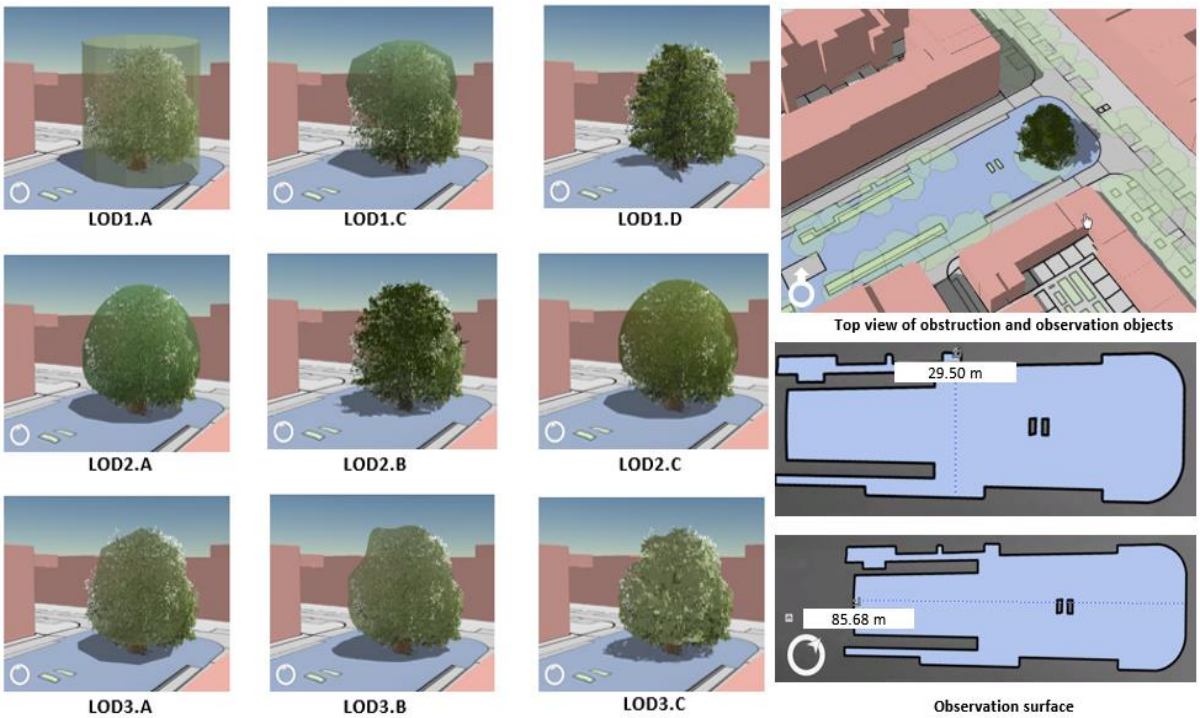


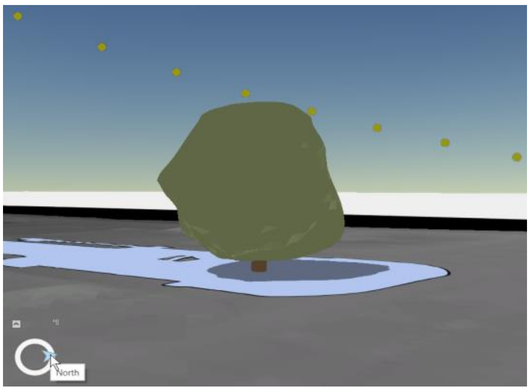
Figure 6.7: LODs of test tree over mobile point cloud and observation surface

Sun positions were generated indicating the observation and obstruction surfaces for the longest day of the year, June 21st from sunrise to sunset. Apart from the date(s) and the DTM layer, time zone, time period, and time intervals are required. Table 6.5 shows the sun movement in the NW side of the tree.

Despite the period set for the entire day: 5:18 AM to 10:06 PM (timetable.com) of 17 hours, the 32 intervals of 30 min. were generated. The last two last intervals were truncated by the tool because the low sun elevation, less than 1.22˚ angle. In the Netherlands, the sun travels around the South and the highest elevation of the sun is slightly above 61˚ at midday. The sun position generated with elevation angles are available in Appendix D

Table 6.5: Sun position settings

Sun Position Settings	
Observation surface	Pedestrian area (colored in blue)
Elevation	Noordereiland’s DTM
Time zone	Amsterdam (UTC+ 01:00) including daylight savings time
Date	June 21st, 2017; longest day
Period	5:18 AM to 10:06 PM
Time interval	30 minutes



- Aesculus hippocastanum, obstacle surface
- Pedestrian surface, observation surface in blue
- Sun positions on sky and NW sunset
- North cardinal direction points to the right

6.4.2 Shadow Capture and Analysis

Three types of maps were generated for the analysis. Figure 6.8 shows the shadow, percent, and comparison maps of LOD1.A and LOD3.C. They show a top view of the pedestrian surface over the DTM and the crown's 2D dripline delineation to show the area under the crown. See all maps in Appendix D.

The *shadow maps* capture the hours of shadow that each 1 m^2 panel (2,286 panels) of the pedestrian area received for 16 hours of daylight. These maps tell, in a cumulative mean of shadow hours the entire surface received for the day and provide a histogram of the shadow hours throughout the panels including those which were not shadowed at all.

The s*hadow percent* maps display the percentage of shadow hours each panel/area on the surface experienced with respect to the total hours of daylight. The darker panels were shadowed for longer periods. When two shadow maps give the same mean shadow, their percent maps distinguish areas in which their duration differs.

The *comparison maps* reflect the difference per panel between two shadow maps. For the analysis, the shadow map of each LOD model was compared to the map of the highest LOD3.C's map (subtracted). Panels with most discrepancy are highlighted in dark purple color. Each comparison map was different in pattern and in statistics indicating all LODs produced distinct shadows.

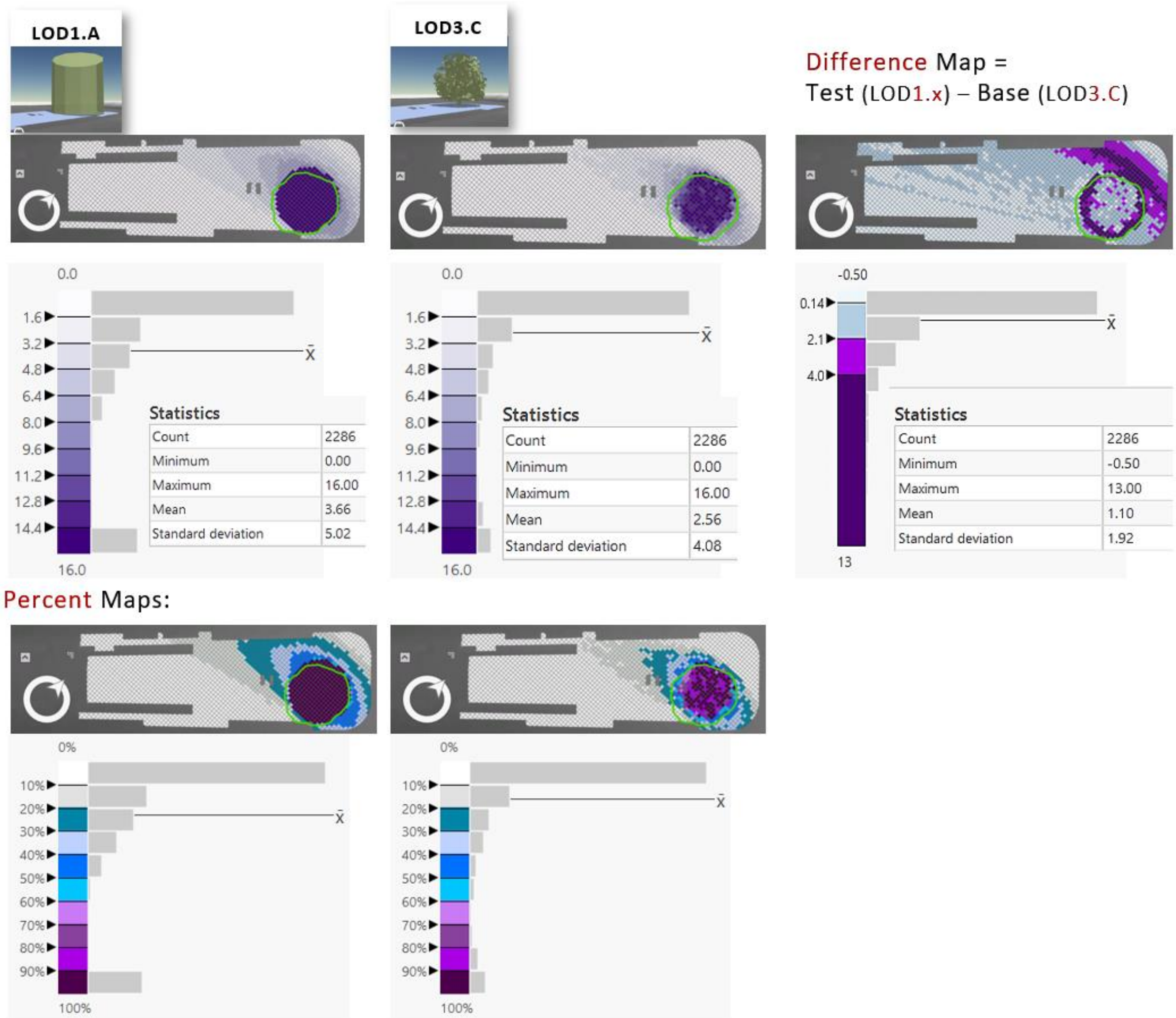


Figure 6.8: Shadow, percent, and comparison maps of LOD1.A and LOD3.C

6.4.3 Analysis

In the analysis, first the shadow maps produced by each LOD are compared to LOD3.C's mean of 2.56 hours. The shadow patterns under the model crown's and throughout the rest of the surface are also compared using the percent shadow maps. The statistics and observed patterns are tabulated for each family (Table 6.6, Table 6.7, Table 6.8) and a chart of the shadow means for each LOD is shown in Figure 6.9.

Table 6.6: LOD1.x shadow on crown underside and on 2,286 panels (1 m^2)

	LOD1.A	LOD1.C	LOD1.D
Mean (hrs.); Std. dev.	3.66 hrs.; 5.02	2.19 hrs.; 2.54	2.41 hrs.; 3.02
Hours of shadow mean vs. LOD3.C of 2.56 hours	Over	Under	Under
Least mean hrs. of shadow		✔	
Most mean hrs. of shadow	✔		
Least Std. Dev.		✔	
Most Std. Dev.	✔		
Pattern under crown	Continuous 100% to 90% shadowed	Radial 100% to 50% shadowed	S: angular; N: elliptical 80% to 30% shadowed
Pattern surface	Elongated eye shape shadow bands W: clearly defined	Elliptical shadow bands W: different pattern and < LOD1.A's	S: Angular, N: elliptical W: different pattern and < LOD1.C's

West (W), East (E), North (N), South (S)

Table 6.7: LOD2.x shadow on crown underside and on 2,286 panels (1 m^2)

	LOD2.A	LOD2.B	LOD2.C
Mean (hrs.); Std. dev.	2.85 hrs.; 4.47	2.51 hrs.; 3.88	3.18 hrs.; 4.83
Hours of shadow mean vs. LOD3.C of 2.5 hours	Over	Under	Over
Least mean hrs. of shadow		✔	
Most mean hrs. of shadow			✔
Least Std. Dev.		✔	
Most Std. Dev.			✔
Pattern under crown	Continuous 90% area slightly < LOD1.A	Irregular star shape 90% to 50% to crown's edge	Continuous 90% area is slightly > LOD2.A 90% area is slightly < LOD1.A
Pattern surface	Elongated *eye* shape shadow band elongation < LOD1.A W: shadow 50% to 10%	Rough elliptical W: shadow 50% to 10% with 50% to 20% area < LOD2.A's	Elongated similar to LOD2.A W: shadow 100% to 10% tapers off quickly from crown

West (W), East (E), North (N), South (S)

Table 6.8: LOD3.x shadow on crown underside and on 2,286 panels (1 m^2)

	LOD3.A	LOD3.B	LOD3.C
Mean (hrs.); Std. dev.	2.85; 4.54	2.98; 4.72	2.56; 4.08
Hours of shadow mean vs. LOD3.C of 2.56 hours	Over	Over	itself
Least mean hrs. of shadow			✔
Most mean hrs. of shadow		✔	
Least Std. Dev.			✔
Most Std. Dev.		✔	
Pattern under crown	Continuous 90% area is slightly < LOD2.C	Continuous 90% area is slightly > LOD3.A 90% area is slightly < LOD2.C	Scattered N: 100% to 50%; W, E: 100% to 20% S: to 0

	LOD3.A	LOD3.B	LOD3.C
Pattern surface	Elongated like LOD2.C; main difference in crown underside W: shadow 50% to 10%; 50% to 40% area < LOD2.C's	Elongated similar to LOD3.A, main difference is in crown underside tapers off quickly W: shadow 50% to 10%; 50% to 40% area > LOD3.A's	Elongated *eye* shape but spotty/scattered W: shadow 100% to 10% with 50% to 20% area < LOD3.B's

West (W), East (E), North (N), South (S)

LOD1.x: each LOD in this family gave a different mean of shadow hours. The distribution of their shadow under the crown and on the rest of the surface had no similarities. Table 6.6 summarizes.

- LOD1.A (cylinder) and LOD1.C (generic) overestimated and underestimated the most with a difference of more than one hour. The cylinder can be considered as the most extreme case for maximum shadow.
- The distribution of shadow under the crown reflects the crown geometry and how high the crown was from the ground. This is noticeable when comparing the cylinder and the generic tree.
- Beyond the crown's underside, the shadow and duration percentage bands reached the most on the West side. LOD1.D's (billboard) asymmetric crown was reflected with the flat shadow pattern.

LOD2.x: shadow patterns from the implicit volumetric tree (LOD2.A) and separately scaled-crown LOD2.C) resembled the cylinder's but their means were less. LOD2.B (realistic) underestimated the shadow but less than the billboard in LOD1. Table 6.7 summarizes these observations.

- The difference between LOD2.A and LOD2.C is the crown base height and the crown size which had a proportional impact in the mean.
- LOD2.B (realistic) shadow pattern in the underside was irregular in a *star* shape, and outside the crown's contour, it was roughly elliptical and spotty compared to the mores solid, elongated *eye* shape pattern of the volumetric models. The spotty pattern reflected to light reaching the underside through branches and leaves of the realistic model.

LOD3.x: there is a distinct difference between the volumetric LOD3.x and non-volumetric LOD3.C. The difference between the volumetric LOD3.x is small. Table 6.8 summarizes.

- LOD3.C (non-convex model) which had the most adherence had a mean shadow of 2.56 and a spotty pattern under the crown ranging from 100% to 50% of shadow throughout the day. It had no area of particular concentration in contrast to the realistic (LOD2.B) model.
- The parametric (LOD3.A) and the convex crown (LOD3.B) overestimated the overall shadow.
- LOD3.A's mean is the same as the implicit volumetric tree LOD2.A.
- The shadow patterns of LOD3.x volumetric models were similar to other volumetric models.

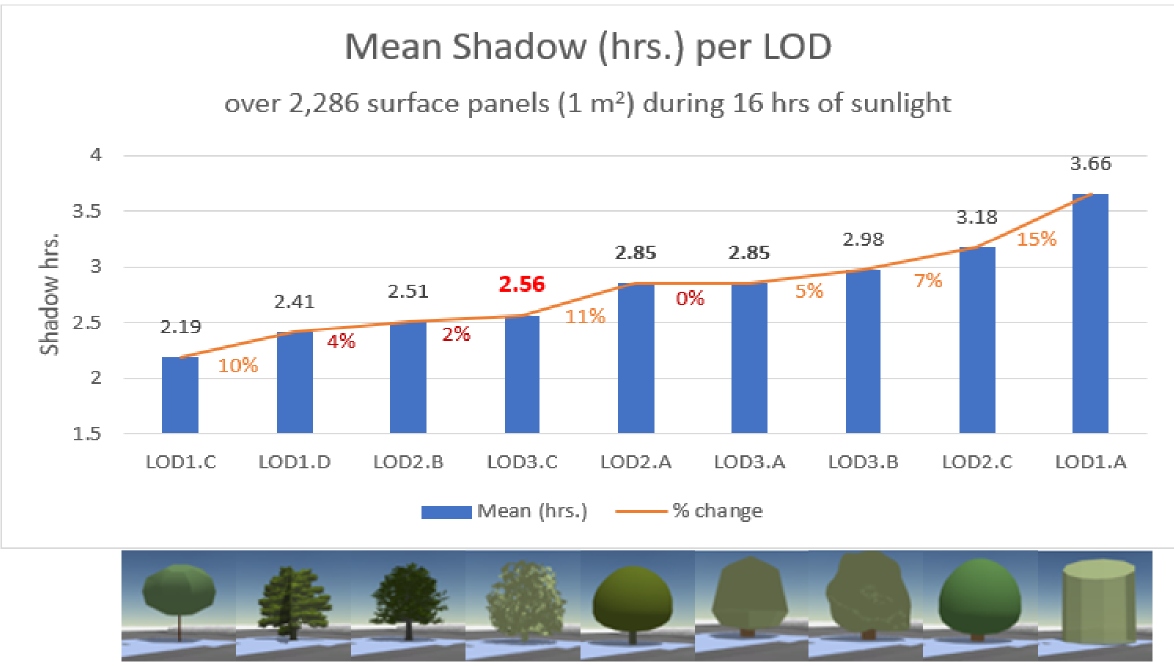


Figure 6.9: Means of shadow casted per LOD. Percent change relative to prev. LOD.

Summing up the comparisons, based on the shadow-hour means of each LOD (Figure 6.9), the comparison maps, and statistics of both maps (Table 6.9), the following is observable:

1. The highest adherence, LOD3.C (non-convex) shadowed in avg. 2.56 hrs. and the closest mean match was the realistic implicit LOD2.B which was a genus match, and both have a regularly shaped crown
2. Non-volumetric LODs had no similarities in shadow distribution due to different forms.
3. LODs in LOD1.x family underestimated and overestimated the most
4. Volumetric LODs with some adhere in shape and crown base height consistently overestimated given the non-transparent, solid nature of the crown in the shadow simulation
5. Non-volumetric LODs mostly underestimated it, and their discrepancies were not as high as those of volumetric LODs.
6. All LODs had different means except LOD2.A (implicit volumetric) and LOD3.A (parametric). these LODs still presented different percent shadow distributions and std. deviation indicating the shadow on the surface s lasted differently in different parts of the surface. This is more visible when looking at the respective comparison map statistics. Each overestimated and underestimated differently when compared to LDO3.C's shadow.
7. No identical shadow percent distribution under the crown and beyond the crown were produced.
8. The std. deviations of all shadow maps were different, and all comparison maps were different from each other in pattern and in statistics.

From the comparison maps**:**

9. Comparison maps displayed a wide range of discrepancies as seen in the Max. hours and Min. hours of discrepancy of all LODs in Table 6.9. These indicate that there were areas that either overestimated and underestimated the amount of shadow at some point in time w.r.t LOD3.C.
10. The smallest mean difference was -.05 with LOD2.B (implicit realistic). One could argue that its shadow was about the 'same' as LOD3.C's, but there were areas where LOD2.B overestimated by almost a half day (8.5hr) and underestimated by 9 hrs.
11. The lowest std. dev. was with LOD2.A (implicit volumetric tree) but it also had areas of seven or more max. and min. hours of difference w.r.t LOD3.C
12. LOD1.A (cylinder) and LOD3.A (parametric) reached the same overestimation (13 hours). In LOD3.A this occurred in less areas.

Table 6.9: Shadow and Comparison maps statistics summary

	Shadow Maps		Comparison Maps (Shadow Difference = LODX - LOD3.C)			
	Mean. (hrs.)	Std. Dev.	Max. (hrs.)	Min. (hrs.)	Mean. (hrs.)	Std. Dev.
LOD1.A	3.66	5.02	13	0.5	1.1	1.92
LOD1.C	2.19	2.54	5.5	-14	-0.37	2.32
LOD1.D	2.41	3.02	4.5	-10	-0.14	1.69
LOD2.A	2.85	4.47	7.5	-7	0.45	1.09
LOD2.B	2.51	3.88	8.5	*-9*	-0.05	1.21
LOD2.C	3.18	4.83	12	-2.5	0.62	1.38
LOD3.A	2.85	4.54	13	-9	0.29	1.27
LOD3.B	2.98	4.72	9.5	-5	0.42	1.13
LOD3.C	2.56	4.08				

6.4.4 LOD impact

Based on 1- 5, above, the LODs incurred shadow changes in pattern, magnitude, and duration (percent shadow). Gained insights:

- LOD1 models, i.e., the lollypop and cylinder offered insights:
    - The cylinder provides the maximum reach that a tree's shadow can have. A scaled cylinder provides the worst or best-case scenario.
    - In complex simulations that take a long time to run because they include other environmental aspects, using a low LOD can first help to identify time periods of most impact or importance, and then a higher LOD can be used to run the more complex simulation for the period of interest. The first test might also help in choosing a more adequate LOD.
- From the LODs that produced the same mean shadow:
    - If mean shadow is the focus, the following aspects are important to consider:

        - The implicit model was selected to be of the same tree genus. Its crown base height was similar; not necessarily the case with all species under the same genus, but if care is taken in this aspect, acquiring an implicit model requires less resources than a parametric model as seen in the implementation in the previous section.
        - If the real-world tree's crown was irregular, the implicit volumetric model would have less adherence.
        - LOD2.A can only be scaled in height and width, while LOD2.C allows adding an implicit crown, which can be implemented separately to resemble the actual crown's irregularity, still in a generalized way and requiring also less resources.
    - If a specific area of the surface is the focus, for example on the South-West side, both LODs gave different amount of shadow hours.

When choosing a LOD, the crown properties of the real-world tree that impacted the most are the canopy's shape regularity, its density, and the height of the crown base. Further, some aspects were consistent based on the model type:

- Non-volumetric models:
    - Better shadow estimations were achieved with non-volumetric LODs that reflected the transparency of the crown based on the statistics.
    - The realistic implicit LOD offers a good option for regular crowns of similar density.
    - For irregular crowns, the non-convex hull offered an option of less implementation cost that still reflect crown transparency than a reconstruction.
- Volumetric models:
    - Implicit models and crowns overestimated the shadow but offered an inexpensive realization.
    - For irregular crowns, higher LODs are appropriate but they still overestimate the shadow.

The above shows that adherence to the real-world object is not the only consideration in selecting a LOD. The type of tree, and seasonal changes need to be considered, i.e., changes of foliage and sun's path:

- The test done was run for June 21st, the longest day of the year. Most of the shadow was on the West side aside even though the sun traveled on the southern side throughout the day. This is because in the Summer the sun rises up to about 61° high generating short shadows on the North. In Winter, the Dutch sun stays low, so shadows in the North would be larger and last longer.
- The test tree was a deciduous tree with a very low crown similar to an evergreen tree. In Winter, the deciduous tree lets more light through, so it gives less shadow. A benefit for sun warmth in Winter time and solar panels on the roof depending on its relative location and height. The evergreen would give shadow year-round, a benefit for cooling areas, or to block winds in Winter or year-round, but also blocks sun from roofs at certain periods depending on its location and height. In either case, the sun's path affects the duration of the shadow.

Test limitations/Incompleteness of the analyses:

- Apart from being a basic shadow capture without including reflectivity and weather conditions, or canopy transparency, and considering the model as a solid, the analysis should have included the shortest day to account for the changes of shadow caused by the change in the sun's path.
- More insights can be gained if the analysis included a tree with an irregular crown.

7 CONCLUSION, FURTHER RESEARCH AND OPEN QUESTIONS

The research question of this thesis and sub questions follow. The sub questions are answered, first.

What is the best approach for modeling 3D vegetation features for their use in the built urban environment?

- *How are current LOD specifications of urban vegetation being described?*
  What are the driving factors that define vegetation LODs? What considerations (acquisition technique, requirements, practices, etc.) are taken in account?
- *Which applications require 3D vegetation?*
- *What impact do LODs have in analysis in a practical implementation?*

Current vegetation LOD specification approaches (nine) have different motivations (Chapter 4.3.1):

- Standards – aim to meet multiple requirements, urban environment applications at different scales
- Geometry focused – aim to provide adherence and to allow acquiring additional data from the models
- Proprietary – aim to add presence to multiscale 3D city models which focus on buildings

So, their vegetation LOD specifications have different requirements and provide different adherence to real-world objects. Few (three) specify PC as an object and most (seven) do not include SVO in LOD0 (Table 4.2). Further, because current SVO specifications are predominantly geometrical, they can be categorized as ether implicit and explicit geometry approaches. Each group has different strengths which complement. CityGML is in the implicit geometry group together with the proprietary approaches (Chapter 4.4).

Factors that define LODs differ based on the type of geometry used: In the implicit geometry modeling group, appearance, geographic extent and accuracy specifications differentiated their LODs. In explicit geometry approaches, component granularity ruled (Chapter 4.3.2).

Acquisition techniques and demand of IT resources are considerations that influenced definitions of vegetation LODs or their adoption (Chapter 2.2, 3.2, 4.1, 4.4):

- Acquisition techniques and demand of IT resources played a role in specifying or not a LOD.
  - In the IMGeo-CityGML standard excludes LOD4 for SVOs given its higher demands of IT resources, possible manual intervention, and not enough automation.
  - CityGML and proprietary approaches have favored implicit geometric LODs because of the lower acquisition and realization costs and are automation friendly. These are strengths of implicit modeling, but they are limited in providing higher adherence to the real-world objects.
- Advances in remote sensing and its increase accessibility have both promoted and enabled needs for vegetation LODs with higher adherence:
  - These advances have enabled geometry focused approaches whose LODs use only explicit modeling and reconstruction allowing them to specify components.
  - IMGeo-CityGML recognized this need and includes parametrical representation (which focuses on crowns). It demands costlier acquisition and IT resources but is still automation friendly.
- Acquisition techniques and maintenance impact LOD's accuracy and dimensionality.
  - With LiDAR data, Ht and Cd and vegetation footprints can be acquired for large regions with higher accuracy than manual measurements. So far SVO LOD1 and respective 2D projections are fairly straight forward to obtain for large geographic extents (based on case study implementation), which is a limitation of manual acquisition**,** but the timeliness of remote sense data depends on scanning intervals which can be years.
  - In daily practices acquiring and updating vegetation data is manual, and the information comes from maintenance and inspections. The accuracy varies depending on the measurement, yet the most up to date data is in 0D, 1D or 2D or 2.5D representations as they are less resource demanding and easier to handle.
- Demand for IT resources is still a limitation for using realistic vegetation representations:
  - Implicit (premade models) with branches and leaves are complex and can have a high polygon count so they can be used in limited numbers.

    - For adherence at a realistic level, reconstruction is the alternative but there is no LOD in either standard that defines this type of modeling. Most likely due its higher demand in acquisition and IT resources.
- Current IT technology is not an issue in producing implicit LODs (volumetric) but there is also no LOD definition of this type of geometry that supports adherence at component level.

Another consideration in defining vegetation LODs is their requirements. Explicit geometry modeling approaches require higher adherence as LODs increase, while implicit approaches lack requirements for meaningful adherence for vegetation given that they are focused on building's LODs (Chapter 4.3.1).

Considering common practices of using SVO representations as mentioned above (Chapter 3.2) is an aspect currently not supported by the implicit geometry modeling approaches as they exclude vegetation objects entirely in LOD0 which is where the non-3D representations are most applicable. Further, these datasets are the most abundant. Furthermore, practitioner's also need a LOD that defines SVOs underground components which is another LOD definition gap.

Many applications drive vegetation models of different levels of adherence and vegetation data acquisition for multiple scales (Chapter 3). They include:

- Managing and sustaining existing urban vegetation while ensuring that public space remains safe above and below ground; requires multidimensional models and data for:
    - Tracking and assessing vertical and horizontal distributions
    - Planning public work above and below ground
    - Communicating above and below ground topology
    - Analyzing tree diversity and distribution for sustainability
- Urban and landscape planning
    - Data for streetscape following spatial and environmental requirements and root spatial requirements for assessing planting feasibility
    - Model for communicating landscape designs and changes projection
    - Models as input to simulations related to UHI and water runoff mitigation
    - Models for spatial analysis, e.g., identifying UHI prone areas, assessing canopy impact to surfaces, underground space distribution
- Environmental policy making
    - Both urban planning and policy making applications target to address the sustainability of continuous urban growth within negative effects brought by climate change to maintain the livelihood of their cities
    - Because climate change resilience adaption measures are applicable at different scales, policy making is further concerned with assessments and goals that leverage and preserve urban vegetation ecoservices for this, requires assessing existing urban vegetation structure, ecoservices output and ecoservices benefits
- Tree properties extraction
    - Models for extracting crown properties not directly measurable, e.g., reflectance and directional, winds tolerance, evapotranspiration estimation
    - for allometric model's refinement
- 3D city model's enrichment

In answering the main research question, based on the above, no one approach fulfilled encountered use cases' needs. Perhaps because the approaches were formulated when remote sensing was still too expensive. While current LOD specifications have different aims for their specifications, they are still predominantly geometric LOD descriptions defined by the geometry they use, and most of the needs they try to fulfil are from applications within the same urban environment. The SVO LODs that a standard like CityGML can provide are most useful if they fulfil the multiple needs that drive both modelling types. Such broad LOD spectrum would indeed meet different requirements across domains.

Based on the analysis done of the needs vs. what all LOD specification approaches provide, the best approach is the one that unites the two camps, therefore providing a range of LODs that facilitates adherence-to-resources demand tradeoffs. But, specifying LODs in both geometry types is not all that is needed. LODs also need to support applications for below-ground feasibility analysis, and above-ground spatial relationships with building surfaces at multiple scales. These needs also highlight the need for LODs at component levels. Further, because specific urban vegetation parameters and attributes permit many important environmental simulations in multiple scales, standardizing such data requirements would elevate vegetation data to participate in 3D city simulations of ecoservices. This highlights the importance of vegetation data, attributes or metadata.

Based on the above, refined SVO LODs therefore introduce:

- Improved CityGML's LODs which combines the strengths of both description approaches
- A broad LOD spectrum that meet different requirements
  - High LODs which can be expanded with further sub-levels by the user
  - SVO components and underground descriptions
    - Crown shapes specifications with expandable crown shapes
    - Root specifications
- Harmonized:
  - Crown shapes terminology
  - Root parameters

With the refine SVO LODs:

- Most datasets can be represented by at least one LOD including underground aspects
- Modelers or users of 3D city models can tell:
  - What LOD is possible based on the data they already have
- For acquisition, it is possible to tell:
  - What data is required for a particular LOD
  - Which LOD can be used to obtain data needed for an application

Limitations include: the LODs do not include PC and reviewed use cases were not exhaustive.

Further, refined LODs specify dimensionality, feature complexity, appearance and semantical requirements for each level. This may appear restrictive since many aspects are required, yet, they are consistent and eliminate vagueness in specifications.

The impact that different LODs can have in a quantitative analysis was confirmed in the shadow analysis case study conducted in this work. Shadow assessments are key to assessing canopy cooling effects. The shadows of nine representations of an Aesculus Hippocastanum tree in Noordereiland, Rotterdam were capture for June 21st, 2017, the longest day of the year, with 16 hours of daylight (Chapter 6). The LODs produced different assessments (Chapter 6. 4.4). Each LOD's shadow changed in pattern, magnitude, duration and had different statistics. Each LOD can then be considered independently differentiated.

The assessments were impacted by model type: volumetric, non-volumetric, and changes in adherence. The LOD of highest adherence, LOD3.C, was compared to all others and the best match was the realistic implicit model LOD2.B, which had a similar regular crown shape and crown base height but differed in its shadow distribution highlighting a mismatch in crown density. Providing LODs of varying adherence seemed beneficial in many ways: lower LODs provided insights, intermediate LODs allow cost-tradeoffs based on the real-world object's crown, and crown LODs provide further options based on real-world object's crown properties. Further:

- Where an overall shadow average is desired, implicit volumetric models of the same species or genus as the real-world SVO may yield adequate estimates provided the (1) real-world object has a regular crown and (2) the crown base height is similar, noting that this type of model constantly overestimates.
- If a specific area is the target of the shadow assessment, the test revealed a wide over and underestimation produced by the different LODs.

Adherence to the real-world object turned out to be not the only consideration in selecting a LOD for shadow assessment. The type of tree, and seasonal changes need to be considered, i.e., changes of foliage and sun's path. Especially in locations where the path changes as in the norther hemisphere. In this aspect, the analysis was incomplete since it did not include the shortest day of the year, which would have provided further insight. Also, running the simulation with an irregular crown would have provided more insights.

LEARNINGS FROM THE CASE STUDY

Acquisition techniques and demand of IT resources for high adherence LODs remain high but are not as limiting as before. The situation in the urban environment has also changed. Current trends of non-stoppable population increase, and climate change require planning for a sustainable urban growth with climate change considerations propelling the need of both vegetation data and models of varying degrees of adherence and for all scales. The demand crosses domains (environmentalist, urban planners, urban ecology, urban forestry, forestry, etc.) and nations. Much research has been done in acquiring and processing vegetation parameters and properties from LiDAR data. In fact, there are many options, methods and algorithms scattered in literature, in codes and language that only specialized users can understand. There is no one process of best practices or tool that takes a practitioner from acquisition of vegetation parameters from LiDAR data to realization of models that offers geometry options, or LOD options when processing hundreds of SVOs.

In practice, fewer LODs would be implemented than in the case study of this work. To acquire and implement the nine LODs, information was pulled from many places and multiple tools were needed. Table 7.1 summarizes difficulties and limitations for each LOD option assuming the acquisition is done from LiDAR data. It was not possible to automate the entire process. The steps for acquiring parameters and implementation provided in this work with cautions and recommendations can make the learning curve easier (Appendix C).

Recommendations:

- Standards can take charge in standardizing parameters, attributes, and acquisition guidelines or best practices, e.g., from point clouds. This would drive tool makers to support them making their processes of acquisition and implementation more user friendly by providing a unified process with options.
- The standardization of proposed LODs can push technology instead of limiting LOD definitions to what technology can do today.
- Standardizing reconstruction which allows extracting information which later is applied to entire collections as an alternative to destroying the trees (not a real option for urban trees), e.g., to improve biomass assessments for ecoservices calculations.

LOD DIFFICULTIES AND LIMITATIONS

Table 7.1: Refined LODs requirements and limitations

Refined SVO LODs	Difficulties and limitations (using LiDAR as 3D source)
LOD0.x • LOD0.A: 0D position coordinates with/out crown buffer • LOD0.B: 2D or 2.5D canopy dripline contour • LOD0.C: Row 1D as lines for rows of trees/hedges	• To obtain Cd, watershed segmentation is lengthy and requires many operations but can be automated • Groups of crowns get segmented as one. Algorithms for separating them is not in yet available in tools
LOD1.x Scaled at least in height: • LOD1.A: Extrusion of LOD0.A • LOD1.B: Extrusion of LOD0.B • LOD1.C: Implicit SVO symbol • LOD1.D: Implicit Billboard SVO	• LOD1.B extrusions rely on LOD0.B extraction • Acquiring the total height requires object-based segmentation workflow
LOD2.x Scaled in height and width, reflect crown shapes S1 – S8 of predominant genus/species in dataset • LOD2.A Implicit volumetric • LOD2.B Implicit realistic separate crown, trunk and scaled separately. Uses volumetric crowns S1 – S15 shapes which are expandable • LOD2.C Implicit crown and Implicit trunk	• Adherence is limited to regular crowns • Cannot rely that all species under the same genus have the same form • LOD2.C requires acquisition of crown base height (Hc) and DBH parameters. Requires one-time mapping step of shapes to datasets and occasional maintenance for mapping the implicit models to the tree dataset.
LOD3.x High adherence to allow extracting other information from the models themselves Crowns: • LOD3.A: Parametric	• Requires manual intervention • Storage format needs to be planned. • For LOD3.A, B and C., once implemented, the storage can be as polygons, whole components or joint as a single object. • Parametric SVOs require saving each tree's LiDAR data separately for more refined coordinates

Refined SVO LODs	Difficulties and limitations (using LiDAR as 3D source)
• LOD3.B: Convex hull SVO: • LOD3.C: Non-convex • LOD3.D: Reconstruction	acquisition. Hc, and Hp Requires a learning curve for acquisition techniques, and scripting • Convex and non-convex LODs needed manual selection of group or SVO • Reconstruction with *SimpleTree* is a manual process but many objects can be processed at the same time
ROOT LODs • Not bonded to a particular SVO LOD. • ROOT.sprd: 2.5D projection or the root spread. • ROOT.vol: indicate underground space requirements in volume, or for simple presence. • ROOT.vtype: visualizing different root systems types in volumetric form • ROOT.realistic: visualizing different root systems types in realistic form	• Many approaches for assessing the horizontal spread and is subjective in terms of how conservative the estimation can be. • Vertical assessments require additional GIS data of undergrounds.

7.1 FURTHER RESEARCH

Because some LODs introduce SVO components (crown, trunk, root), further study could be done to determine optimal CityGML storage of the components along with semantic and appearance descriptions.

Acquiring tree species, a very important attribute still requires a human eye. Research for extracting species information from point clouds are still needed.

This work focused on SVO LOD specifications partly because of the data available, and because many LOD description approaches do not consider PC in their LOD descriptions. Yet, PC complements and plays a role in mitigating climate change negative effects, e.g., ecosystems sustainability, water rundown mitigation, and in noise pollution mitigation, for example.

Further work would help to establish whether generalization and aggregation is applicable to PC, groups of SVOs, and perhaps only SVO crowns at certain scales. Given today's important role that urban vegetation in urban growth sustainability, it is perhaps as important as buildings in generalizing feature LODs research.

In the quest for assessing trees and urban forests ecoservices, i-Tree Eco is becoming the standard worldwide tool for their assessment. An ADE with a GIS spatial, topological description, and specifications of required data to harmonize it in a global cope would make datasets more integrable and compatible with other simulations pertinent to canopy impact on buildings.

7.2 OPEN QUESTION

Because destroying urban trees is not an abundant option for extracting tree data for adjust allometric equations, the digital reconstruction urban trees from TLS has proven to be a promising alternative (Liang et al., 2016; Tanhuanpää et al., 2017; Tigges, Churkina, & Lakes, 2017). To account for varying local growing conditions of urban trees, reconstructions allow update species models for estimating biomass useful for assessing sequestered carbon. This implies continuous reconstruction efforts in the future. Is standardizing tree reconstruction process for this purpose feasible?

I realize that this study did not resolve all questions related to vegetation LODs, but I hope that it will contribute to a better inclusion of vegetation in 3D city models.

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APPENDIX A

USE CASE DESCRIPTIONS

Below are brief descriptions of the 30 use cases listed in Table 4.1.

URBAN VEGETATION MANAGEMENT, MAINTENANCE AND SUSTAINABILITY

(1) In the Netherlands tree owners are liable for tree damages and for the safety of surrounding space. Municipalities and province administrators rely on up to date tree inventory data such as the municipality of Rotterdam's or the Dutch tree registry for maintenance decision making.

Tree structure properties (height, crown size, life stage: young, old, type, etc.), location, and surroundings (stand alone or near groups of trees) are recorded and tracked to ensure trees remain risk-free in public spaces. In the Netherlands, billions are spent in tree maintenance (Meijer et al., 2015) because tree owners are liable for damages caused by their trees. In Rotterdam, tree structure, health condition, risk assessment, and safety pruning are tracked. Young trees are monitored more frequently to ensure they develop properly, and in contracting maintenance work, the tree's height determines the type of equipment and personnel to be deployed. Planting condition determines watering needs. Similar maintenance is done to trees along public roads by province administrators.(Pol et al., 2016; Zwiep, 2016).

(2) For telecommunications companies, tree location, height and surroundings are important for determining the ideal location of cell towers. For them, it is importance that the dataset is available nationwide. and

(3) For tram operators, because many times per year, trees cause damage on overhead rails, knowing the location and characteristic of trees nearby rails aid to proactively limit operation disruption (Pol et al., 2016).

(4) 0D tree data and 2.5D underground network data are used in the municipality of Rotterdam for planning public work above and below ground. To assess impact on city trees of underground network maintenance work, vegetation asset managers and underground network administrators share via an internal web on a multilayer portal point tree representation and short and long-term underground work areas (Figure 0.1). Impacted trees are colored based on their risk, e.g., red dots for trees over a sewage pipes to be worked on. A separate layer identifies the underground network beneath the trees. The location of each tree and its desired vertical (elevation) accuracy is of +/- .05 m. The terrain elevation accuracy is most important because a change of over 20 cm up smothers a tree killing it (Berger et al., 2009; Zwiep, 2016).

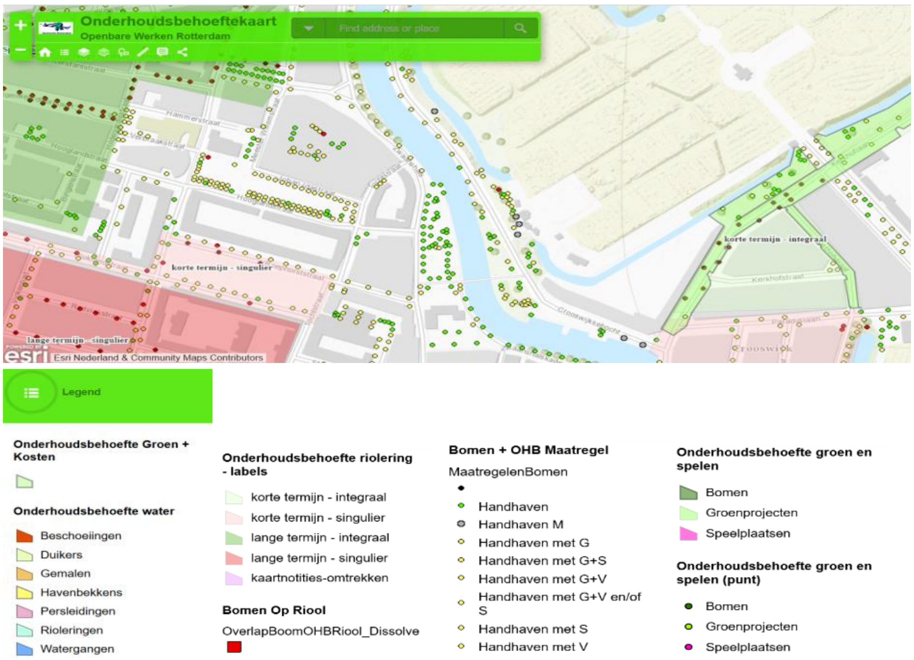


Figure 0.1: 0D and 2.5D representation (Maintenance Public Work in Rotterdam,2016)s

(5) 3D models of trees, roots, street components, and underground structures communicate above and below ground topology, and planting measures after underground work is done. Measures consider tree location and surround elements above and below ground (Figure 0.2). The goal is for tree roots have enough space to avoid them from anchoring and damaging pipes, while an accessible underground network for maintenance and repair. The topology between tree, roots and underground structures consider the tree-size classification (small, medium, large), function, life stage, possible lifespan, and crown spread. Measures describe vertical and horizontal distances between the trees and each of the underground elements in detail based on the tree's characteristics (De Goederen, 2012; Slee & Tjan, 2015).

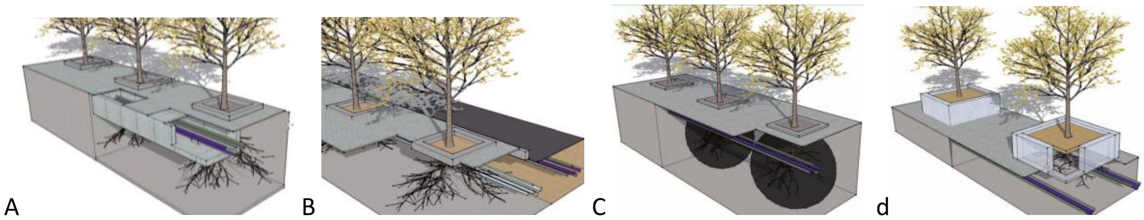


Figure 0.2: Examples of roots and underground network placement
and planting measures (De Goederen, 2012). A: Use of a cable tray, cables and pipes around roots. B: Near roads .C: Prepare tree for replanting considering extend of root. D: raising soil level for additional root space.

(6) To preserve the benefits urban canopy brings to a city, its healthy ecosystems need to be sustained. They are linked to both the diversity and distribution of species, age, and heights. Viewing the vertical and horizontal distribution facilitates detecting areas where future planting is necessary, and in seeing the potential spread of plagues (NYC Parks, 2015). An interactive pilot 3D model of the municipality of Rotterdam's canopy aids in viewing the distribution of tree types, size, and age to identify areas in need of improvement. The model uses appearance changes to represent different tree properties, i.e., Distinct crown appearance reflects age and tree type. Color-coded trunks reflect height classes. The visualization also helped identifying data discrepancies (Figure 0.3).

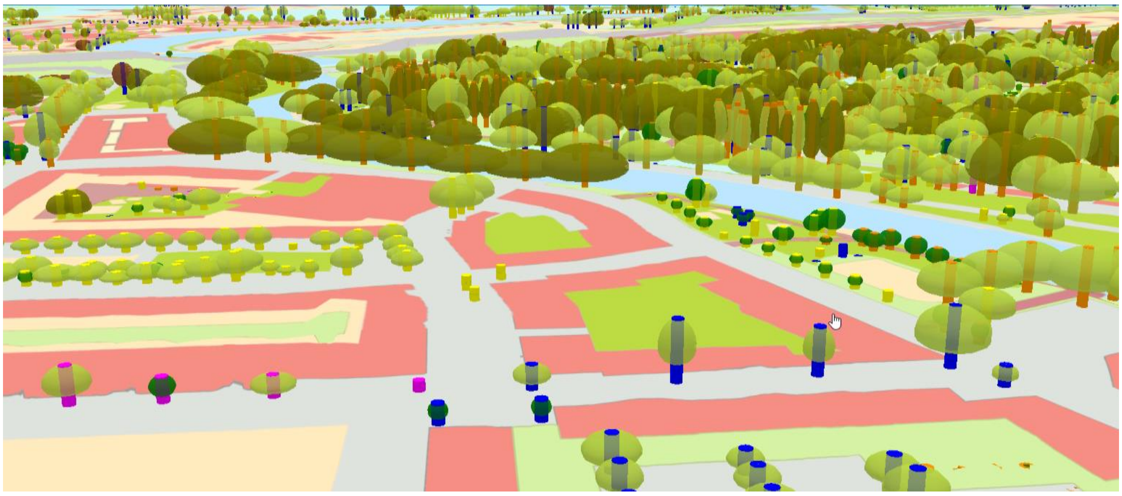


Figure 0.3: Procedural, navigational canopy model for distribution of age, type, and heights

URBAN PLANNING AND LANDSCAPING

(7) Vegetation data and sketches (crown projection and profiles) are used for both planning and communicating spatial requirements that apply to Rotterdam's streets and district level. The placement of trees on streets and near roads involve meeting spatial requirements with environmental implications. Temporal tree properties, i.e., growth rate and type (deciduous/evergreen), etc. play a role in selection for planting along residential roads and city structures. 3D structure data of vegetation and nearby objects above and below ground (buildings, sidewalks, roads, underground pipes, building foundations) are used in spatial analysis to assess interference, communicate spatial requirements, and to resolve topological conflicts. Road configuration (roads and other lanes widths and building heights) and tree types are considerations for placing trees along roads to avoid trapping polluted air under canopy. Future crown sizes and tree-type data is used to ensure space between crowns for air circulation. Trees with open crown structures allow more air circulation and are effective in the removal of contaminated air particles. Coniferous trees with sticky needles offload particulate matter from the air. Depending on the pollutant, one or another tree type is better suited. A dataset of trees approved to be used in the municipality of Rotterdam provides different options (De Goederen, 2012; Slee et al., 2015).

(8) Placing trees along streets involves estimating root spatial requirements. That is in spread and depth, or in volumetric form. In Rotterdam, trees grow in a delta that steadily settles downward, so planting feasibility considers the space around the roots that is not already taken by hard surfaces, underground pipes, building foundations, garbage containers, and rising underground water levels that drown them. Estimating the underground water level at desired locations and the maximum root spread helps in assessing feasibility, and in justifying to dwellers why trees are sometimes not planted in their streets (Berger et al., 2009; Zwiep, 2016).

MODELS

(**9 - 12)** 2.5D and 3D vegetation models are used by city architects and urban planners to communicate changes to by showing current vs. future, or alternate designs (Gugten, R., 2016). Renovation or revitalization projects use highly realistic 3D vegetation models, i.e., to explore park design options (Lu & Wang, 2014), or to elicit community collaboration in Donaldson-et al. (2007). Online models with augmented reality as the Lijnbaan Panorama in Rotterdam (2016) are used for promotional purposes and online feedback. Temporal variations of size, shape, and appearance aid to achieve ambiances in city greening programs (Berger et al., 2009).

MODELS IN SIMULATIONS

(13) 3D simulations (ENVI-met) of thermal interactions in the urban environment requires vegetation coverages and street structures data. The analysis of the UHI effect and the mitigation effect of nearby vegetation can be simulated as in downtown in Montreal. The micro-scale thermal interaction used as input data buildings and ground surfaces' materials, land use, building heights, vegetation coverages of grass, and trees of different heights. Tree canopy reduced solar radiation absorption of surfaces through shadowing up to 3 C° temperature and increased winds up to .5m/s from induced temperature differences (Wang & Akbari, 2016). A separate study using the same simulation model, ENVI-met, building details and tree crown properties were input to simulate the cooling effect of trees on building-height-to street-width variances. The impact of tall trees of low canopy density with high crown base height perform better in deeper canyons streets, and vice-versa for shallow canyons and open-areas (Morakinyo, Dahanayake, Adegun, & Balogun, 2016).

(14) Vegetation data is input in studies of storm water runoff mitigation where heavy rainfall from climate change that does not get intercepted runs off causing floods and pollution of natural water deposits. Trees, shrubs, plants, and grass slow down the storm water, absorb it and make the soil more infiltrating (Rogers et al, 2015). The mitigation potential around different surface types was assessed to be about 7% and up to 12% with modest increase of canopy average (Sanders, 1986). In other estimates, it reduced runoff from asphalt by as much as 62%. This was attributed to s trees planted on grass and associated to crown pits (Armson et al., 2013). Yearly avoided water runoff attributed to trees by tree species or by provided vegetation strata data are also estimated by i-Tree Eco (2016) simulations, which uses canopy projection or *percent tree cove*r of existing trees and urban forest as input.

Many aspects change in tandem to increasing urban population. One is an increase in traffic and housing near roads. Trees, shrubs, bushes, offer noise mitigation, which is another benefit that urban vegetation brings.

(15) Different tree types of varying stem sizes and placements are input for noise reduction simulations of vegetation placed along roads. Apart from estimating the reduced noise of light weight vehicle traveling at 70km/hour, the optimal spacing of the trees and stem sizes, were assessed along with the downward scattering effects from tree crowns. Further, the study showed that the mitigation improved with the presence of shrubs and with the type of ground. The effects on the tested vegetation yield vegetation noise reduction comparable to classical noise barriers on grassland of 1 to 1.5 m high (Van Renterghem et al., 2012).

(16) Vegetation models are used in simulations for optimizing placement of trees to cool parking lots. Generic volumetric tree models of standard size were used in the simulation (Bajsanski et al., 2016). Tree canopy shadowing reduces radiance heat absorption mitigating UHI. Further providing shadow to parked cars provide cooler gas tanks which reduces evaporative emissions of VOC which form ground-level ozone, e.g., for the city of Sacramento, CA, a daily reduction of VOC emission was estimated with a tree canopy increase from 8% to 50% in parking lots (US EPA, 2008). 3D Tree models are used to optimize the cooling effects of tree canopy shadowing on residential buildings surfaces (Hwang et al., 2015). Trees models of different tree types and heights are used in simulations that consider building orientation and planting distances. Placement configurations and the shadowing effects of different tree crown structures are then estimated. Finding the optimal tree placement translate in energy savings potential (Hoi Hwang, Eric Wiseman, & Thomas, 2016). Further, volumetric shapes serve in estimating crown volumes to derive other properties. The adherence of the shape is proportional to the accuracy of estimates (Mawson et al., 1976; McPherson et al., 1988).

MODELS FOR SPATIAL ANALYSIS

(17) At a city-block level, the 3D building proximity to greenery index (Li et al., 2016) uses building floor heights and vegetation types and within a distance. It helps identifying areas in need of urban greening programs. A tree-to-building volume indicator helps urban planners assess areas prone to UHI effects. It considers the 3D effects of overshadowing, evapotranspiration effects, and the volume of buildings which are indicative of urban canyon geometry and the formation of the UHI effect. Parametric trees are used to model trees of the study area for their canopy volume calculation (Rafiee et al, 2013).

(18) The impact of the tree canopy on solar panels is analyzed by modeling the structural characteristics of both buildings and trees: heights, volumes, building-tree height ratios, and the influence of trees on the radiation to buildings (Tooke et al., 2011). However, as stated in a state-of-the-art review of modeling the potential solar panels in urban areas by Freitas et al. (2014), vegetation is often excluded or is represented as a simple solid shadow caster. Four GIS-related analyses were reviewed which deployed 3D urban models. Two had detailed rooftops with tilted surfaces and vegetation. Others had flat roofs and no vegetation. While the diffused reflectance of different materials was considered and outputs were detailed in shadow and irradiance for all surfaces involved, in both studies trees were solid shadow casters. Freitas et al. (2014) observe that while urban vegetation extraction from LiDAR data and processing algorithms are emerging, much is yet needed in modeling 3D trees light passing through canopies to account for their semi-transparency and irradiance influence on urban surfaces, e.g. ground, roof and walls.

(19) Modeling the heights of city buildings and vegetation allows analyzing their vertical relationships to identify urban landscape patterns. The third dimension allows comparing sites whose 2D layout would have similar patterns. This type of spatial analysis is valuable for understanding interactions between landscape patters and ecological processes to then enhance landscape configurations that benefit urban environments, inhabitants, and wildlife. For example, diversity, and, the variety of heights, as the 3D structures of buildings and trees influence bird distribution (Chen et al., 2014).

(20) Urban growth continuously demands underground space and costs for moving underground infrastructure are high. In Rotterdam, models of underground objects including root volumes help to assess space availability (Figure 0.4) to reserve spaces for foreseen projects (Smit & Boelhouwer, 2017; Veldhuis, 2016) as shown Rotterdam's 3D city model v2 of underground infrastructures.

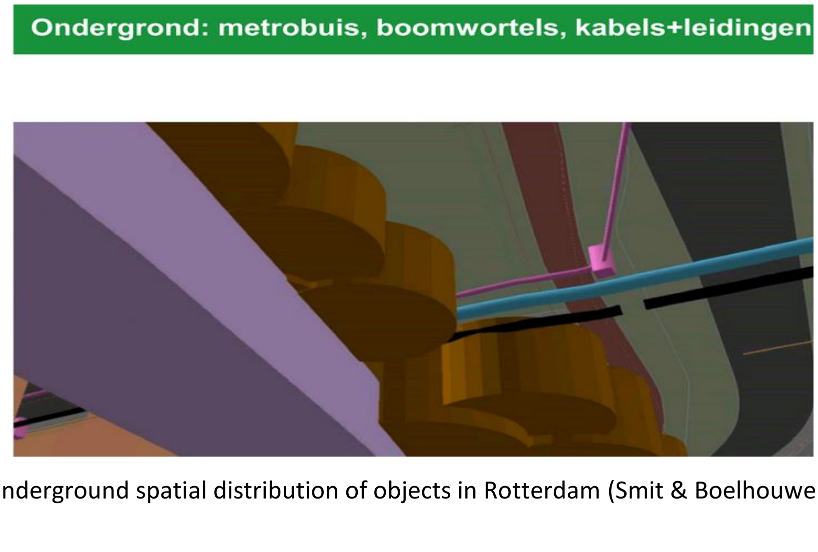


Figure 0.4: Underground spatial distribution of objects in Rotterdam (Smit & Boelhouwer, 2017)

(21) A first step for sound environmental policy making is to assess the current trees or urban forest structure. Such structural analysis ranks the species that serve the most ecoservices. This analysis is possible with simulation tools like i-Tree Eco (2016). Identify the dominant tree species requires:

1. Tree species population numbers
2. Respective leaf area, which is calculated form: given species–to identify shade coefficient, total height–to estimate height of the crown, crown base height – to estimate height of the crown, crown width–to identify crown width dimension, percent crown missing–to modify base leaf area for actual amount present (Table 0.1).

Main ecoservices benefits are directly linked to the healthy leaf surface area. The most abundant trees with the largest leaf areas are most impacting in delivering existing benefits. Planting programs should consider their preservation along with climate change issues and the future construction of neighborhoods, streets and developments (i-Tree, 2016; Rogers et al., 2015).

Table 0.1: Bottom up tree data for ecoservices estimation (i-Tree Eco, 2016)

	DERIVED VARIABLES		ECOSYSTEM SERVICES										
DIRECT MEASURES	Leaf Area	Leaf Biomass	Carbon Storage	Gross Carbon Sequestration	Net Carbon Sequestration	Energy Effects	Air Pollution Removal	Avoided Runoff	Transpiration	VOC Emissions	Compensatory Value	Wildlife Suitability	UV Effects
Species	D	D	D	D	D	D	I	I	I	D	D		
Diameter at breast height (DBH)			D	D	D						D	D	
Total height	D	D	D	D	D	D	I	I	I	I		D	
Crown base height	D	D	C				I	I	I	I			
Crown width	D	D	C				I	I	I	I			
(1) Crown light exposure (CLE)				D	D								
(2) Percent crown missing	D	D	C			D	I	I	I	I			
(3) Crown health (condition/dieback)				D	D						D	D	
Field land use			D	D	D						D	D	
Distance to building						D							
Direction to building						D							
(4) Percent tree cover						D	D	D				D	D
Percent shrub cover												D	
Percent building cover						D							
Ground cover composition												D	
	D	Directly used			I	Indirectly used			C	Conditionally used			

(1) Sides the crown receives light from above or side (maximum of five); (2) Percent of the crown volume not occupied by branches and leaves; (3) A visual estimate of dead branches due to shading from a building or another tree
(4) Percent of area covered by tree canopies estimated to nearest 5%

(22) Ecoservices estimation can involve a bottom up vegetation data shown in (Table 0.1):

- The estimation of CO_2 stored, the gross and net carbon sequestered are linked to crown size, crown properties, healthy leaf area, and tree species (Mcpherson et al., 1999; Nowak et al., 2007; Stephenson et al., 2014). In i-Tree Eco (2016) it is estimated with a *land use* input, and eight attributes: species, DBH, Ht, crown diameter, crown base height, crown light exposure, percent crown missing, crown health/die back. Other required data is calculated by the tool itself using entered data, e.g., leaf biomass for evergreen or palms.
- Energy consumption reduction effects are assessed as impact of tree canopy on buildings' energy use due to canopy shadowing of surfaces cooling effect, and from sheltering from Winter cold winds. It requires canopy cover estimates and data of surrounding buildings and
- Canopy cover--typically as the top down canopy projection or *percent tree cover* in allows estimating other benefits, which increase proportionally with canopy cover (London & Ham, 2006):
    - Pollution removal is estimated in hourly amounts removed with yearly percent of air quality improvement.
    - Avoided runoff from rainfall interception and reduced storm water runoff
    - VOC emissions

- UV effects
- Urban wildlife sustainability (also requires *percent shrub* and *grown composition* data)

Canopy cover as 2D or 2.5D canopy projection allows estimating green-gray ratio. The data provided by Dutch Tree inventory is provided as 2.5D canopy projection from which canopy cover can be calculated (Figure 3.2). Tree crowns with heights over 3 m were extracted from the nationwide aerial LiDAR data (Schouten et al., 2012).

(23) Forecasts of tree and urban forest's growth serve in managing and sustaining their benefits. Predictive models use regression fits of DBH as a function of age by species to then develop prediction models of leaf surface area (LSA), crown diameter, and crown height metrics as a function of DBH. Projected mortality rates, yearly canopy growth are included (Jennings, 2012). i-Tree Eco (2018) factors-in tree planting inputs, pest and disease, and storm impacts.

3D MODELS FOR TREE PROPERTIES EXTRACTION

(24) Modeling convex hulls of trees generated from LiDAR data allow to model irregular tree crowns. "Wrapped" surfaces generated by Kato et al. (2009) allow acquiring more accurate and basic tree parameters from irregular shapes, e.g., height, crown width, crown base heights, and crown volumes.

(25) Allometric equation refinements for urban tree is possible by reconstructing them. Doing so generates more accurate ecoservices estimations, e.g., to estimate CO_2 sequestered and stored by urban trees, species allometric models are typically used, but they are mostly derived from forest trees and through destructive methods not readily available in urban areas. The target population should be similar to the one used for creating the model. Volume-based models from terrestrial LiDAR data have shown to be a better alternative. Urban trees are different from those in forests because they are influenced by local climate, pollution, and different underground conditions so they are smaller and have a shorter lifespan than those in forests (Tanhuanpää et al., 2017; Tigges et al., 2017).

(26) Tree reflectance and directional transmission properties can be simulated from tree reconstructions from terrestrial LiDAR data allowing to then calculate vertical foliage, wood area profile, and shoot orientation distribution. These properties are difficult to acquire reliably in the field. Reflected and transmitted light through tree canopy play a role in shadowing and cooling effect (Côté et al., 2009).

(27) Tree structure tolerance to storm winds is estimated. Using measured tree parameters and the reconstruction of tree branches in 3D data as input for developing a predictive dynamic model to analyze the mechanical response of trees to turbulent winds (Sellier et al., 2008).

(28) Tree crown microclimate cooling effect through evapotranspiration was investigated through tree reconstruction from terrestrial LiDAR data. Reconstructed tree models were put through radiation absorption, transpiration and photosynthesis for simulating crown microclimate, and then, into further simulations for estimating leaf evapotranspiration and photosynthesis (Bournez et al., 2016).

The goal was to find the optimal LOD at which a reconstruction can still yield acceptable estimates of a tree's microclimate cooling effect through evapotranspiration.

3D CITY MODELS

(**29)** Vegetation features are included to semantic 3D city models to add realism the model as those in Cities Around the World with Open Datasets (CityGML.org, 2017), and as used in city models developed by proprietary urban city modelers, i.e., Vertex and Blom ASA. Typically, implicit volumetric and realistic models are used which sometimes are scaled as described in chapter 4.

(30) 3D visualization with the ability to query the data associated to each object is a tool for sharing tree information internally and with the general public as done with the Municipality of Rotterdam 3D v2 model (2017). The model includes different implicit 3D tree models reflecting overall appearance of associated tree whose data can be queried making each tree instance a meaningful representation.

USE CASES NEEDS

Table 0.2 Use cases needs of urban vegetation models and data

Use cases needs	
Urban Vegetation Management, Maintenance and Sustainability	
1	Managing urban vegetation and public space safety maintenance
	Tree inventory data needs to be up to date location, ownership, structural development (height, width, life state), and assessments of crown form and health (especially if young) to plan risk and maintenance for public space safety for damaged trees, branches, line of sight pruning, and for maintaining regular crown forms. Tree height class determines equipment and personnel to be deployed. Note: Monitoring aspects can benefit from using 3D models. See note 1.
2	Determining cell of tower locations
	Tree location, height, width, and distribution in large geographic areas is needed in finding optimal locations for placing cell towers.
3	Maintenance of rails overhead
	Tree location, type, height, spread and topology with respect to rail locations allows to proactively manage maintenance and reduces down time in tram operation.
Urban Vegetation Management, Maintenance and Sustainability - Models for communication and analysis	
4	Planning and managing impact to trees from underground network repair
	To determine relocation, replanting, alternative planting, or elimination of trees due to repair of underground network (gas, water and sewage pipes, especially), 2.5D spatial relationship of impacted trees and underground network is needed for visualizing their topographic setup.
5	Communicating underground topology, and tree planting alternatives
	3D visualizations communicate required topology to prevent roots from anchoring and damaging underground pipes as they grow, root location spatial relations are needed with respect to objects in underground and at ground level (surrounding soft and hard surfaces, e.g. road, sidewalks, bike paths). Planting measures are based on tree size, function, life stage, and potential lifespan. See note 2.
6	Analyzing urban vegetation diversity and distribution for sustainability
	Because healthy ecosystems are linked to diverse horizontal and vertical distributions of canopy heights, species, and life stages, to assess areas in need of new plantings, visualizing existing diversity with 3D models that differentiate key properties with appearance and shapes. See note 3.
Urban Planning and Landscaping	
7	Streetscape spatial requirements
	Planting trees along streets and roads involves assessing spatial and environmental requirements. Spatial requirements above, at, and below ground levels. Data and multidimensional models are needed for assessing spatial relationships, formulating and communicating plans. • Above ground distances between trees, buildings and roads are observed in relation to street pollution. Tree type and projected mature size or growth rates. Air contamination or removal of particulate are addressed with different types of trees with particular crown properties, i.e., sicky leaves or sparse crowns along with required sun exposure, wind, and salt tolerances attributes are needed. • At ground level, sufficient surface root access together with below ground spatial requirements also need assessment. • Space for tree roots needs to exist (use case 8) and topology requirements with underground objects need to be met (use case 5).
8	Tree root spatial requirements
	Root space for trees needs to be adequate for them to reach a mature size. It is necessary to estimate how deep and wide roots can spread. It depends on the species and the 3D space occupied by structures (hard surfaces, building foundations, underground pipes, garbage bins). For depth estimation underground water levels, bedrock, or elements that are barriers need to be known for possible depths at tree-locations.

Urban Planning and Landscaping - Models for communication	
9	Promote sites and projects

10	Solicit collaboration and participation
11	Design alternatives decision making
12	Communicate site renovation /current-future changes
	Realistic tree and vegetation models are needed by urban landscapers that show seasonal changes of flower, fruit, foliage variations, different life stages to communicating current vs. future landscapes, for visualizing alternate designs and to elicit collaboration or support of stakeholders. Local data: soil, sun exposure and site issues (road salt, wind, pollution) influence the selection of trees or vegetation. Projected mature sizes that meet spatial requirements are needed. Where online communicating is key, virtual and interactive 3D models complement plans.
Urban Planning and Landscaping - Models for simulations	
13	Mitigate negative effects of climate change - UHI
	Assessing the optimal tree morphology for mitigating UHI effects is a key step in urban landscaping. Knowing optimal total tree and crown base heights is key. The optimal tree morphology depends on street widths and building heights. It can be assessed in simulations where tree data and street configurations are inputs.
14	Urban vegetation avoided runoff contribution
	Urban landscapes prone to flooding from rain water runoff benefit from estimating avoided runoff attributed to canopy cover: tree canopy, shrubs, plants or grass. Simulation assess the mitigation potential, before and after modest canopy increase. Estimates of canopy cover is needed. It can be the percentage of the 2D projections of canopy to other surfaces.
15	Use of vegetation morphology and placement for noise reduction
	Where housing near roads are planned, 3D models of trees and other vegetations of different stem sizes are input to simulations to optimize placement and vegetation type combination to reduce road traffic noise
16	Tree placement for cooling houses and parking lots
	Simulations for optimizing the placement of trees for cooling need 3D models of varying tree types with different crown shapes, heights and crown base heights. Optimal placement reduces UHI and energy consumption. Cooler gas tanks reduce evaporative emissions of VOC that form ground-level ozone.

Urban Planning and Landscaping - Models for spatial analysis	
17	Identification of UHI prone areas
	• Volumetric or parametric tree models are needed to assess tree canopy volume for the tree-to-building volume indicator, which assess areas prone to UHI effects. • The 3D building proximity to greenery index needs input of tree and vegetation data and distances to buildings to identify urban areas in need of greening plans.
18	Tree shadow impact on solar panels
	GIS data, 2D, 2.5D or 3D models, and structural characteristics of buildings and trees are needed, i.e., eights, volumes, building-tree height ratios, to assess the influence of trees on the radiation to buildings. Limitations in these assessments are that many studies exclude trees or represent them as solid shadow casters. There is a need for 3D tree models with light passing through canopies to account for their semi-transparency for more realistic irradiance on urban surfaces, e.g. ground, roof and walls.
19	Vegetation and building vertical relationships for urban ecology
	Modeled 3D building and canopy vertical relationships are studied to identify urban landscape patterns where the third dimension differentiates sites with similar 2D layout. The spatial analysis serves to enhance landscape configurations that benefit urban environments, inhabitants, and wildlife.
20	Underground open space, object distribution assessment
	There is an increasing need for below ground 3D models with structures and root systems to assess the availability of underground open space. Such models are planning tools for reserving space for upcoming projects avoiding future underground network relocation expenses.
Environmental Policy Making	
21	Urban vegetation and urban forest structure analysis
	A first step for environmental policy making is to assess the current trees or urban forest structure, which ranks the tree species that serve the most ecoservices. The assessment needs tree species population numbers and their leaf area estimates. Leaf area is estimated using tree species, total height, crown base height, crown width, and percent of crown missing. Knowing the trees that most deliver existing benefits is key to planting programs for preservation and to meet environmental goals along with climate change issues strategies.

22	Ecoservices estimate and benefits analysis
	To estimate ecoservices themselves, e.g., CO_2 stored, gross and net carbon sequestration, energy consumption reduction, pollution removal, avoided runoff, UV effects, and VOC emissions, for example, aside from the data needed for calculating leaf area, the DBH, crown light exposure, crown health, canopy cover (2D), as well as, land use, distance and direction to building are needed as input to ecoservices assessment tools.
23	Growth forecast
	In managing and sustaining tree and urban forests benefits, predicting forests growth is needed especially for meeting established targets. These models need inputs of DBH and age by species, respective leaf surface area, and projected mortality. Other impacting events such as tree planting, pest, disease, and storm impacts can also be included.
Tree Properties Extraction - models	
24	Tree crown properties extraction
	Via convex hull of tree crowns from aerial LiDAR data to reflect irregular crowns, basic tree parameters can be acquired more accurately, i.e., height, crown width, crown base height, and crown volumes calculations.
25	Urban tree allometric equation
	Tree reconstruction is needed for extracting local tree data to then adjust allometric equations of species properties, e.g., for estimating sequestered and stored CO_2. Traditional methods for generating these equations require destruction of sampled trees. Reconstructed urban trees are an alternative to needed adjustments since the equations are usually derived from forest trees which do not reflect the urban environment influence in urban tree properties.
26	Tree reflectance, directional light and radiation transmission
	These properties can be simulated from tree reconstructions allowing to also calculate of distributions of vertical foliage, wood area profile, and shoot orientations, which are difficult to acquire reliably in field work. These properties are useful in better understanding tree canopy cooling and shadowing effects.
27	Tree structure tolerance to storm winds
	Tree reconstructions is needed for estimating their tolerance to strong winds. Measured tree parameters and reconstructed branches serve as data input for developing a predictive dynamic model to analyze mechanical responses.

28	Tree crown evapotranspiration estimate
	Simulating the microclimate cooling effect through evapotranspiration of tree crowns is possible after tree reconstruction. Reconstructed tree models are input to radiation absorption, transpiration and photosynthesis for simulating crown microclimate.
3D City Models- models	
29	Vegetation models for 3D datasets enrichment
	Semantic 3D city models are enriched with implicit volumetric and realistic vegetation models. Sometimes they are scaled to acquired height and width, other times they are standard representations.
30	Inventory tree properties and data query
	3D Implicit and realistic models of existing trees displaying real-world dimensions and appearance serve as query objects in shared semantic 3D city models. Users can retrieve metadata and attributes of each object in interacting 3D city models.

APPENDIX B

COMPILATION OF CROWN SHAPES TERMINOLOGY

Coder crown shapes: Where many of the tree parameters are unknown, volumetric shapes that resemble the crown shapes are used provided the crowns are regular. Coder (2000) presents standard shapes used in forestry, arboriculture, and ecology described as solid geometric forms S1 to S10 (Figure 0.5). Crown volumes can be estimated with the *Shape value* and the crown's diameter and height.

Prior, Mawson et al. (1976) established that out of the five side profiles of geometric shapes mostly found in forests: circle, triangle, neiloid, parabola and the ellipse, the least fitting was the neiloid, and out the three crown bases only the circular was most fitting. Later, McPherson & Rowntree (1988) extracted shapes of open ground trees with full foliage planted in usual urban growing conditions (e.g. under utility lines, in parking lot planters, on front lawns, in narrow street side planting strips), of different ages, heights and types (coniferous and deciduous). They determined that urban tree shapes fit best to: cone, horizontal and vertical ellipsoid, paraboloid, and a sphere found in Coder (2000).

Approved tree species for planting in New York City (Department of Parks and Recreation of NYC, 2015):

This open dataset describes crown shapes as listed below. To clarify what was meant by *upright* shape, the species *Quercus Fastigia* was researched. Wikipedia refers to its crown as of *columnar* shape. "a cultivar from Quercus Robur (European oak or English oak) carefully propagated to maintain its narrow columnar habit " (Haywood-Samuel, 2003).

Shape descriptions used

- upright
- vase-like
- pyramidal
- rounded

In the municipality of Rotterdam assorted shape descriptions which include qualifiers are used to describe shapes in their approved tree species dataset (Van de Vondervoort, 2016) :

Qualifiers (Dutch/English)

- Afgeplat/ flattened
- Breed/ wide
- Smal/ narrow
- Variable/ variable
- Opgaand/ going up
- Los/ loose
- Onregelmatig/ irregular

Shapes (Dutch/English)

- Zuilvorm/ columnar
- Oval/ oval
- Bol/ bol
- Rond/ round
- Eirond/ round egg
- Ei/ egg
- Piramidaal/ piramidal
- Kegel/ cone
- Waaier/ fan
- Vaas/ vase
- Treur/ wipping

The national Dutch tree registry setup in 2012 and uses about 14 crown shape descriptions in their dataset. They were graciously provided by Cobra Adviseurs (2017), a partner of the Dutch Tree Registry *Boomregister.nl* (Alterra Wageningen, Neo, Geodan, & Cobra Adviseurs, 2016).

Tree shape Dutch/English	Note
• Rond/Round	
• Eirond/Egg shape	
• Omgekeerd eirond/Inverted egg shape	
• Ovaal/Oval	
• Langwerpig/ Elongated	
• Driehoekig/Triangular	
• Naaldvormig/Needle-shape	Needle-like foliage
• Schubben/Scales	Scale-like foliage
• Waaiervormig/Fan shape	Vase-like with flat top
• Ruitvormig/Square shape	
• Handvormig/Hand shape	Diamond-like foliage
• Handvormig samengesteld/ Hand-shape Composite	Diamond -like with layers
• Veervormig samengesteld(enkelvoudig)/ Feather-Shape (Single)	Feather-like foliage
• Veervormig samengesteld/ Feather-shape	Feather-like foliage + layers

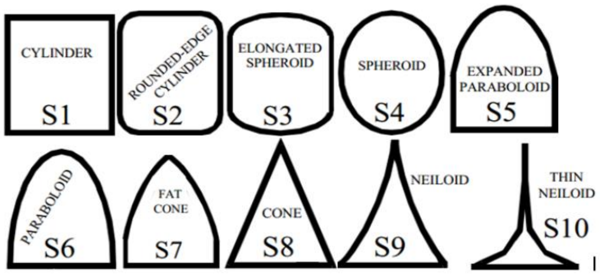
Material for certification as an European Tree Worker (ETW) through the international Vocational Training Centre Groene Ruimte in the Netherlands (2017), tree-crown shapes are described as shown in Figure 0.6, below. The crown shapes are under the *Kroonvorm + dichtheid; toepassing* column which translates as *Crown form+ density; application*. They are also differentiated by their width.

There are many large European nurseries which supply trees internationally. Two of them are Van den Berk B.V. and Ebben Nurseries. The shapes shown in Figure 0.7 and Figure 0.8 depict the crown shapes they use for selecting trees in their websites.

Aside from crown characteristics such as flattened, wide, or narrow, which are set by the crown parameters themselves, the shapes to which most of the above tree-crown-descriptions fall are 13 shapes displayed in Figure 4.1 in Chapter 4. Shapes S1 to S8 are Coder shapes and shapes S11 through S15 were found in preceding sets. Coder shapes S9 and S10 were excluded since they were not found in any of the above sets. The 13 shapes including a trunk shape (cylinder) in Figure 4.1 are described with sections of Coder (2000) shapes so volumes can be estimated using his methodology, if so desired. Mawson et al. (1976) provide volume formulas if using frustums. An approach also seen in (Chen (2013) and Wu et al.(2008).

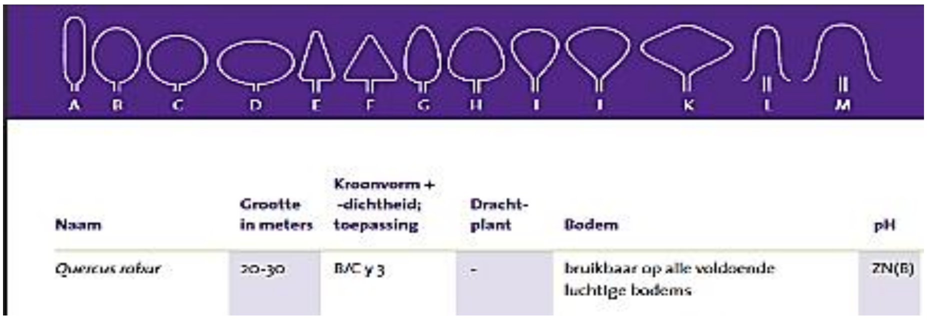
They are posted as *3D Models of Tree Crown Shapes* in ArcGIS.com (link). Each shape represents the following:

- *S1* can represent a tree stump, and *S2* a cactus, a hedge, and square topiary, hedges where by default, there are no crown base heights.
- *S3*, columnar shape with a round ends
- *S4,* spherical, flattened round, or oval shape based on the crown height and diameter.
- *S5* and *S6* are similar except for the width of their tops. S6 also describes wiping or drippy shapes
- *S11* or diamond shape S11 is the sum of S7 shapes with one of them inverted. It can have rounder top and bottom if *S5* or *S6* shapes are used instead of *S7.*
- *S12 r*epresents shapes from some coniferous, multiple trunk trees bushes, plants or canopy that reaches the ground.
- *S13* and *S14,* vase, or fan shapes are differentiated by the roundness of their top and the height of their crown perimeter. An inverted *S7* shape can be used for the bottom sections.
- *S15* shape reflect columnar shapes and can be composed of two S7 halves for the top and bottom, and a cylinder for the center of shape.
- Setting a crown base height of 0 makes shapes rise from the ground.



shape number	shape value	shape formula	shape name
S1	8/8 (1.0)	(Crown Diameter)^2 x (Crown Height) x (0.7854)	CYLINDER
S2	7/8 (0.875)	(Crown Diameter)^2 x (Crown Height) x (0.6872)	ROUNDED-EDGE CYLINDER
S3	3/4 (0.75)	(Crown Diameter)^2 x (Crown Height) x (0.5891)	ELONGATED SPHEROID
S4	2/3 (0.667)	(Crown Diameter)^2 x (Crown Height) x (0.5236)	SPHEROID
S5	5/8 (0.625)	(Crown Diameter)^2 x (Crown Height) x (0.4909)	EXPANDED PARABOLOID
S6	1/2 (0.5)	(Crown Diameter)^2 x (Crown Height) x (0.3927)	PARABOLOID
S7	3/8 (0.375)	(Crown Diameter)^2 x (Crown Height) x (0.2945)	FAT CONE
S8	1/3 (0.333)	(Crown Diameter)^2 x (Crown Height) x (0.2619)	CONE
S9	1/4 (0.25)	(Crown Diameter)^2 x (Crown Height) x (0.1964)	NEILOID
S10	1/8 (0.125)	(Crown Diameter)^2 x (Crown Height) x (0.0982)	THIN NEILOID

Figure 0.5: Top: side view of idealized crown shapes. Bottom: volume formulae (Coder, 2000)



Naam	Grootte in meters	Kroonvorm + -dichtheid; toepassing	Dracht-plant	Bodem	pH
Quercus robur	20-30	B/C y 3	-	bruikbaar op alle voldoende luchtige bodems	ZN(B)

Figure 0.6: Tree crown shape names used in ETW training books (Janson & Janssen, 2013)

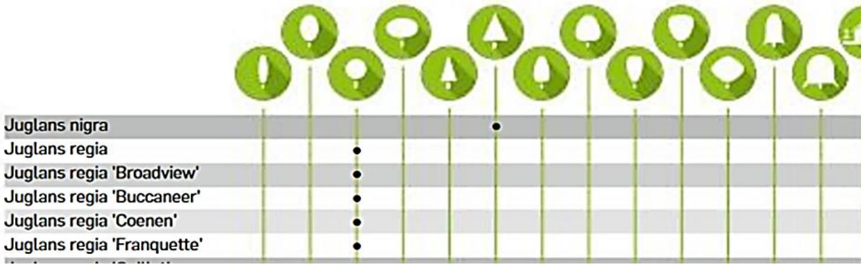


Figure 0.7: Tree crown shapes used by Van den Berk B.V Nurseries – www.vdberk.com

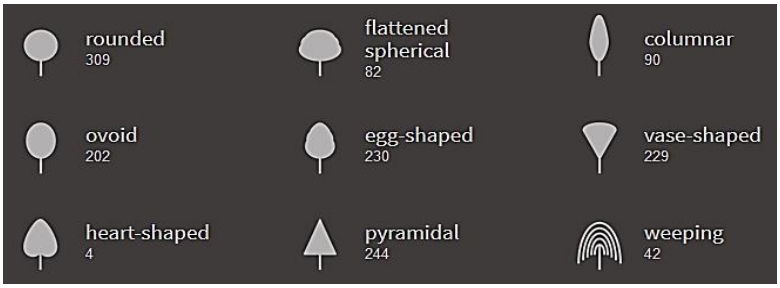


Figure 0.8: Tree crown shape denominations used by Ebben Nurseries - www.ebben.nl

APPENDIX C

Table 0.3: Municipality of Rotterdam Vegetation data attributes

Parameters (meters)
Location (x, y) coordinate
Trunk diameter
Crown radius
Crown diameter

Location Related (with codes)
Area name
Neighborhood name
Suburb name
Street name
Road category
Street stretch from
Street stretch to
Data creation date
Data last update

Ownership/maintenance
Property of…
Owners: cemetery, park,
Maintained by …
Theme: Court yard, park, etc.

Attributes	No.
Genus	219
Species	768

Form (type)	No.
Skeleton/candle holder	2
Climbing	15
Pollard	9472
Espalier	789
Natural (no trimming)	6870
With a specific shape	1096
Standard (trimmed)	155929

Temporal	No.
Plant year	
Maturity:	
- End phase	6145
- Young	46445
- Old	13645
- Adult	107938

Status	No.
To be lost	2036
Risk group	61708
Re-planted	1712

Special Status	No.
Gift	38
Memorial	110
Millennium	7
Monument Foundation	32
None	172258
Baby boom	121
Unique	1607

Standing structure	No.
Neighborhood	16666
city	28835
region	66940
residential	61732

Underground type	No.
Clay	34435
Unknown	5060
Peat	69297
Sand	49542

DATA ACQUISITION WORFLOW

Required spatial data for each LOD for the shadow analysis is listed in Table 0.4. The data source in this table is described as follows:

- *a:* extraction from the aerial LiDAR or from derived rasters
- *m:* extraction from the mobile LiDAR
- *a, m:* aerial LiDAR was used to process the trees for the entire island and the mobile data was used for the shadow analysis tree
- Cr: models were created manually
- *ESRI*: acquired models from this vegetation library
- *In/m*: Td from the inventory was used and the mobile data was used for the shadow analysis tree
- BGT: topographic data was used

Table 0.4: Required data per LOD and for shadow analysis setup

	LOD1.x			LOD2.x			LOD3.x			Other
Required data/LODX.x	B	C	D	A	B	C	A	B	C	
2D location	a	a	a	a	a	m	m	m	m	
Location elevation (Hb)	a	a	a	a	a	a	a	a	a	
Total tree height (Ht)	a	a	a	a	a	a	a	a	a	
Crown base height (Hc)						*a, m*	*a, m*			
Trunk diameter (Td)						In/m	In/m			
Crown periphery pts							*a, m*			
2D crown dripline	a									

	LOD1.x			LOD2.x			LOD3.x			Other
Required data/LODX.x	B	C	D	A	B	C	A	B	C	
3D volumetric tree		Cr								
3D billboard shape			ESRI							
Coder (S1 – S8) crowns				ESRI						
Realistic tree models of common species					ESRI					
S1 – S15 crowns						Cr				
Primitive cylinder shape						Cr	Cr			
Volumetric Convex hull								m		
Non-convex, 3D mesh including crown holes									m	
BGT Building heights										a
BGT building footprints										BGT
The surface for shadow										BGT

1. LIDAR PRE-PROCESSING

Data inspection -- The LiDAR data was inspected with LasInfo. The aerial LiDAR data acquired in (2015 -2016) is of the entire municipality of Rotterdam. It has a point density of 30 to 50/m^2 with the higher density of city areas. The point spacing is .13 m for all returns, and .15 m for last returns with a scan angle between -38 to 35. Existing classifications are High Vegetation, Ground, Water, and Tower; however, the High Vegetation class was the catch-all class: buildings, cars, poles, vegetation, etc. were classified as High Vegetation. Up to 5 returns per pulse and their intensity are also available. Spot accuracy checks done by the municipality using random street crossing lines revealed vertical differences of 1 cm to 3 cm. A semi-conservative standard deviation of 5 cm and a conservative error of 15 cm are attributed to the data. Horizontal accuracy checks done were within the centimeter. Derived DTM and a DSM in both 100 cm and 50 cm cell sizes were checked against buildings' point cloud coordinates. The mobile data acquired in 2014 partially covers the island. No quality assessment is available for it and the information available was mentioned provided earlier.

Classification -- Because all points except ground and water were classified as High Vegetation, they were re-classified (Figure 0.9).

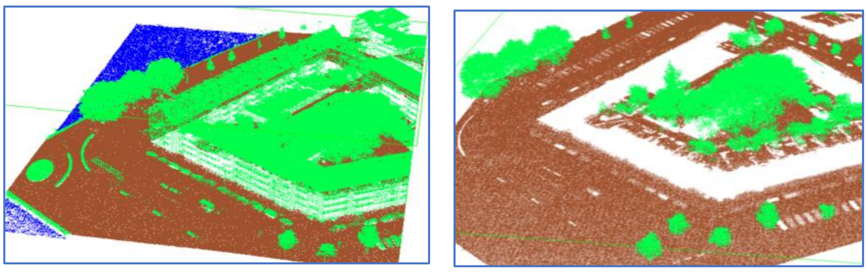


Figure 0.9: Point cloud classification
Left: before point re-classification. Right: classified High Vegetation and Ground points

Figure 0.10 illustrates the key steps in classifying the aerial point cloud. LasTools was used to process the point cloud and ArcMap to make vector masks from BGT polygon data.

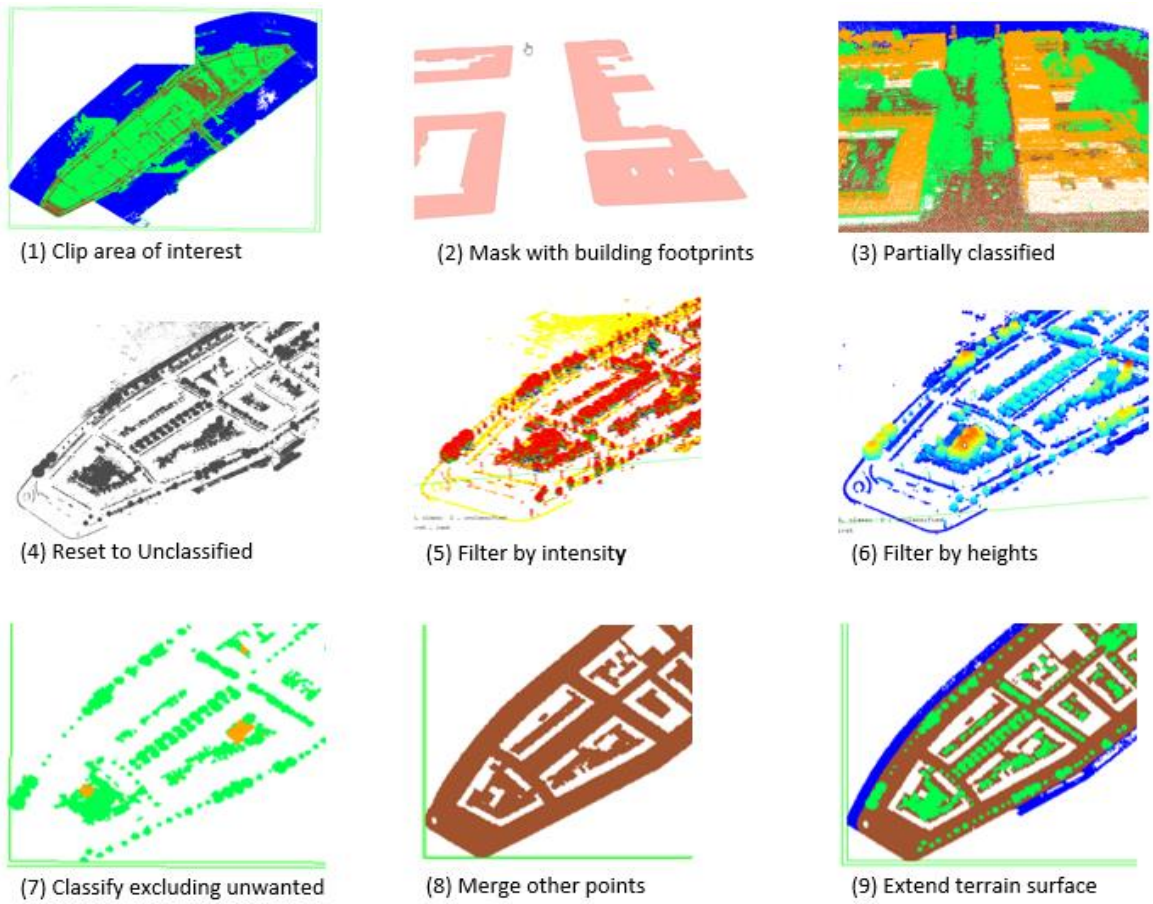


Figure 0.10: Aerial LiDAR data re-classification workflow

(1) 13 aerial scan tiles were indexed, merged, and clipped to the administrative border of the island. The Dutch projection (RD New) was set during the merge, and the height of each point relative to ground-classified points was calculated and stored with LasHeight. They are used later for normalizing the data. Merging point cloud tiles evaded having to use tile buffer and overlap to avoid tile edge artifacts. Because many points in the water side were mis-classified as vegetation, they were masked out leaving only those classified as ground and above them.

(2) – (3) Building footprints extracted from the topographic BGT were used to mask-classify *Buildings* points. The footprints were buffered as described earlier.

(4) All points still classified as *Vegetation* were changed to the *Unclassified* class.

(5) The intensity of the points was checked and displayed by intensity values. The intensity of the points were verified to be between 30 to 60 (Hug & Wehr, 1997; Mao, Zeng, Liu, & Lai, 2008). Figure 0.10- (5) shows the surfaces with intensity > 100 in yellow belonging to low lying walls. First returns (red) dominated the vegetation objects with intensity values less than 100. It was also noticeable that most of non-vegetation objects, e.g., cars, waist bins, benches. were within a 2 m ground offset (Figure 0.11).

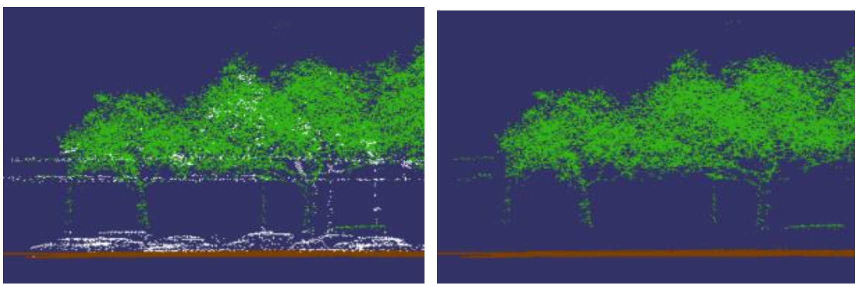


Figure 0.11: Classification using pulse intensity and ground offset

(6) The highest tree top was less than 35 m so all points above this offset were filtered out (Las2Las). This included towers from the bridges that reach the island.

(7) Remaining points were processed with LasClassify uses the nearest neighbor algorithm to classify LiDAR points as *Ground*, *Building* and *High Vegetation* for a given ground offset. During this process, points with intensity > 100 and below a two-meter ground offset were dropped. This included low density tree trunk points characteristic of aerial scans. Small sheds below trees were added to the *Buildings* class dataset (not shown). The original ground classification was preserved by extracting these points into a separate file earlier.

(7) – (9) *Ground* and *Vegetation* were merged.

Artifacts were created by tree crowns points overhanging the island shores as seen in Figure 0.12. To add ground points so the TIN would extend beyond the crown's horizontal projection points belonging to water were added back, however, they added more artifacts from barges and crane points sitting at the shore, which had mis-classified points. They were re-classified using a 2D water mask and filtered keeping only those within a vertical .5 m offset. The water extent was clipped to 50 m from the edge of the island to reduce processing time.

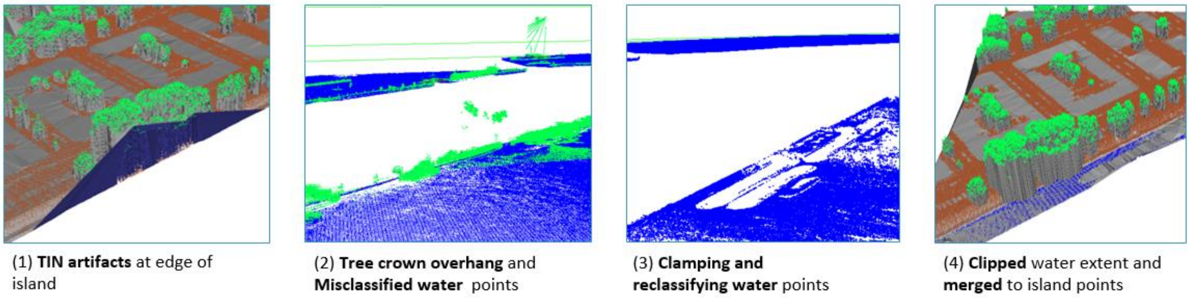


Figure 0.12: TIN edge artifacts reduction

2. DTM, DSM, CHM GENERATION

2D crown dripline contours were used for object-based segmentation to then extract required tree parameters. Watershed delineation was used, which required a canopy height (CHM) model. A model was be generated by subtracting the DTM from the digital surface model (DSM) (Chen, 2013; ESRI, 2016; OpenTopography, 2011). Both rasters were provided by Aerodata Surveys contracted by the municipality. The resulting height-normalized DSM was optimal for extracting building heights but not for canopy heights because: (1) too many low-lying objects were around the trees which can be interpreted as crowns in watershed delineation, and (2) the surface above tree tops were far lower than the vegetation-classified point cloud (Figure 0.13). Another DSM was extracted directly from the point cloud using a pit-free methodology (Khosravipour et al., 2014) enhanced by Isenburg (2016). For visual verification, the point cloud was overlaid on the pit-free DSM (Figure 0.13). A pit-free CHM model was created from the height-normalized pit-free DSM. In Figure 0.14, It is observable that tree crowns fall straight to the ground with no obstruction, optimal for crown delineation in watershed methodology. The tree tops are smoother improving the extraction of the total heights. Trees shorter than 3 m show as small peaks and groups of large trees formed mounds making individual tress not identifiable. Many were private trees inside donut shape buildings. Spot checks were done on the CHM with point cloud coordinates showed better alignment of heights (Figure 0.15).

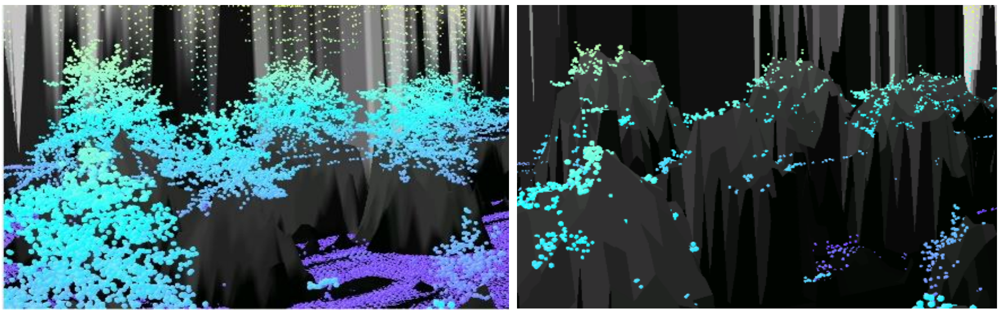


Figure 0.13: Comparing DSM and point cloud
Left: Overlay of point cloud on first DSM. Right: Same over a Pit-free DSM (Isenburg 2016)

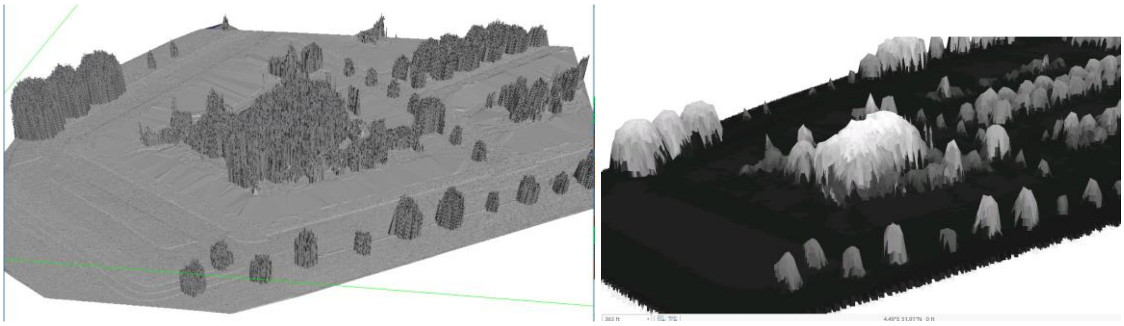


Figure 0.14: Left: TIN created by LasTools prior to rasterizing. Right: Pit-free vegetation DSM.

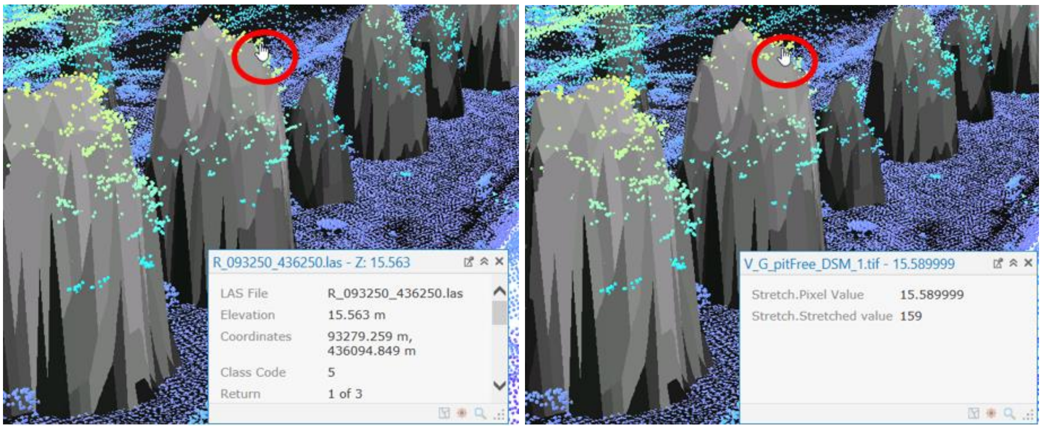


Figure 0.15: Spot check of CHM with point cloud coordinates

3. WATERSHED SEGMENTATION

The CHM is reversed changing vegetation canopy into surface depressions whose depth reveal their height, and when 'filled', the water delineation reveals the vegetation's contour. The analysis computes drainage points which are interpreted as tree tops and for which different methods are used (Edson & Wing, 2011; Swamer, 2012) and overall watershed analysis variations are described and compared by Amiri et al. (2014). In this research, tree tops are extracted directed from the point cloud, so the focus is in vegetation contour delineation. Swamer (2012) workflow was used with ArcGIS hydrology tools. The CHM converted to integer type, and to avoid truncation from the conversion, a 0.05 was added and rounded to the first significant digit. This conversion speeds processing and is necessary for converting resulting watershed areas to polygons. Many watershed areas and minima points for a single depression were generated (Figure 0.16) because a watershed is an area that influences surface water convergence and drainage, so each watershed has its own minima or drainage point. Different tree crown areas formed different watersheds. Those smaller than 1 m^2 were excluded since the municipality SVOs are above that size. Areas shallower than 3 m were also excluded to reduce over-segmentation and to focus the segmenting on medium and high vegetation.

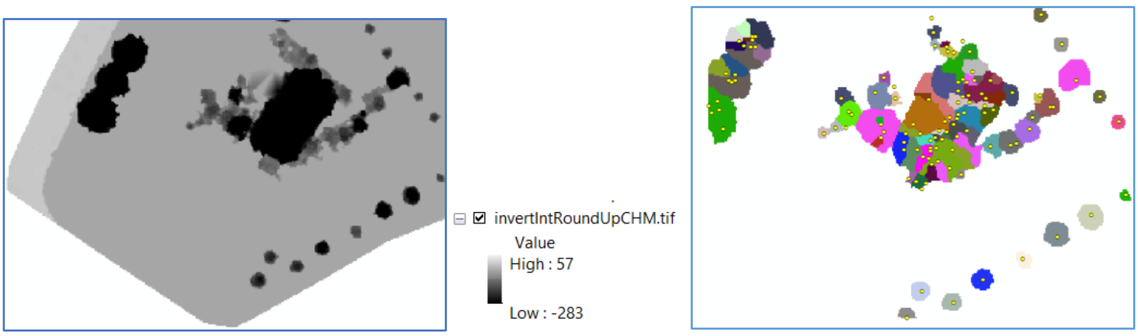


Figure 0.16: Left: Inverted CHM; right: watershed segments with minima points in yellow

2D crown dripline contours—derived by converting watershed segments to polygons. They were associate to inventory tree IDs with spatial joins: *a* associating the minima points with the watershed polygons, *b* associating minima points with crown projections of municipality with tree IDs. Using the minima points as a common field, segmentation polygons were associated to tree IDs. Polygons with the same ID were dissolved to form segmentation contours (Figure 0.17).

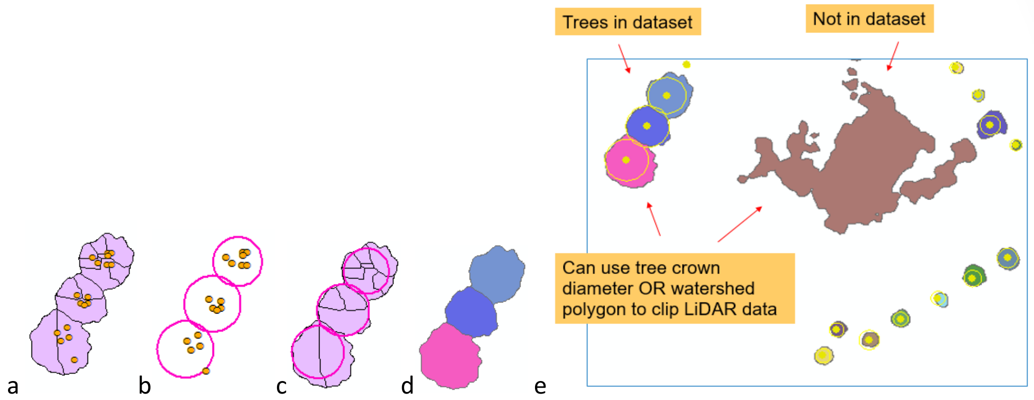


Figure 0.17: Spatial joins and overlays

a: minima points (MP) + watershed polygons; b: MP + trees in dataset; c: crown diameter projections of trees over watershed polygons; d: dissolved segmentation polygons; e: municipality crown projections and location points on segmented crown contours

537 vegetation objects from the point cloud were segmented. Almost all medium to high vegetation in the island. 73 were not associated and considered private based on their location. Five were not associated because they were misplaced in the municipality dataset. Private vegetation was dissolved and separated so they could be processed separately from the municipality data (Figure 0.17.e and Figure 0.18).

Figure 0.18: Segmented municipality and private trees
Left: Trees in the municipality of Rotterdam's dataset. Right: Private trees and vegetation

Segmentation polygons (yellow lines) and crown projections from the municipality dataset (pink lines) were checked against a satellite photo (Figure 0.19). A couple of large adjacent crowns did not have a clear delineation (Figure 0.19-b). Polygons of vegetation in the park area did not associate reliably with the municipality dataset. A side-by-side (Figure 0.19-c, d) shows many crowns in the municipality's dataset overlapping so segmenting individual trees within groups is difficult. A benchmark by Rottensteiner et al. (2014) noted slightly over 50% success in segmenting vegetation from aerial LiDAR data even if supplemented with different methodologies especially where (1) vegetation of different heights is present in largely vegetated areas, (2) is close to buildings, walls or sheds, or is in inner gardens near walls.

Out of the 503 trees in the municipality's dataset, 436 were segmented and associated after manually fixing five that had a wrong location and the two shown in Figure 0.19.b. From the 67 that were not associated, 43 were in the park and 24 scattered throughout the island. 28 segmentation polygons out of the 43 in the park were excluded from parameter extraction because of multiple association (Figure 0.20). In the end, 87% (436 out of 503) of the municipality trees and 73 private vegetation objects (dissolved) were segmented.

Figure 0.19: Satellite photos .8m cell size, taken in May. 15th, 2017
(NEO bv Netherlands Space Office, 2017)

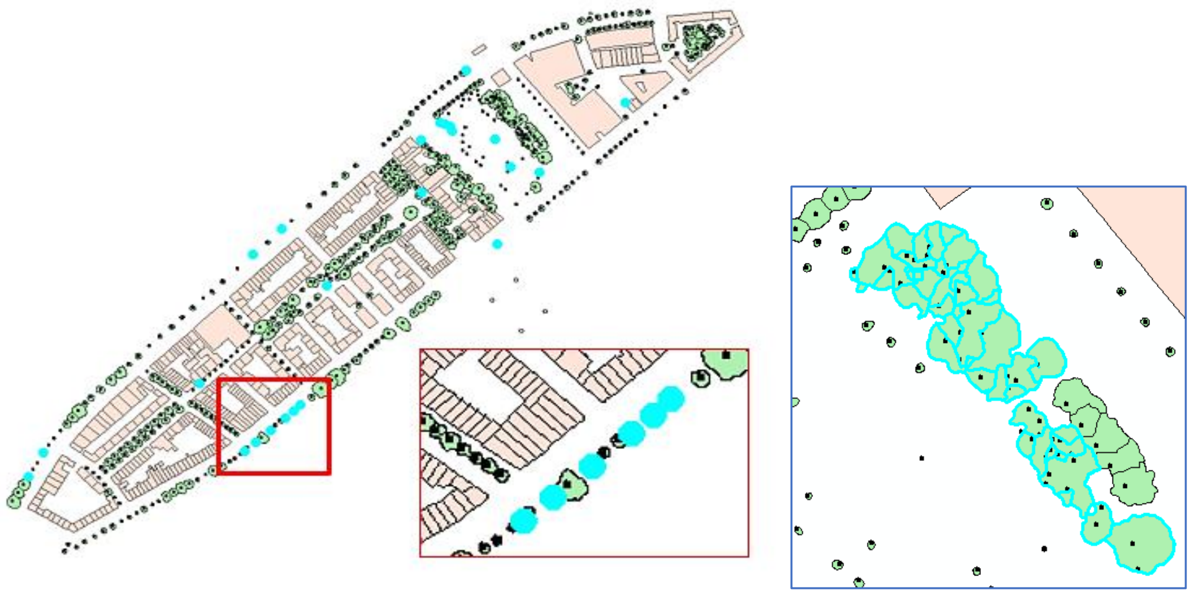


Figure 0.20: trees which did not segment properly

Left: Scattered 24 trees not segmented and the area were five trees were misplaced. Right: Excluded 28 polygons from object-based segmentation in the park (Figure 0.19) are highlighted.

Figure 0.21: Trees with wrong location and fixed crown delineations

Left: little trees in the dataset that were off in location compared to segmented watershed polygons. Four are in the bottom row in the center and one is on the very right of the same row;
right: manually fixed crown delineations shown in Figure 0.19.b

4. TREE PARAMETER EXTRACTION

The total height (Ht), crown base heights (Hc), and tree base elevation (Hb) of the municipality trees were extracted clipping the aerial LiDAR data with the segmentation polygons. The parameters validation is to be done by the municipality of Rotterdam and is out of the scope of this use case but checks with the point cloud were done.

Ht--The maximum height (Max_Z) and the 99-height percentile (H_99P) were extracted from the normalized LiDAR data with LasCanopy. The Max_Z height value is the z coordinate of the highest point within the polygon. H_99P is the height at which 99 % of the points were in the polygon. From charting these heights (Figure 0.22) about third of the 436 trees are about 13 m. Further, choosing the maximum height seems to add up to 2 m when compared to the H_99 height, a difference that impacts other calculations, e.g., crown volume. Choosing the 99-height percentile value may avoid over-estimations.

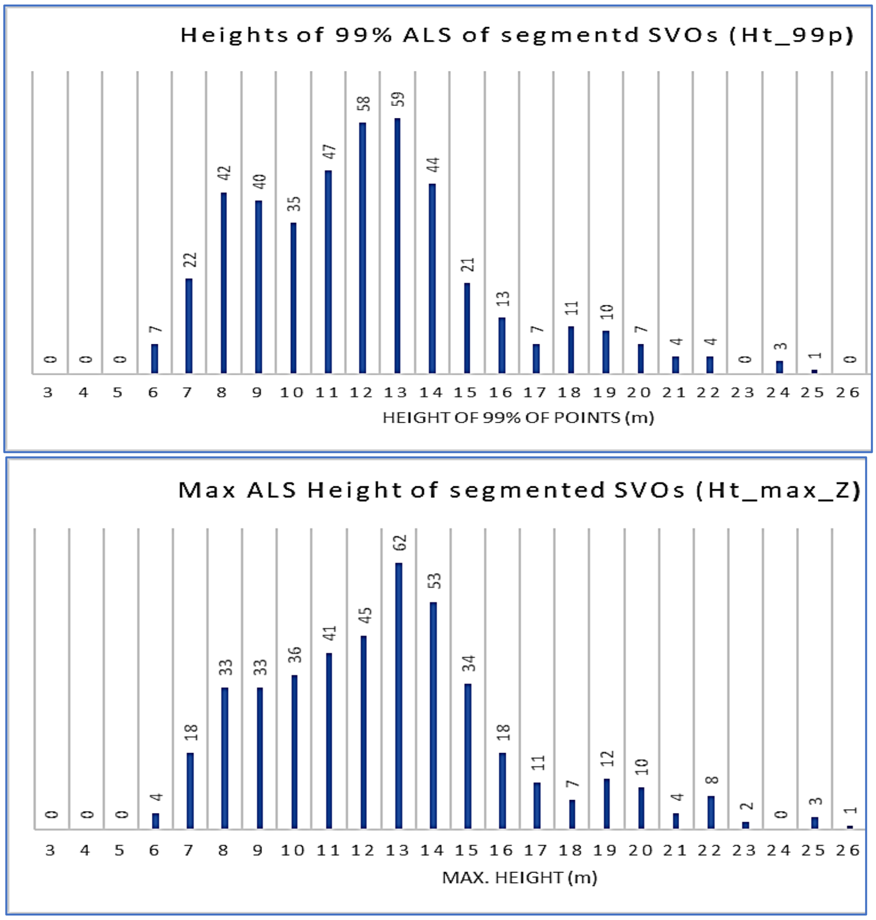


Figure 0.22: Extracted 99-percentile heights of segmented SVOs

Hc--The crown base height (Hc) is the minimum height of the underside of the tree crown. The 1-percentile height (Hc_01p) or the 5-percentile height (Hc_05p) can be considered as the Hc. Both were extracted from the 3rd, 4th, 5th pulse returns and excluding the last returns of the normalized point cloud data (Tanase, 2017) with LasCanopy. Other methods for estimating Hc treat each tree as an independent plot and Hc is the height where a second positive change occurs (M. Chen, 2013), or is the point of inflections of height changes (Volkova, 2014). In general, city trees are trimmed to maintain a clear line of sight of at least 3 m. In plotting Hc and respective Ht (Figure 0.23), 29 crowns start above 5 m and a proportional relationship of Hc with its Ht is observable.

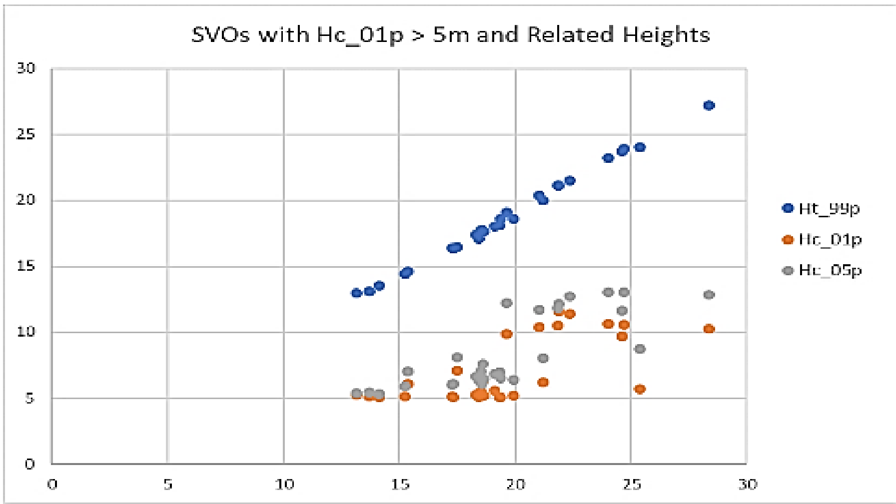


Figure 0.23: SVO total heights, Ht , where crown base heights, Hc, is higher than 5 m

Checking the LiDAR points of the tallest tree, the lowest z value from the crown underside (clicked) is lower than the extracted Hc_01p as expected, and the Hc_01p height is slightly higher than the bottom of the crown in Figure 0.24).

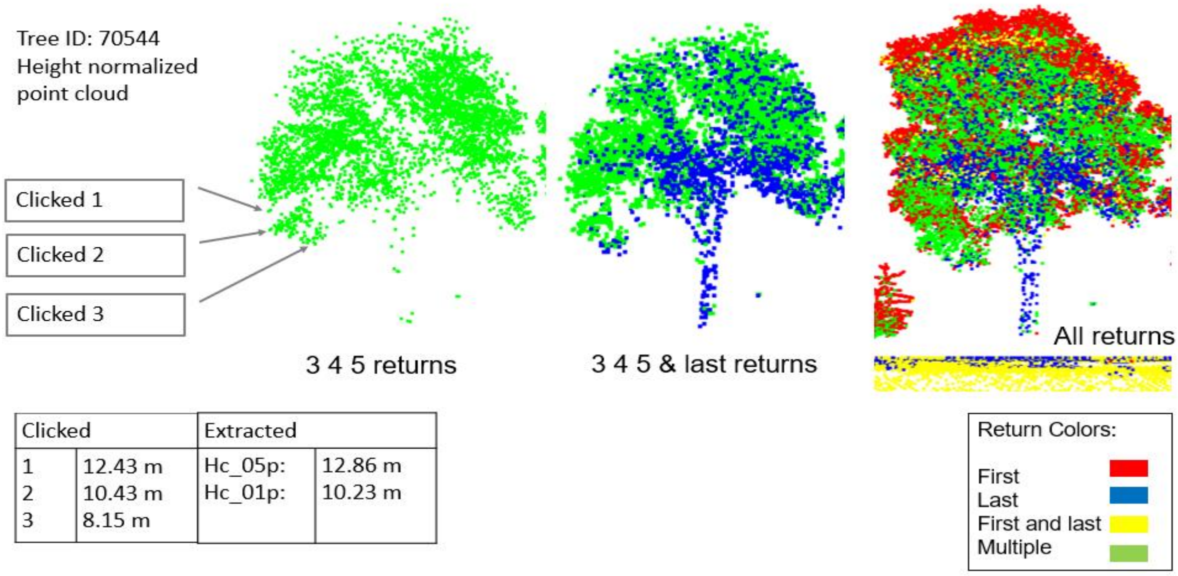


Figure 0.24: Point cloud of tallest tree and extracted Hc heights

Hb – The object's elevation on the terrain gives their vertical placement on a 3D model where the align-to-terrain feature is not available, and it has to be added to heights extracted from height normalized data to obtain tree top elevation. Because the municipality's data had mis-placements (Figure 0.20), the 2D centroids of the segmentation polygons were extracted. When compared to the municipality's, 10 centroids where more than 3 m apart. 9 were located in vegetation groups (Figure 0.25). Trunks are not always at the center of the crown and the low density of trunk points in the aerial data makes their detection unreliable. For generating the LODs for shadow analysis tree, the mobile LiDAR data was used to estimate the trunk's location to then extract its elevation. Elevation coordinates were extracted from the DTM with ArcGIS Extract Values to Points tool, and segmentation polygons' centroids were computed with the Feature to Point tool.

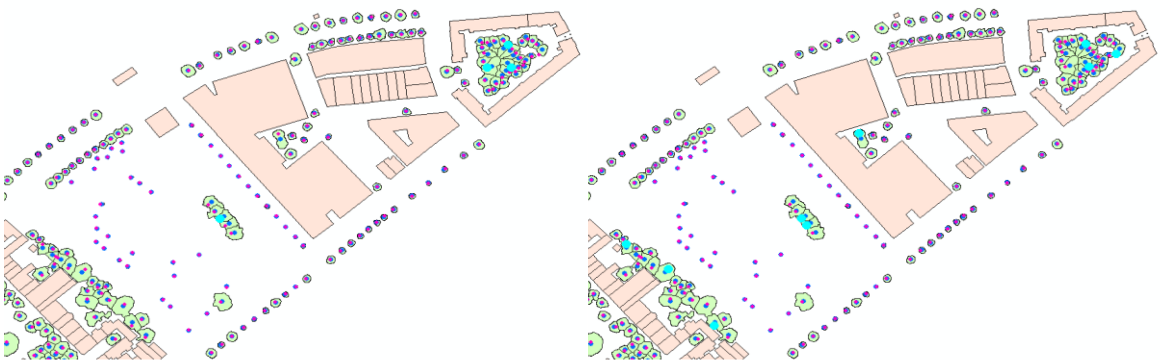


Figure 0.25: Tree location discrepancies
Left: Tree locations with > 3m in the X direction discrepancy between municipality dataset (pink) and segmentation centroids (blue). Right: Locations with > 3m in the Y direction. 9 out of 10 are highlighted.

P1, P2, P3 and P4—the (x, y) coordinates of four crown periphery points (CCP) were extracted from the bounding box coordinates of the segmentation polygons, which were extracted with LasTools. PX1, PY1, PX2, PY2, PX3, PY3, PX4, PY4 were calculated from midpoints of the bounding box coordinates (Figure 0.26). Another way of extracting such coordinates is by selecting the North, East, West and South points from a point cloud of each tree after storing it as a separate cluster (Chen, 2013). Additional points required for additional crown faces above and below the four CPP are interpolated during the realization of the crowns.

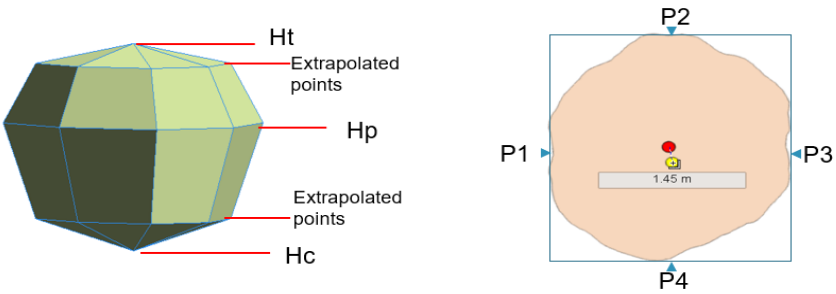


Figure 0.26: Hp points for parametric tree creation
Left: parametric crown with required heights; right: Four CPP extracted from segmentation polygon bounding box, polygon's centroid, and the municipality data tree location point in yellow

Hp -- The height of the widest spread of the tree crown was considered the height interval where most points were located. Using a LasTools script, segmented aerial LiDAR points were counted at intervals of 1 m. LasTools CSV output of the count was processed with Excel to extract Hp for all trees in the island. For the shadow analysis tree, it was extracted directly from its mobile LiDAR point cloud.

Hc – The crown base height of the shadow analysis tree was extracted from the normalized mobile LiDAR data using the segmentation polygon. The 1, 5 and 99 percentiles heights, and max Z height were extracted with LasTools.

Hb -- The locations of the trunks below parametrical crowns were extracted from the center of mass of the segmentation polygons. For the shadow analysis tree, it was extracted from its trunk footprint, which coincided with the location in the tree data inventory. The location of the tree in the municipality data is at about 1.45m from the centroid of its 2D crown delineation (Figure 0.26).

Td –The trunk diameter in the tree inventory data was used. For the shadow analysis tree, it was measured from ISO curves from the mobile LiDAR data. The curves were generated at heights near the BHD at 1.37m with LasTools (Figure 0.27). The trunk cross-section is elliptically shaped. The bounding box North, South, East and West dimensions were averaged.

The aerial and mobile LiDAR data of the shadow analysis tree (Figure 0.28) shows the mobile scan captured more points of the underside of the crown and trunk. The aerial data captured the crown top better, therefore respective values were used in LOD3 models of this tree. Table 6.4 lists the parameters extracted from both datasets. Bold values were used where two values existed.

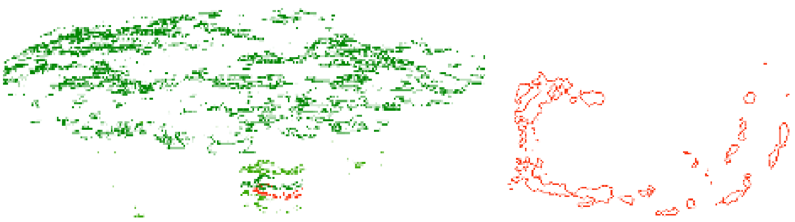


Figure 0.27: Iso curves of shadow analysis tree for trunk diameter estimation.
Red contours at 1.37 m or BHD height

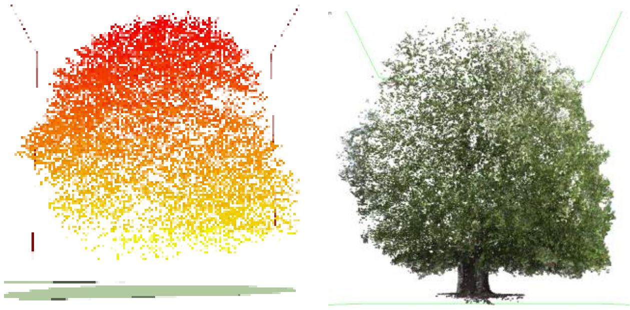
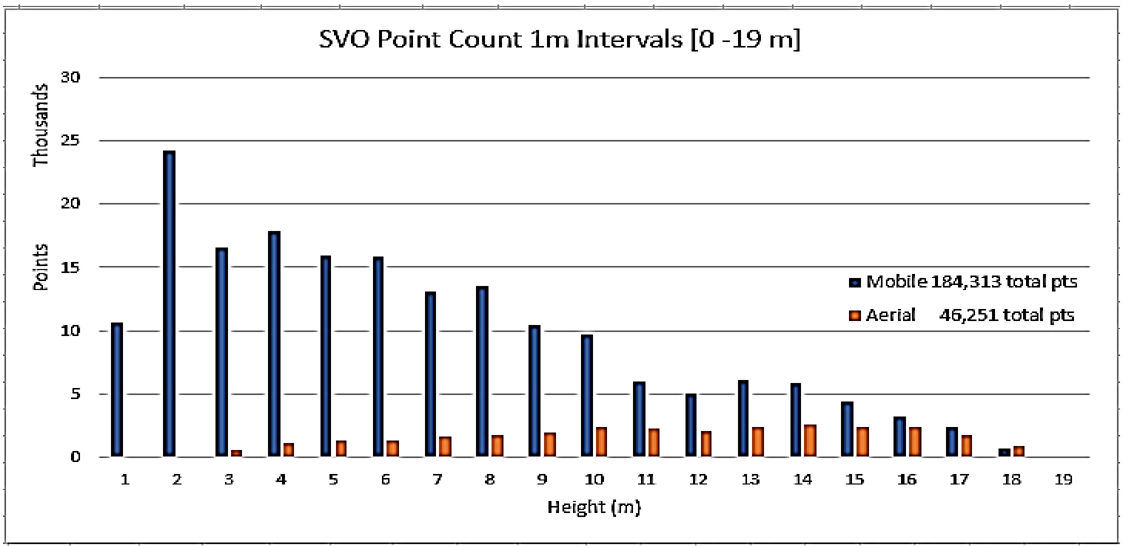


Figure 0.28: LiDAR data of shadow analysis tree. Left: aerial; right: mobile

In comparing the parameters extracted for the shadow analysis tree, its crown is unusually low. The aerial LiDAR data has no points below 2 m as vegetation class to cut off low lying objects around the crowns, but it is well capture with the mobile scan which gives a lower crown base height, which was extracted from point count percentiles. Similarly, the widest crown perimeter height is lower than the aerial's since it was extracted as the max. point count height. Table 0.5 shows the contrasting heights.

Table 0.5: Point cloud counts at 1 m intervals of both aerial and mobile LiDAR datasets



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
10617	24257	16534	17883	15968	15855	13077	13515	10424	9705	5965	5087	6134	5848	4390	3253	2390	713	25
0	125	619	1107	1364	1370	1627	1802	1970	2436	2315	2088	2371	2598	2382	2393	1771	874	53

3D Crown shapes, trunk, and tree models – Crown shapes corresponding to each tree species (47) in the municipality's dataset were acquired from other datasets and by research and recorded in a mapping table described in the next section. Models for LOD1.D, LOD2.A and LOD2.B corresponding to billboard, implicit volumetric trees with crowns S1 – S8, and realistic counterparts were acquired from ESRI's vegetation model library. Crowns S1 -S15 as defined in Chapter 4.2.1, a generic tree model for LOD1.A, and a trunk model for parametrical trees were all created with Autodesk Maya and stored (obj format) in a second model library. ESRI's trees that fulfill crown shapes S1 – S8 are models of entire trees, while S1 -S15 crowns include additional shapes but are individual crowns which can be scaled separately to acquired crown parameters.

Building height extraction – For a contextual reference for the 3D vegetation implementation and for subsequent shadow impact analysis on building surfaces, building heights for generating LOD1 buildings were extracted from the aerial LIDAR data. Using the 2D BGT building footprints as clipping plots and LasTools, their 95 percentile heights were extracted. Another method for estimating building heights is using the building footprints as statistical zones of the normalized DSM. This approach also rasterizes the footprint polygons as an internal process of the tool in ArcGIS and does not provide a Std. deviation calculation for each estimate.

APPENDIX D

CASE STUDY SHADOW MAPS

Table 0.6: Sun positions generated for June 21st, 2017 used for shadow analysis.

OBJECTID	Shape	LOCAL_TIME	AZIMUTH	ELEV_ANGLE
1	Point Z	6/21/2017 5:18:00 AM	59.19	6.1
2	Point Z	6/21/2017 5:48:00 AM	64.78	10.18
3	Point Z	6/21/2017 6:18:00 AM	70.3	14.45
4	Point Z	6/21/2017 6:48:00 AM	75.81	18.87
5	Point Z	6/21/2017 7:18:00 AM	81.36	23.41
6	Point Z	6/21/2017 7:48:00 AM	87.04	28.01
7	Point Z	6/21/2017 8:18:00 AM	92.94	32.63
8	Point Z	6/21/2017 8:48:00 AM	99.19	37.23
9	Point Z	6/21/2017 9:18:00 AM	105.92	41.74
10	Point Z	6/21/2017 9:48:00 AM	113.32	46.1
11	Point Z	6/21/2017 10:18:00 AM	121.61	50.2
12	Point Z	6/21/2017 10:48:00 AM	131.03	53.93
13	Point Z	6/21/2017 11:18:00 AM	141.82	57.12
14	Point Z	6/21/2017 11:48:00 AM	154.09	59.58
15	Point Z	6/21/2017 12:18:00 PM	167.68	61.09
16	Point Z	6/21/2017 12:48:00 PM	182.01	61.51
17	Point Z	6/21/2017 1:18:00 PM	196.21	60.78
18	Point Z	6/21/2017 1:48:00 PM	209.47	58.98
19	Point Z	6/21/2017 2:18:00 PM	221.32	56.3
20	Point Z	6/21/2017 2:48:00 PM	231.71	52.94
21	Point Z	6/21/2017 3:18:00 PM	240.79	49.09
22	Point Z	6/21/2017 3:48:00 PM	248.81	44.91
23	Point Z	6/21/2017 4:18:00 PM	256.01	40.5
24	Point Z	6/21/2017 4:48:00 PM	262.59	35.95
25	Point Z	6/21/2017 5:18:00 PM	268.73	31.34
26	Point Z	6/21/2017 5:48:00 PM	274.56	26.72
27	Point Z	6/21/2017 6:18:00 PM	280.2	22.14
28	Point Z	6/21/2017 6:48:00 PM	285.73	17.63
29	Point Z	6/21/2017 7:18:00 PM	291.23	13.25
30	Point Z	6/21/2017 7:48:00 PM	296.76	9.02
31	Point Z	6/21/2017 8:18:00 PM	302.39	5
32	Point Z	6/21/2017 8:48:00 PM	308.15	1.22

LOD1.x Shadow hours and Shadow %

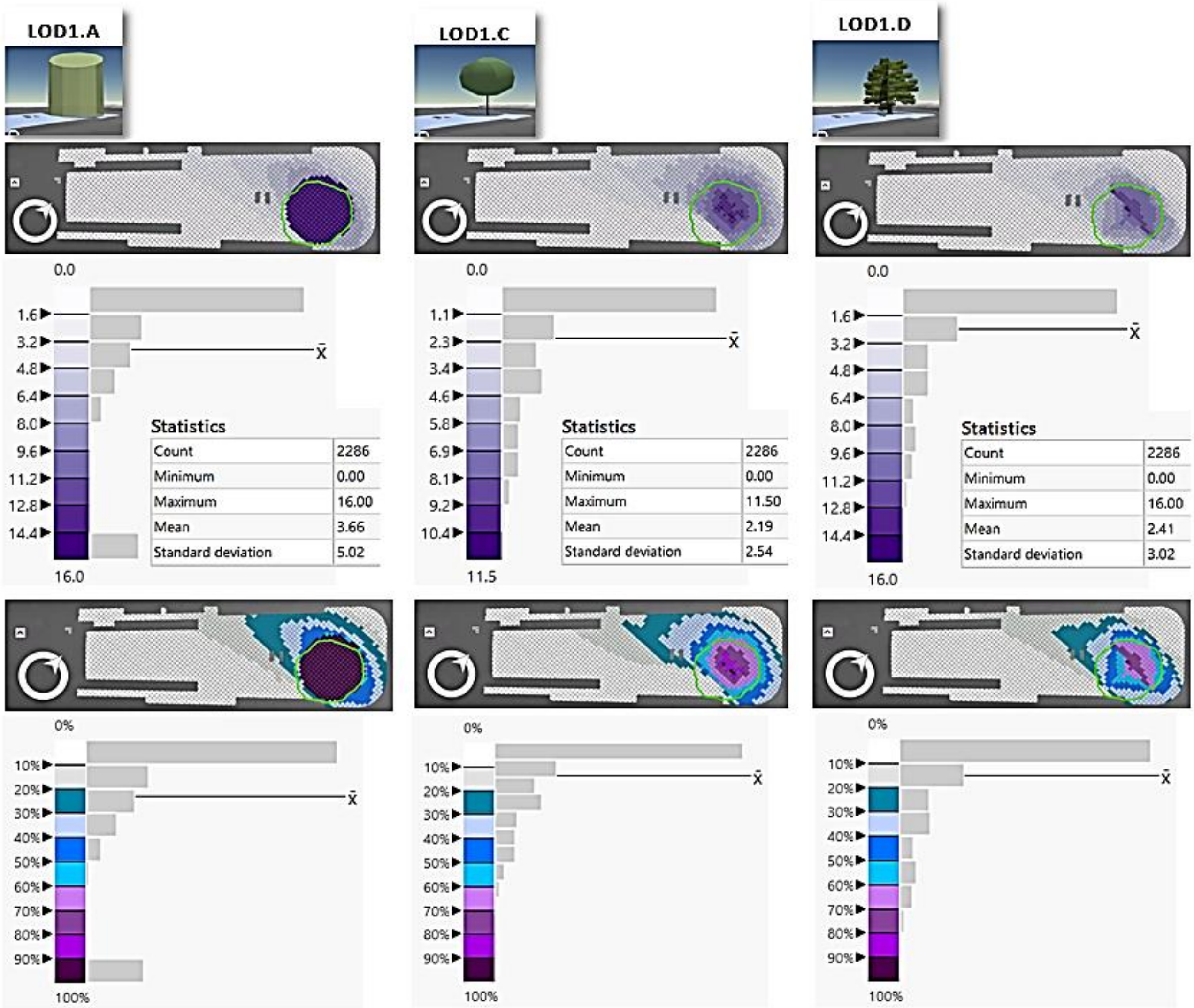


Figure 0.29: LOD1.x shadow and percent shadow
captured by each 1 m^2 panel during 16 hrs. of sunlight

LOD2.x Shadow hours and Shadow %

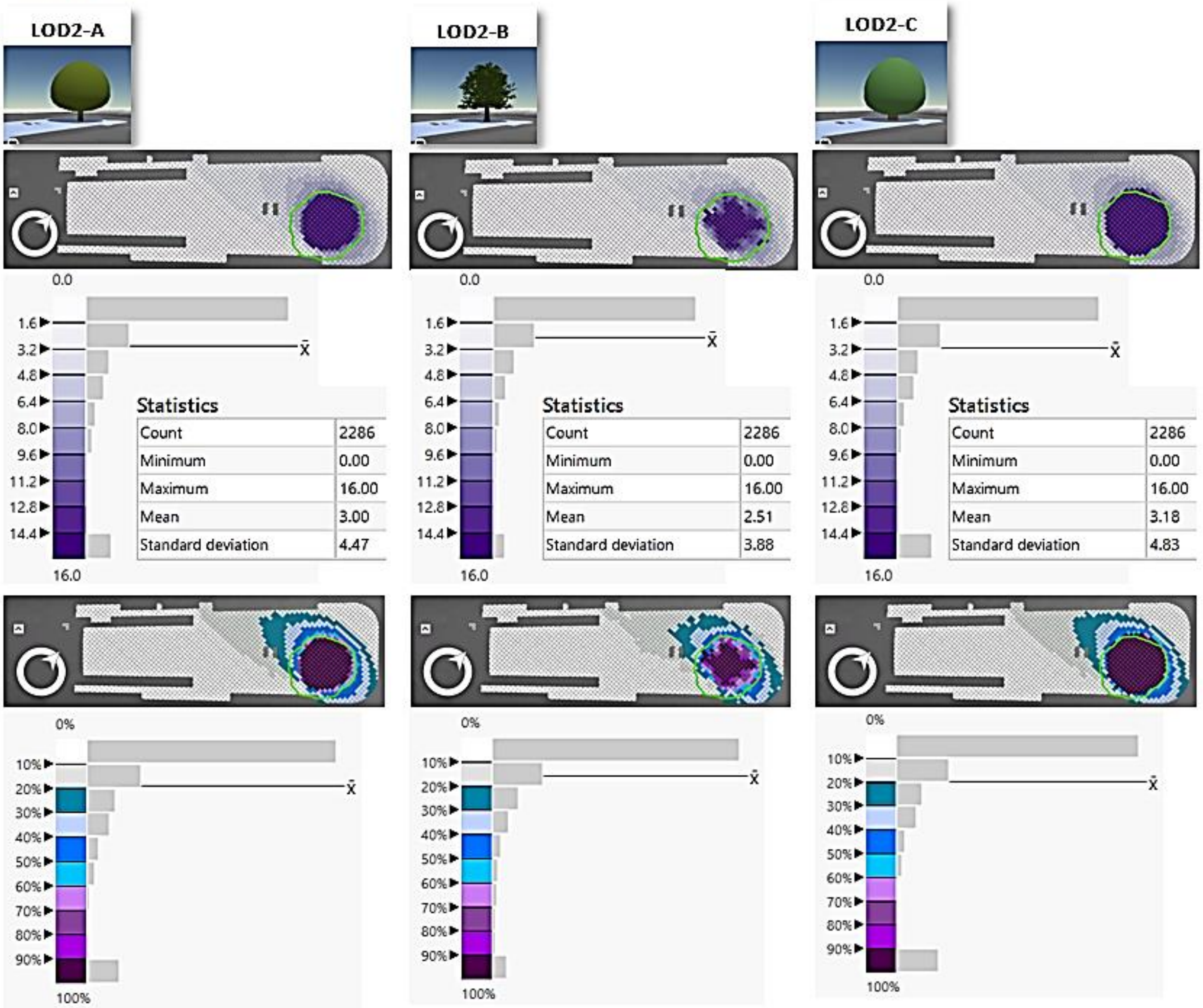


Figure 0.30: LOD2.x shadow and percent shadow
captured by each 1 m^2 panel during 16 hrs. of sunlight

LOD3.x Shadow hours and Shadow %

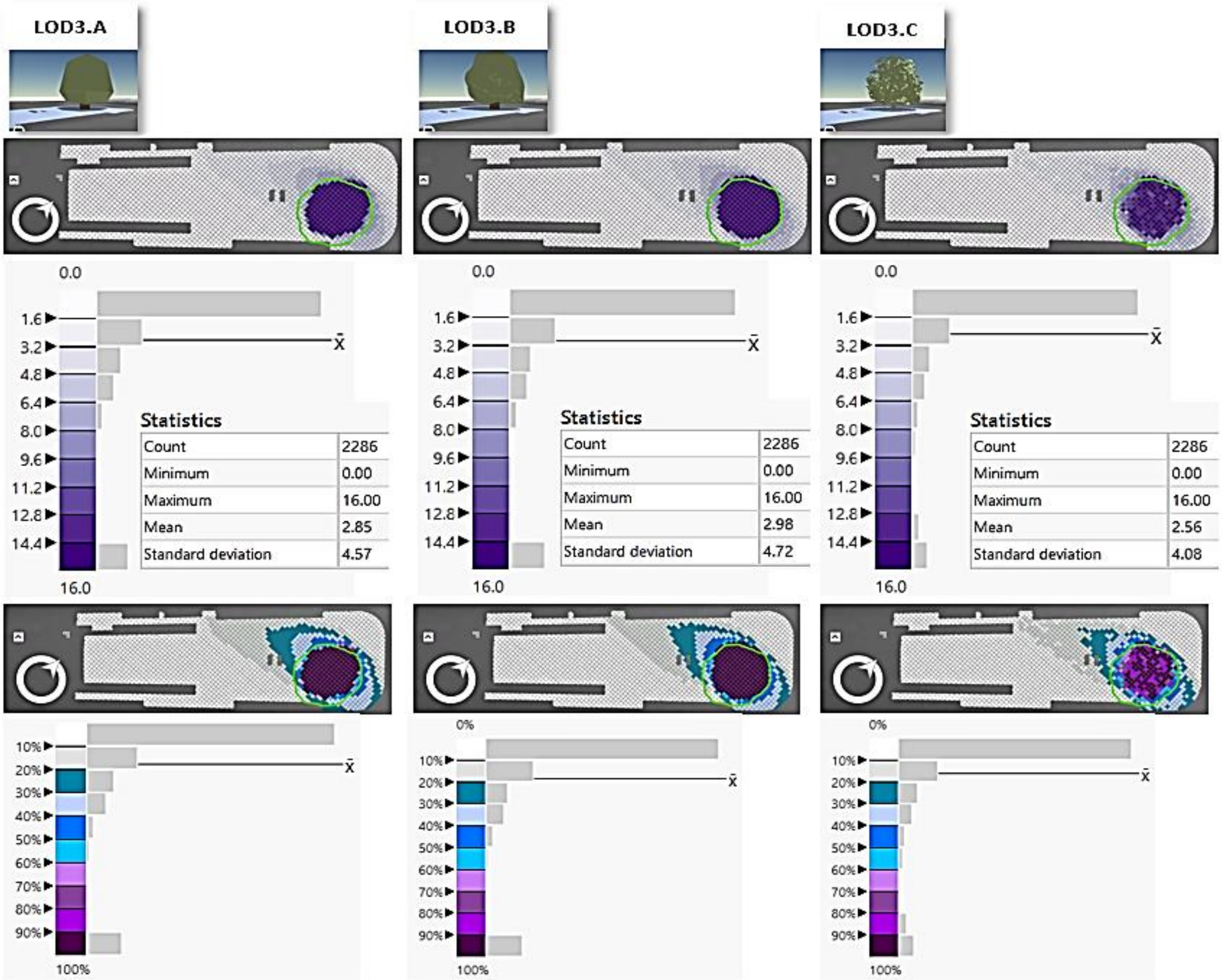


Figure 0.31: LOD3.x shadow and percent shadow captured by each 1 m^2 panel during 16 hrs. of sunlight

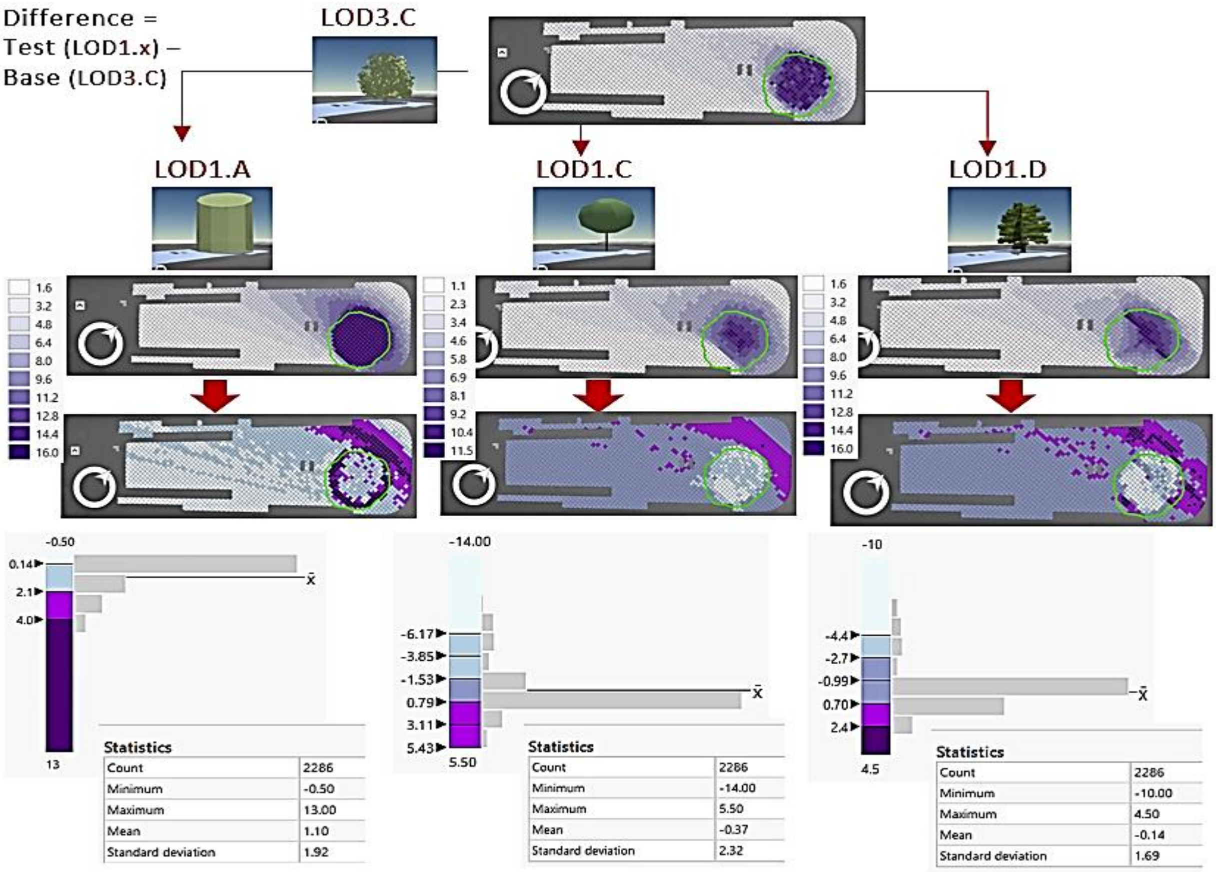


Figure 0.32: LOD1.x differences in shadow hours compared to LOD3.C

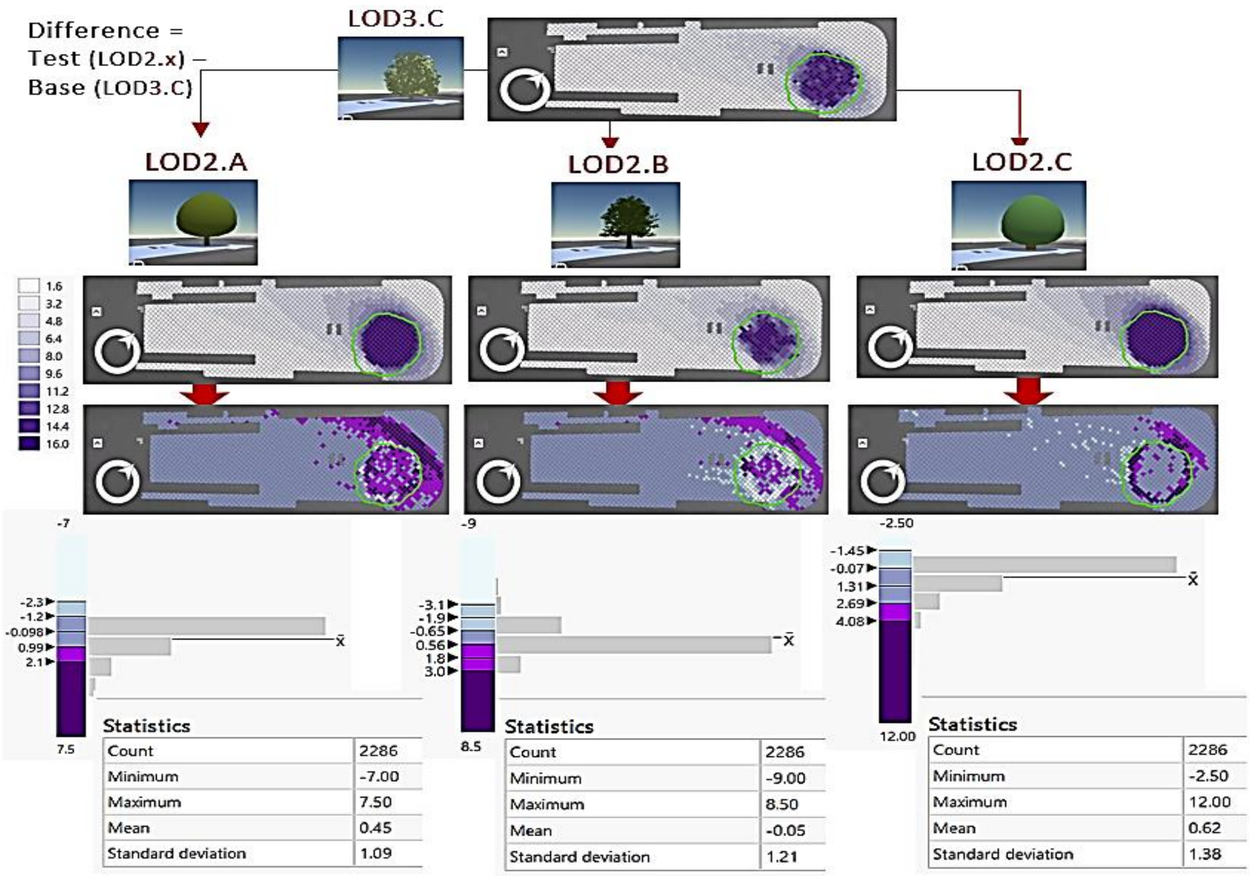


Figure 0.33: LOD2.x differences in shadow hours compared to LOD3.C

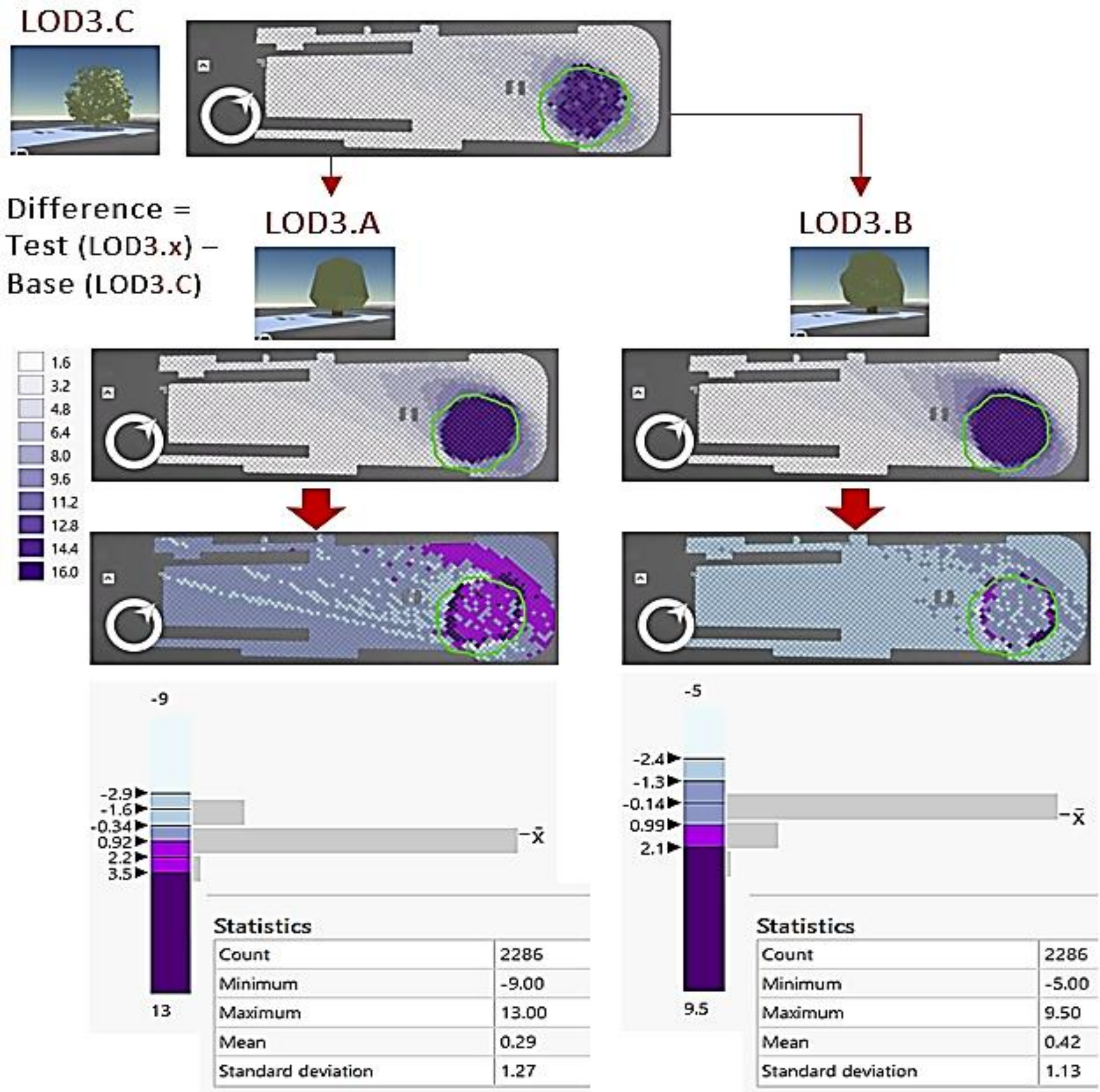


Figure 0.34: LOD3.x differences in shadow hours compared to LOD3.C