Conceptual Model of Graph-based Individual Tree and Its Utilization in Digital Twin and Metaverse of Urban Forest

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Abstract

3D city models are an important cornerstone in the development of digital twin cities, allowing for various analyses and simulations. CityGML, as an open standard for 3D city models, emphasizes five main aspects: scale or level of detail (LoD), semantics, geometry, topology, and appearance. One of the important elements in CityGML 3D city models is representation of vegetation. Vegetation in CityGML, especially individual trees, is still limited in terms of detail and resolution, reducing its effectiveness for specific applications. This paper proposes a graph-based conceptual model for individual trees that conforms to the CityGML v2.0 specification. The model refers to the morphological structure of a tree consisting of roots, trunk, and crown (including branches, twigs, and leaves), and considers the five main aspects of CityGML. By enhancing semantic information and geometric details, the model aims to provide an information-rich and realistic representation of individual trees in a 3D city environment. The 3D tree model created based on this conceptual model may be applicable in the development of digital twin urban forests and virtual forest simulations that utilize immersive technologies such as the metaverse. This research opens up new opportunities in the development of solitary vegetation objects through CityGML ADE by including more detailed semantic and topological information.

1. Introduction

The concept of digital twin has been rapidly evolving and is becoming increasingly popular in various disciplines, including smart city planning and management. Digital twins enable detailed and dynamic digital representations of complex physical objects, processes or systems (Barricelli et al., 2019). In the urban context, the digital twin serves as an important tool for effectively modeling and managing elements of the urban environment. To support this need, the city geography markup language (CityGML), as an open standard for the representation and exchange of 3D city models, provides a comprehensive framework for modeling and integrating various urban elements (Gröger and Plümer, 2012). CityGML-based 3D city models have been widely used for various analyses and simulations of urban areas, including noise and air pollution modeling, daylight potential analysis, construction project visualization, and shadow analysis (Biljecki et al., 2015).

One crucial aspect of the urban environment is the urban forest, which provides various environmental benefits and helps maintain ecological balance (Pataki et al., 2021). Digital representations of urban forests or vegetation elements in virtual environments will enhance the extension of environmental analysis towards three dimensions. Many modeling tasks require 3D vegetation representation, including simulation of urban microclimates, daylight potential, tree-building interactions, noise mapping, and mitigation of the urban heat island effect (Münzinger et al., 2022). In CityGML, vegetation elements are classified into two categories: single vegetation objects (individual trees) and plant cover (e.g., forests or plant communities). Single vegetation objects are modeled using the *SolitaryVegetationObject* class, which is the focus of this paper, while areas containing specific vegetation use the *PlantCover* class (Gröger et al., 2012).

In recent years, researchers have created a variety of different tree model representations to meet their application needs. Gobeawan et al. (2018) created a 3D tree model for Virtual Singapore in multiple levels of detail (LoD) as per CityGML version 2.0. LoD1 tree models were represented using simple geometrics (not cylinders). LoD2 was represented using seven common tree shapes to represent all tree types in the city, namely irregular, hemispherical, roun, oval, palm, conical, and oblong. Trisyanti et al. (2019) modeled individual trees into three levels of detail for landscape architecture analysis. The LoD1 tree model is represented using two crossed polygons, LoD2 follows the geometry of the real object but is simple, and LoD3 is more detailed than LoD2 and already has semantic information following the tree hierarchy level, namely roots, trunk, and crown. Each tree model is textured according to the original tree image. Suwardhi et al. (2022) represented individual tree models using spherical, ellipsoid, and spherical harmonics.

From the perspective of virtual city modeling, current vegetation representations are limited in detail and resolution, and only support limited 3D spatial analysis (see Figure 1). This limitation is due to the simplicity of the model and the lack of detailed information about the tree structure, such as branches, twigs, and leaves. Therefore, there is a need to develop a more sophisticated model in CityGML that can better represent individual tree structures. In addition, a deep understanding of the key aspects of CityGML, such as semantics, geometry, topology, appearance, and scale or level of details (LoD), in building the tree model is crucial to ensure its optimal usability.

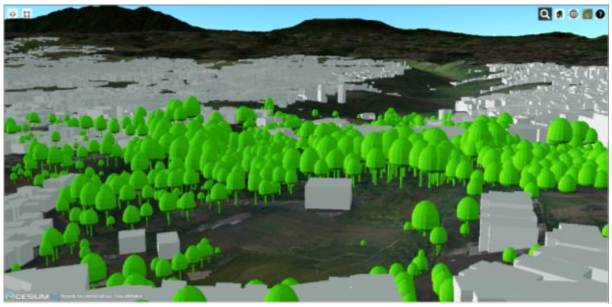

Figure 1. LoD2 tree model of Cimahi urban forest, West Java, Indonesia under development

This paper presents a graph-based conceptual model for individual trees that conforms to the CityGML specification and explores its potential application in digital twin technologies and the metaverse. The proposed model aims to provide a more detailed representation of the attributes and relationships between semantic structures of trees, such as trunks, branches, twigs, and leaves.

2. Existing Vegetation Model

CityGML provides a comprehensive framework for the representation of various elements of the urban environment in 3D city models, including vegetation. In the current CityGML standard, vegetation models, especially individual trees, are represented in the *SolitaryVegetationObject* class. Solitary vegetation object can have basic attributes about trees, such as class, function, usage, species, height, trunkDiameter and crownDiameter. The geometry of this object can be defined explicitly using GML geometry or prototypically using implicit geometry. The UML diagram of a solitary vegetation object is shown in Figure 2.

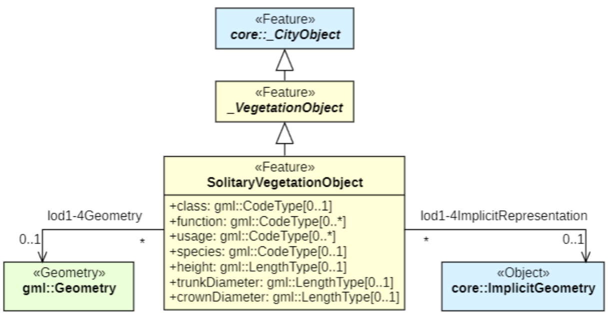

Figure 2. UML diagram of solitary vegetation object in CityGML

To meet the needs of specific applications, further development of the vegetation model in CityGML has been proposed. Guerrero Iñiguez (2017) presents a geometric approach to model tree roots at different levels of detail. There are three types of root systems that reference the proposed geometric root model, including taproot, heart root, and surface root. These different root geometry representations allow for the analysis of tree anchoring, the underground space potentially occupied by tree roots, their interaction with urban elements, and the resulting damage to the existing environment. Meanwhile, Zhang et al. (2022) proposed an extended semantic information model for different types of urban vegetation by analyzing requirements at different levels of detail. The model includes both above-ground and below-ground plant components, especially at the LoD4 level. It aims to overcome the problems found in existing 3D vegetation models, such as single functions and lack of unified data standards.

3. Proposed Conceptual Model

CityGML defines individual trees into vegetation themes, i.e. solitary vegetation objects. In many applications, the representation of individual trees often only takes into account a low level of detail, as well as a lack of attention to richer information about the tree's structure and interaction with the surrounding environment. Therefore, we propose a new graph-based conceptual model for individual tree representation in CityGML. This model is designed to provide higher detail and richer semantic representation than current models. The proposed model uses a graph approach to represent the tree structure, where we refer to a common tree morphology structure. Trees are made up of three main parts: roots, trunk, and crown. The crown consists of branches, twigs and leaves. The trunk supports the branches and twigs, which in turn support the leaves (Figure 3). Each part of the tree, such as the trunk, branches, twigs, and leaves, will be represented as nodes in the graph. Meanwhile, the relationships between these parts will be represented as edges. The UML diagram of the proposed CityGML solitary vegetation object is shown in Figure 4.

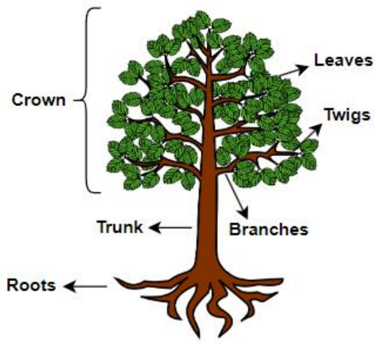

Figure 3. Morphological structure of a tree adopted in the proposed conceptual model

In general, the basic attributes of trees in our model are not much different from the *SolitaryVegetationObject* class built into CityGML. However, we extend it by adding some attributes, such as trunk length and branch length, into a more detailed tree semantics. Currently, most of the attribute descriptions of each semantic tree in this conceptual model are a work in progress. Basically, the CityGML base specification is not intended to describe single vegetation structures in detail, and descriptions of tree structures, such as branches, twigs, and leaves, are almost non-existent in the base specification. To that end, CityGML provides a mechanism called Application Domain Extension (ADE). CityGML ADE is designed to extend the semantic 3D city model provided by standard CityGML. It enables the addition of new features and properties to standard classes already defined in CityGML (Biljecki et al., 2018), including attributes and tree semantics for solitary vegetation objects.

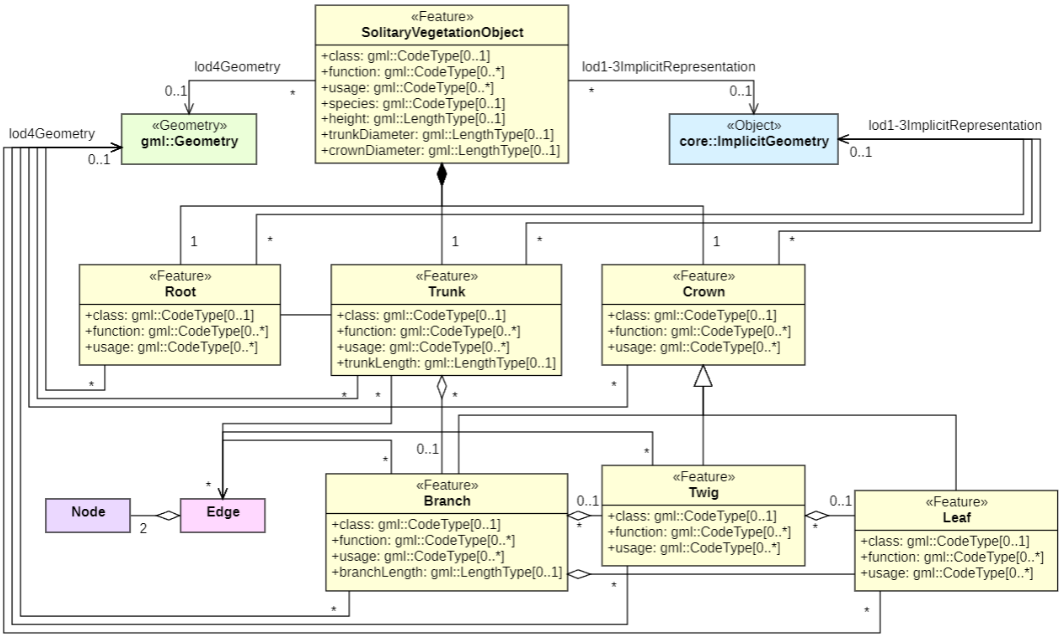

Figure 4. UML diagram of proposed CityGML's Solitary Vegetation Object

Our individual tree conceptual models are based on the CityGML version 2.0 standard, which is currently the most commonly used version and is widely supported by various tools and applications, including the 3DcityDB database specification. In an effort to provide a comprehensive standard for 3D city models, CityGML emphasizes five main aspects, namely scale or level of detail (LoD), semantics, geometry, topology, and appearance (Kolbe, 2009). Therefore, our proposed conceptual model also considers these five aspects in its development. By integrating these aspects, CityGML enables rich and accurate representation of solitary vegetation objects in 3D city models, thus supporting a wide range of applications, including digital twins and metaverse for urban forests.

3.1 Scale or Level of Details (LoD)

CityGML specifies five levels of detail (LoD0-LoD4) for 3D objects, where objects become more detailed with increasing LoD in terms of their spatial and thematic differentiation. The availability of these LoDs provides flexibility in choosing the level of detail that suits the needs of the application. This enables its use in various urban modeling and analysis contexts. Based on the LoD concept in CityGML, trees can be modeled in several levels of detail, from LoD0 to LoD4 (see Figure 5). In LoD0, the tree is modeled as a 2D horizontal plane that reflects its location and size, while LoD1 is a 2.5D representation of the tree's height or root depth. LoD2 is a representation of the crown and trunk, LoD3 depicts more complex 3D point morphological structures, and LoD4 includes the internal space of the tree (e.g., cavities). LoD4 is the highest level of detail that includes detailed representations of 3D solid components as well as structured semantic information (Tarsha Kurdi et al., 2024).

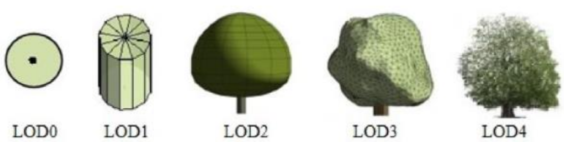

Figure 5. LoD0 to LoD4 model based on canopy morphology. Figure adapted from Tarsha Kurdi et al., (2024)

3.2 Semantics

Semantic aspects refer to the information or meaning associated with geographic objects in a 3D model. Specifically, in CityGML, semantics include attributes, relations, and the aggregation hierarchy between them that provide context or explanations about the object, such as the function, type, or characteristics of the object. With rich semantic information in the 3D model, applications that require a deep understanding of the structure and characteristics of city objects can be well accommodated.

In the proposed model, the semantics of individual trees include the actual tree structure, including the roots, trunk, and crown, as well as the crown components consisting of branches, twigs, and leaves. The use of the quantitative structure model (QSM) method on individual tree point cloud data makes it possible to quantify and identify tree structures (Raumonen et al., 2013). QSM can describe the branch structure of a tree and provide valuable information about the hierarchical organization of the branches. This information can be used to enrich the tree model representation in CityGML through the ADE mechanism. An experiment on using the QSM method to extract tree structure information from individual tree point cloud data is shown in Figure 6.

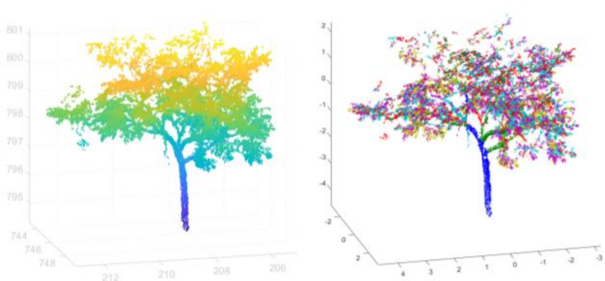

Figure 6. Application of QSM method on individual tree point clouds (left) to extract tree structure (right)

3.3 Geometry

Geometric aspects refer to the representation of the exact shape, size, and spatial location of geographic objects in a 3D city model. It deals with creating virtual models that look like real objects by using geometric structures based on GML, such as points, lines, and polygons. GML3 provides classes for 0D to 3D geometric primitives, 1D-3D composite geometry, and 0D-3D geometry aggregates.

CityGML supports geometric representation of individual trees at various levels of detail (LoD1-LoD4), ranging from simple shapes to more complex models. Detailed geometric modeling of trees should include detailed representation of branches, twigs, and leaves to enable accurate 3D spatial analysis. This is very complicated when using only simple parameters. Our individual tree geometric model. For this reason, we split the individual tree geometry model into two geometry models based on the CityGML LoD. The LoD1-LoD3 tree model can be represented using implicit geometry, while the LoD4 tree model uses geometric primitives and composites.

Detailed tree geometry models can be built using cylinders and truncated cones as basic blocks. The main trunk and branches of the tree can be represented as a series of cylinders connected at the ends with different start and end ratios, thus forming a more complex structure. In addition, twigs can be added using geometry in the form of a cylinder with an additional truncated cone at the end, thus providing a more detailed and realistic representation. Then, with the tree structure information extracted using QSM, geometry for each part of the tree (trunk, branches, and twigs) representing the semantics of the tree can be constructed. An illustration of an individual tree model with detailed semantic information is shown in Figure 7.

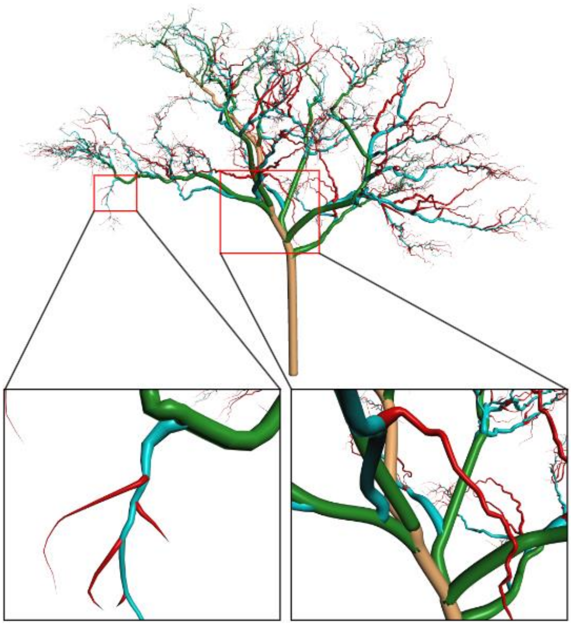

Figure 7. Geometric representation of each semantics

This approach provides a robust framework for describing the space occupied by tree branches and twigs. On the other hand, leaf representations can be created using simple geometries such as flat polygons placed on branches with appropriate distributions, based on point cloud data from laser scanning. In this way, the tree model not only provides realistic visualization but also enables in-depth 3D spatial analysis. The complete 3D tree geometry and semantic representation according to the tree structure is shown in Figure 8.

Figure 8. Geometric and semantic representation of 3D trees with leaves

3.4 Topology

The topology aspect in CityGML allows modeling of the spatial and hierarchical relationships between individual trees and other elements in the urban environment. This includes how trees interact with buildings, roads and other infrastructure, and how they contribute to the overall structure in a 3D city model.

Topology in this context refers to the connectivity and interactions between different parts of the tree (such as trunk, branches, twigs, leaves) that can describe the basic functions of the tree. Tree topology can be detailed and represented in graph form, which is often generated from point cloud data (Figure 9), as done by Straub et al. (2022). This graph model can be implemented using point and line geometry, where each part of the tree is represented as a node, while the relationships between these parts are represented as edges in the graph. This allows for more sophisticated analysis and simulation, including tree limb pruning simulations.

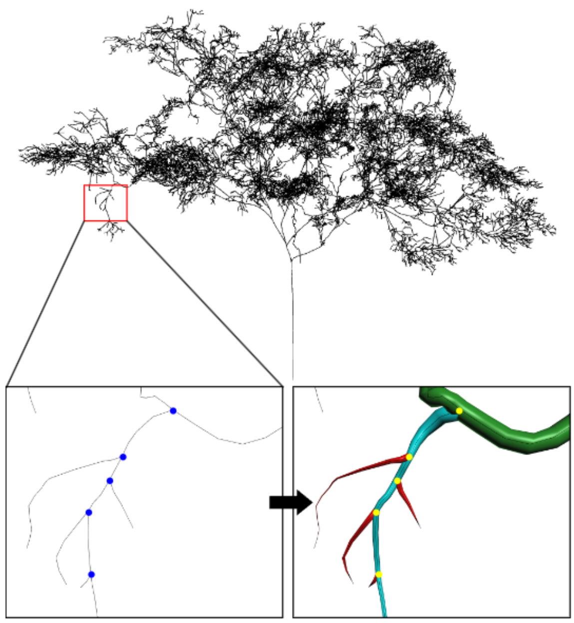

Figure 9. The tree graph structure extracted from the point cloud and the relationship between the tree parts

3.5 Appearance

Appearance refers to the observable properties of the surface of a feature or object, and is an integral part of a virtual 3D city model along with its semantic and spatial properties. Appearance in CityGML individual tree models can be represented by texture or color. This is important to support the realistic visual representation of individual trees in 3D city models, as well as their application in the digital twin and metaverse of the urban forest.

The appearance aspect concerns the way in which the 3D tree model is displayed with optimal visual quality. Since the tree model in LoD4 has a high complexity, the use of advanced visualization techniques is very important. For example, optimization with textured billboard techniques and simple geometry by Malheiros and Walter (2011) allows for realistic visual results as well as savings in polygon usage.

4. Potential Application

Vegetation features, especially individual tree models, are important components in 3D city models. In addition to visualization, 3D tree models have significant potential and benefits in analysis and simulation, especially in urban environment management through digital twin and forest management through virtual forest.

4.1 Urban Forest Digital Twin

Urban forest digital twin offers important benefits for urban sustainability. With virtual representations of urban trees, planners and managers can optimize the design and maintenance of green spaces. The technology enables accurate visualization and modeling of green spaces, helping to create more livable and environmentally friendly cityscapes. Digital twin also helps assess the environmental impact of trees, such as improving air quality and reducing the heat island effect. In addition, this technology facilitates the integration of urban forests with existing infrastructure, providing insight into potential conflicts and synergies between trees and buildings (Chen et al., 2024).

3D tree models created based on these conceptual models make it possible to support detailed simulations of the interaction of tree structures with their environment, as well as enable precise analysis of factors such as light and shadow. In addition, 3D tree models can serve as a dynamic repository of data, generating valuable structural and ecological information, which can drive research on tree growth patterns, health, and ecological contributions.

4.2 Virtual Forest

A virtual forest is a digital representation of a real forest, created using 3D modeling and simulation technology. Virtual forests are designed to mimic the appearance and dynamics of forest ecosystems, so that users can interact and analyze the forest environment without the need to be physically present (Murtiyoso et al., 2024).

3D tree models in virtual forests have several important functions. In environmental studies, 3D tree models created based on the proposed conceptual model can help visualize the response of forest ecosystems to various management practices and natural influences. For forest managers and researchers, 3D tree models can be used to simulate future forest conditions, as a basis for planning sustainable management strategies. In addition, 3D tree models provide an educational tool, enabling interactive learning experiences that can simulate real-world scenarios, such as tree limb pruning.

5. Conclusions

Accurately modeling trees is a challenging task, given the complex structure that trees have. The proposed CityGML-based individual tree conceptual model can be used as a basis for modeling vegetation in 3D urban environments, especially individual trees. The model considers five main aspects in CityGML, namely scale or level of detail (LoD), semantics, geometry, topology and appearance. This approach enables the creation of more realistic and information-rich tree models, including morphological structures such as trunks, branches, twigs, and leaves. In addition, the proposed conceptual model not only improves the limitations of existing vegetation representations in CityGML, but also provides a basis for the integration of more detailed scanning data, such as from LiDAR technology. By using a graph-based structure, this model can facilitate a wide range of applications, especially in the development of urban forest digital twin and virtual forests.

Through a comprehensive representation of individual tree models, stakeholders can perform more detailed analysis and simulation, from growth patterns to environmental interactions. This can lead to better decision-making processes in urban forest management. In addition, the integration of detailed tree models into the twin and metaverse digital platforms offers opportunities for innovative applications, including augmented reality experiences and interactive educational tools. Thus, the adoption of this conceptual model not only improves the visual fidelity of urban forest representations but also facilitates broader social benefits and advancements in environmental management.

This research opens up opportunities for further development, including coupling with the root model in Guerrero Iñiguez (2017) and extending the semantic model to different vegetation types according to the level of detail of CityGML in Zhang et al. (2022). The next step is the development of a CityGML ADE for Solitary Vegetation Objects that includes more detailed semantic and topological information.

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