Semantic Urban Vegetation Modelling Based on an Extended CityGML Description

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Abstract: With the continuous development of smart cities, 3D vegetation models are increasingly used in urban planning, city design, ecosystem service assessment, and other aspects. City geography markup language (CityGML) is a common semantic information model presenting 3D urban objects, and it can be shared by multiple programs. CityGML is a widely-used open international standard for simulated cities and landscape architecture modeling. Based on the existing CityGML standard for urban levels of details (LODs), this study proposes semantic information model for urban vegetation types (trees, shrubs, ground cover) by analyzing the application requirements at different LODs. The vegetation model consists of above-ground and below-ground parts with plant components (flowers and fruits) introduced into the LOD4. A CityGML-based multi-scale 3D semantic model construction method is proposed, and it can be used for visualization and informatization of plant parts in digital cities to solve the problems with existing vegetation 3D models, such as single function and the lack of unified data collection standard.

Keywords: CityGML, vegetation modelling, LODs

1 Introduction

3D vegetation models have many applications, such as dynamic growth simulation, climate and environmental impact analysis, and ecosystem service assessment. Compared with ordinary geometric models, the semantic models contain attribute and relationship information to meet the visual demands and to better reflect the information of physical entity (GROEGER & PLUMER 2012).

The existing standards for representative semantic vegetation models mainly include CityGMLand IFC, while modeling software primarily include SpeedTree plant modeling developed by IDV and XFrog. There is multiple modeling software used for vegetation modeling such as ENVI-met and i-tree. CityGML is a universal semantic information model reflecting 3D urban objects, and it can be shared by different application programs. CityGML is also the most important international standard for modeling simulated cities and landscaped architecture. CityGML defines geometry and attributes of most 3D features and objects in cities and provides a rough description of vegetation modeling, However, the existing urban 3D modeling is mainly focused on buildings. For example, in the 3D city database, the virtual 3D New York City model created by the geoinformatics team of Technical University of Munich (Figure 2) only focuses on buildings, roads, squares, and green spaces without vegetation modeling. The vegetation element is less reflected in the current 3D city modeling, and only the plant geometry model is in the 3D city model. CityGML mainly focuses on building infrastructure, thus resulting in the ambiguity of the urban vegetation content, eventually causing the inability to spatially simulate urban vegetation and assess the ecosystem services (LESSIE 2018).

Journal of Digital Landscape Architecture, 7-2022, pp. 200-212. © Wichmann Verlag, VDE VERLAG GMBH · Berlin · Offenbach. ISBN 978-3-87907-724-3, ISSN 2367-4253, e-ISSN 2511-624X, doi:10.14627/537724020.

Fig. 1:
Three-dimensional green volume of the city of Boston, USA, reflected using ovoid geometry

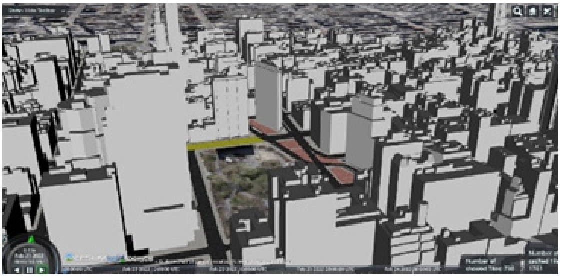


Fig. 2:
NYC LOD2 Model

Most software classify vegetation based on canopy morphology and planting location of trees, shrubs, and ground cover by vegetation modeling standards. The morphological, physiological and biochemical modeling metrics are selected depending on visualization or scientific research purposes. The current 3D vegetation model still suffers from standard inconsistency and construction metrics confusion, and thus its value cannot be fully fulfilled.

Table 1: 3D vegetation modeling software, modeling methods, and attribute indicators

Software	Description	Vegetation type	Vegetation modeling indicators
ENVI-met (Albero)	Modeling based on canopy voxel grid and leaf area density; visualized vegetation based on voxel model; simple components; mainly used for simulating outdoor microclimate; low authenticity and aesthetics.	Cylindrical, spherical, heart-shaped	Plant geometric characteristics (tree height, crown voxel size, voxel resolution); basic plant attributes (carbon fixation type, leaf characteristics, leaf shortwave reflectance, leaf shortwave transmittance); advanced plant attributes (leaf unit mass, rubber productivity); root system characteristics (root depth, root diameter, root zone geometry); plant monthly variation (plant leaf area index, month-to-month variation factor)
i-tree	The database is rich in vegetation types. The benefits and values of trees around the world can be quantified. However, it cannot reflect the dynamics of vegetation growth seasons.	Trees, shrubs, etc.	Family, name, species code, growth form, leaf density, leaf type, growth rate, age, height at maturity

Table 1 (continued)

Software	Description	Vegetation type	Vegetation modeling indicators
Speed Tree	Manual modeling is integrated with procedural modeling.	Trees, shrubs, ground cover	Branches, knots, leaf webs, leaves
Xfrog plant	It adopts Gragh-Based modeling approach, and it can express the complex structural information of trees through prototype diagrams.	Trees, shrubs, flowers	Height, origin, growing environment, climate, seasonal changes

Table 2: Vegetation modeling methods and attribute metrics in 3D modeling standards

Software Name	Description	Vegetation type	Vegetation modeling indicators
CityGML	Modeling is performed based on XML format. The international standard for scalable spatial data exchange and encoding storage are published by the open geospatial consortium (OGC) and ISO TC211.	Solitary Vegetation Object/Plant Cover	Solitary vegetation object: properties species, tree height, crown morphology, diameter at breast height Plant Cover: Properties, species, average tree height
Urban 3D modeling technical specificationsCJJ/T 157-2010	Modeling is conducted using one modeling technique such as CAD, fractal modeling or in combination of multiple modeling techniques.	Roadside trees planted in rows along highways or roads; landscape plants planted in green spaces, parks, communities, and courtyards	Name, species, age, height, ownership unit

The city geography markup language (CityGML) standard is an interoperable format proposed by the open geospatial consortium (OGC) in 2008 to present and store semantic 3D city models. The latest version is CityGML 3.0. Based on the current CityGML standard of the different levels of details (LODs), this study proposes different levels of information model standards for visualization and informatization of plant parts of urban vegetation in the city information modeling, and put forward a 3D vegetation model construction method.

2 Semantic Information Structure of Building Models in CityGML

When the building model is established by the CityGML standard, the semantic information of each surface such as wall surface and roof surface is constructed at the LOD3. CityGML uses *BuildingSurface, BuildingInstallation, IntBuildingInstallation, Opening, Room, and BuildingFurniture* to define different types of special sections (Table 5). At the LOD1, a building 3D model is only represented by volumetric geometry. At the LOD2, *MultiSurface* and *MultiCurve* attribute types are added and applied to the detail representation of the building model such as railings. At the LOD3, *BoundarySurface* and *BuildingInstallation* attribute types are added and applied to provide semantic information of the outer building. The *BoundarySurface* includes special features such as *WallSurface* (wall) and *RoofSurface* (roof). The general *BuildingInstallation* includes three attribute types (class, usage, and function). At the LOD4, the semantic information of the interior building is reflected by *IntBuildingInstallation*, including balcony, stairs, rooms, and others.

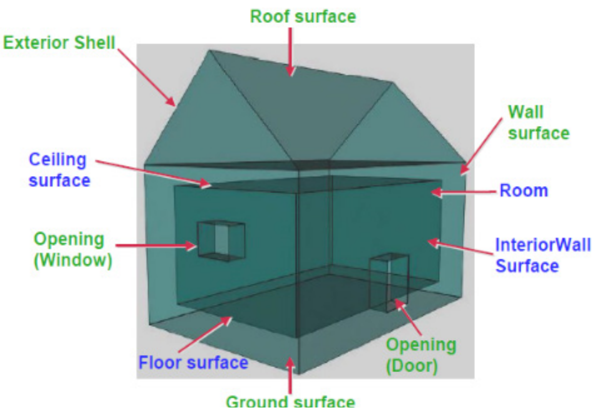


Fig. 3: Semantic information components of a building

Table 3: LOD1-4 of geometric semantic types for building models

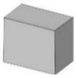
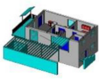
Geometric / semantic theme	Property type	LOD1	LOD2	LOD3	LOD4
Volume part of the building shell	*gml:SolidType*	*	*	*	*
Surface part of the building shell	*gml:MultiSurfaceType*	*	*	*	*
Terrain Intersection Curve	*gml:MultiCurveType*	*	*	*	*
Curve part of the building shell	*gml:MultiCurveType*		*	*	*
Boundary surfaces	*_BoundarySurfaceType*		*	*	*
Outer building installations	*BuildingInstallationType*		*	*	*
Openings	*_OpeningType*			*	*
Rooms	*RoomType*				*
Interior building installations	*IntBuildingInstallationType*				*

3 Extended CityGML Description of Urban Vegetation

CityGML has 5 levels of details for building models (ARROYO et al. 2018). LOD0, as the coarsest level, is a 2D plane. LOD1 is a 2.5D extruded geometry model. LOD2 is building model with different roof structures. LOD3 refers to building model with detailed wall, roof, balconie structures. LOD4 is the componentized LOD3 model with 3D interior structures (rooms, doors, stairs, furniture, and others).

In this study, the LODs of the vegetation model correspond to the LODs of CityGML's building. Although there are some differences between buildings and vegetation in terms of morphological structure, CityGML's modeling scheme of dividing the building model into external and internal components and the definition from LOD0 to LOD4 provide reference for the methods and ideas of vegetation modeling. Referring to CityGML's definition of architecture, the single vegetation model includes trees, shrubs, and ground cover. Parametric components are used for 3D modeling, and the vegetation model consists of above-ground and below-ground parts, and plant components including canopy, branches, flowers, and fruits are introduced to the more detailed LOD4 (Table 4). The geometric contents and attributes at the 5 LODs are shown in Table 6.

Table 4: Comparison of 5 LODs between proposed vegetation model and building model

	Building	Vegetation		Description
		Overground part (canopy)	Underground part (root)	
LOD0				2D plane presenting the position and size
LOD1				2.5D extruded solid presenting height/ root depth of buildings and vegetation
LOD2				Simple 3D solid, with coarse morphology
LOD3				Complicated 3D solid presenting morphological structure of the model
LOD4				3D structured components and semantic components presenting model details

LOD2 is responsible for the abstraction of trees into geometry. According to the classification of garden trees by Chen Youmin (2006) in his Garden Arboriculture , the garden trees are abstracted into 6 categories at LOD2 (Table 5), and the LOD3 is the geometric surface model composed of triangular surfaces.

Table 5: Multiple forms of LOD2&LOD3

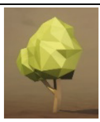
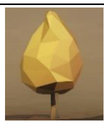
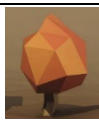
LOD2						
Canopy morphology	Hemisphere	Oval	Sphere	Spherical sector	Cylinder	Cone
LOD3						
Canopy morphology	Different morphological triangular surface model					

Table 6: Attributes added to LODs

LOD	Additional attributes relative to the previous level
LOD0	Vegetation canopy size
LOD1	Vegetation volume and height presented by geometric volumes
LOD2	Canopy morphology of vegetation
LOD3	Simple external structure of vegetation
LOD4	Internal structure of vegetation including branches, crown, fruits, and flowers

3.1 Five LODs of Vegetation Model

The dimension, composition, and visualization of the 5 LODs of the vegetation model corresponding to LOD0-4 of the building model in CityGML are shown in the table below.

Table 7: 5 LODs of urban vegetation model

	Dimension	Description	Composition	Visualization
LOD0	2D	Planar graphs	Above-ground plant body + underground roots	Top view of above-ground and below-ground parts abstracted based on regular circles or irregular polygons
LOD1	2.5D	geometric solid	Above-ground plant body + underground roots	Above-ground and below-ground parts are abstracted based on simple geometry (such as columns)
LOD2	3D	Simple geometry in the shape of a tree	Above-ground plant body + underground roots	Differences between tree species are reflected by simple geometry (which is classified by canopy and root morphologies)
LOD3	3D	3D morphology	Above-ground plant body + underground roots	Above- and below-ground parts of plants are presented by triangular surfaces and voxels
LOD4	3D	authentic 3D tree model	Above-ground plant body (Canopy+stem+ branch+flower+fruit) + underground roots	Above- and below-ground parts of plant are constructed with canopy, stems, branches, flowers, fruits, and roots

3.2 Attributes of Vegetation Model at Different LODs

The CityGML-based semantic information of single plant vegetation consists of 6 categories: classification, function, species, height, trunk diameter, and canopy breadth. The attribute types of the vegetation model were enriched based on semantic information of the building model (Table 8).

Table 8: Extended Attributes of urban vegetation at different LODs

Attribute Type	Attribute	Description	Corresponding LODs
Taxonomic indicators	Species	Latin name	LOD 0-4
	class	Trees/shrubs/ground cover	LOD 0-4
	Family and genus	Taxonomic information of plant	LOD 1-4
Morphological characteristics indicators	Canopy shape	Common tree canopy morphology is summarized	LOD 2-4
	Height	The distance or height of a tree from the rootstock at ground level to the top of the tree	LOD 1-4
	Canopy breadth	The average of the north-south and east-west width of tree	LOD 2-4
	Diameter at breast Height	Trunk circumference at 1.3m above ground level	LOD 2-4
	Root depth/root ball volume/root ball areas	Root indicators	LOD 2-4
Physiological indicators	NDVI	Normalized Difference Vegetation Index	LOD 1-4
	LAI	Leaf Area Index	LOD 1-4
	LAD	Leaf Area Density	LOD 1-4
Temporal	Age	Specific age or description of life stage	LOD 3-4
Components	Leaves	Leave size, area, shape, and others.	LOD 4
	Twig	Length	LOD 4
	Branch	Nutrient branches, fruiting branches	LOD 4
	Limb	Length	LOD 4
	Trunk	Length	LOD 4
	Stump	Area	LOD 4
	Large roots	Area, Volume	LOD 4
	Fine roots	Area, Volume	LOD 4

3.3 Vegetation Components

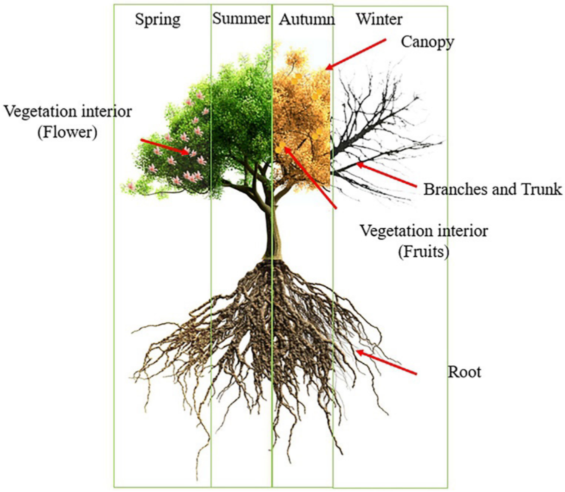


Fig. 4:
Semantic components of Vegetation Model

Referring to the modeling approach of buildings, 6 attribute types including vegetation volume vegetation surface, canopy, trunk, roots, and vegetation interior are adopted to construct the vegetation 3D model. At the LOD1, the 3D model of vegetation is presented by geometric volumes. Only from LOD2, the vegetation basic morphologies such as spire, cone, and spindle are presented, and the MultiSurface attribute type is added to express the features of tree components such as canopy, branch, and trunk. At the LOD3, the attribute types of crown and branch are added to provide more detailed semantic information on vegetation exterior morphology. At the LOD4, the interior morphology of vegetation canopy is reflected, including vegetation branch morphology, flowers, fruits, and other vegetation components (Table 9).

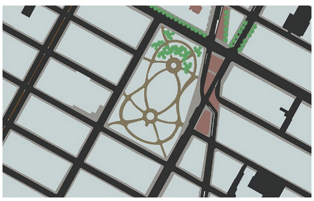
Table 9: Geometric semantic types at LOD1-4 of vegetation model

Geometric semantic types	Attribute type	LOD1	LOD2	LOD3	LOD4
Vegetation volume	*gml:SolidType*	*	*	*	*
Vegetation surface	*gml:MultiSurfaceType*	*	*	*	*
Root	*RootType*	*	*	*	*
Canopy	*gml: MultiSurfaceType*		*	*	*
Branches and Trunk	*BranchesandTrunkType*		*	*	*
Vegetation interior	*VegetationinteriorType*				*

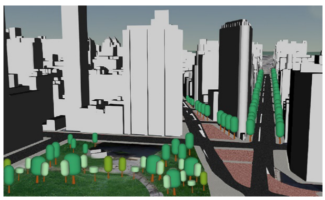
Vegetation components are mainly divided into 5 parts: crown, branches, roots, flowers, and fruits. Vegetation components exist only at the LOD4. However, in the current classification at the LOD4, vegetation components are set only for trees and shrubs with no vegetation components set for ground cover.

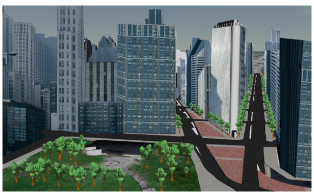
4 Modeling Methods of CityGML-Based Multi-Scale 3D Vegetation

Based on the above definition of vegetation models at different LOD levels, the construction method of vegetation semantic models is proposed.


LOD0


LOD1


LOD2


LOD3

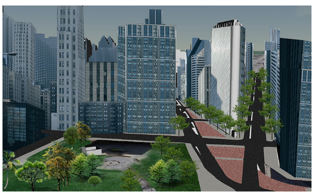

LOD4

Fig. 5: LOD0-4 schematic

4.1 LOD0

CityGML defines building LOD0 as a polygon of building footprints or roof edges formed by using elevation coordinates. At vegetation model LOD0, two-dimensional graphics can be expressed using the polygons of plant canopy breadth, and the collected vector data of vegetation canopy breadth are overlaid with geographic locations to display a 3D space.

4.2 LOD1

CityGML uses simple geometry to represent building models at the LOD1, which can be automatically generated using 2D contour data of buildings in combination with simple stretching of building heights. Similarly, vegetation models at LOD1 can also be formed automatically using 2D canopy breadth contours in combination with the stretching of vegetation height. The height data of single plant vegetation can be obtained by field measurement or estimation, while those of tree group vegetation such as forests can be derived from remote sensing images, LiDAR data. and others. The two-dimensional vegetation canopy breadth data can be obtained by field measurement or remote sensing image estimation. After obtaining the two-dimensional vector data of vegetation, the LOD1 model can be generated by fast stretching according to the height field using ArcGIS and other software, and then the generated LOD1 is converted to the CityGML model using ArcGIS toolbox or other software. Alternatively, the information of vector data can be obtained by programming, and then CityGML LOD1 geometric model was directly outputted by code.

4.3 LOD2

The CityGML LOD2 model mainly focuses on a detailed semantic representation of vegetation canopies. In the current research, the canopy is classified into six types, hemisphere, oval, sphere, spherical sector, cylinder and cone. At the LOD2, the mesh model of vegetation can be constructed using 3D interactive design software such as SketchUp and Autodesk 3ds Max. Finally, the geometric-semantic integration model is constructed based on the determined CityGML LOD2 vegetation specification.

4.4 LOD3

Compared with LOD2, the CityGML LOD3 vegetation model is added with a simple external structure, and 3D modeling can be implemented using spatial data conversion software such as Feature Manipulate Engine (FME). FME not only supports the reading and writing of various 3D models generated by such software as SketchUp, Autodesk 3ds Max, Autodesk Revit, IFC, and CityGML, but also provides a large number of semantic and geometric processing functions such as FeatureTypeFilter, GeometryFilter, GeometryPartExtractor, GeometryCoercer and GeometryPropertySetter, which is conducive to the rapid conversion of different 3D model data. At the LOD3, the triangular surface model can be established using SketchUp software, and the vegetation model components defined by LOD3 such as capony, trunk, and roots can be manually drawn and presented at different layers. Subsequently, the converter provided by FME software is used to convert .skp into .gml, and finally the LOD3 hierarchical model is constructed.

4.5 LOD4

Since LOD4 has some addional vegetation components, authenticity and vegetation detail characteristics are emphasized in the visualization of the model. For example, components such as fruits and flowers are added into LOD4, compared with the LOD0-3. The basic construction idea of LOD4 is similar to that of LOD3. Specifically, the SketchUp model can be converted into CityGML LOD4. However, in terms of model visualization, the LOD4 components require higher precision and richer semantic information, therefore the professional vegetation modeling software such as speedtree are suggested to be used to meet the requirements for high precision. The obtained file can be saved in dae or fbx format. Conversion software LandXplorer and FME support LOD hierarchical storage, and LandXplorer supports semantic editing, both of which are conducive to the construction of vegetation model LOD4.

5 Potential Applications of CityGML-Based Vegetation Model at Different LODs

5.1 Project Demonstration and Visualization

3D vegetation model is mainly used for visualization and analysis on different scales in the following aspects: (1) spatial analysis of vegetation; (2) simulation of vegetation growth and seasonal variations with authentic models; (3) assisting landscape design and enhancing the expressiveness of landscape design.

LOD0 and LOD1 are mostly used for visualization analysis such as spatial analysis of vegetation and analysis of the relationship between vegetation and the surrounding environment. GU et al. (2021) used MOD13Q1 image data to analyse the spatial and temporal change characteristics of vegetation cover and future change trends of vegetation in Qianxinan in 2000-2015. Our proposed LOD0-4 models, especially LOD4 model, are used to analyse the growth state and seasonal changes of vegetation. AIDAN et al. (2021) used Blender and Unity 3D to visualize the scenes of tree mortality to investigate the impact of tree mortality on the whole forest, and their finding provide the guidance for forest tree maintenance management. ZHAO (2016) employed 3DS MAX software to create models of Moso bamboo in different states and conducted 3D visualization and spatial analysis of Moso bamboo forests. Our five LODs have been employed to assist landscape garden design throughout the entire design process from site analysis in the pre-design stage to the presentation of design results in the post-design stage.

5.2 Ecosystem Service Assessment

The green infrastructure constituted by urban vegetation provides multiple types of ecosystem services and exerts important ecological, environmental, and social functions. Although common LODs can be used for ecosystem service assessment and spatial analysis, the refined LODs can provide more accurate and reliable data, but the corresponding information collection process is more complicated. Ecosystem service calculations at different LODs are performed by different methods for different purposes.

Table 10: Ecosystem Service Evaluation of Vegetation at Different LODs

	Ecosystem Services Assessment Tool	Topics
LOD0	SWMM/ National Stormwater Management Calculator/Long-Term Hydrologic Impact Analysis/Rainwater Harvesting Calculator	Carbon Sequestration & Avoidance / Stormwater management/Rainwater harvesting
LOD1	InVEST/Universal Floristic Quality Assessment Calculator/System for Observing Physical Activity and Recreation in Natural Areas (SOPARNA)	Habitat quality/native plants/ habitat restoration
LOD2	i-tree streets/ Resource Conserving Landscaping Cost Calculator/Public Life Tools	Stormwater management/Trees/ Native Plants
LOD3	ENVI-met/Ladybug/COMET-Farm/Pathfinder: Landscape Carbon Calculator/i-Tree Eco/Resource Conserving Landscaping Cost Calculator	Carbon Sequestration&Avoidance
LOD4	Growth model/iNaturalist/iNaturalist	Species richness/ Species change

5.2.1 LOD0

LOD0 can show the location and coverage of vegetation, and it can easily estimate the coverage area of the urban vegetation. Hydrologic management models such as SWMM can be used to assess the benefits from urban hydrologic function regulation by urban vegetation.

5.2.2 LOD1

LOD1 allows easy LOD0-based calculation of NDVI, leaf area index, root depth, root volume, and other indicators. At the LOD1, such indicators as land type and ground cover are more easily available with higher accuracy for the assessment of ecosystem services by using tools such as InVEST and Universal Floristic Quality Assessment Calculator.

5.2.3 LOD2

The LOD2 vegetation model can provide i-tree software with parameters such as tree type and canopy breadth for ecosystem service evaluation, and it can solve the problem of cumbersome input of tree information.

5.2.4 LOD3

Based on LOD3 model with 3D entities, the impact of vegetation on the ecosystem could be predicted and assessed by analyzing climate with software such as ladybug and Envi-met.

5.2.5 LOD4

At the most refined LOD4, the concept of 3D plant construction is introduced, and the construction of plant components including roots, stems, branches, flowers, and fruits can provide the growth state and seasonal changes of vegetation at different time dimensions, thus facilitating the calculation of the ecosystem service capacity of vegetation in the inter-temporal dimension.

6 Discussion

6.1 Future Applications

The proposed CityGML-based vegetation modeling method can be used as a standard for the urban vegetation model establishment at different scales, and it will promote the development of landscape architecture digitization. Our 3D vegetation models can be used to obtain attribute information and to construct a plant information database. GHOLIZADEH et al. (2018) created a vegetation database through a field investigation and analyzed the vegetation of the Hyrcanian forest in detail based on this database. The semantic information contained in the vegetation information model at different levels is mainly on the physiological and biochemical properties of vegetation. The addition of information such as seedling source, price, and root zone soil information will contribute to the construction of a plant model database to be used for city information modeling. The integration of vegetation information into building information will promote the development of a full informationized project operational platform. The vegetation database can be used to calculate the value of ecosystem services provided by the urban vegetation and provide a scientific basis for policy making.

6.2 Limitations and Further Research Suggestions

In this study, the semantic structures and attributes of CityGML-based vegetation model at different LODs are defined referring to the LODs of building model. However, differences in the major structure and specific components between vegetation and buildings might influence vegetation model actual application effect. In addition, the vegetation semantic information collected currently fails to cover the full features of a certain plant species. Further research is needed to cover more features of plant species based on CityGML through information collection, programming, and software modeling conversion.

Currently, CityGML standard classifies the vegetation into solitary vegetation object and plant cover. This study focuses on the solitary vegetation object only. However, the modeling of group plant is different from that of single plant, and thus further research is still needed for the definition of the geometry and attributes of group plant vegetation.

Acknowledgement

This study was financially supported by the National Key Research and Development Program of China (Grant No. 2019YFD1100401) and the Fundamental Research Funds for the Central Universities (Grant No. 2662021JC009).

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