Towards a Conceptual Model of CityGML 3.0 Vegetation ADE

Dessislava Petrova-Antonova[1], Simeon Malinov[1], Laura Mrosla[2], Aleksandar Petrov[1]

[1] Sofia University, GATE Institute, 1164 Sofia, Bulgaria – dessislava.petrova@gate-ai.eu, simeon.malinov@gate-ai.eu, aleksandar.petrov@gate-ai.eu
[2] Tallinn University of Technology, FinEst Centre for Smart Cities, 19086 Tallinn, Estonia – Laura.Mrosla@taltech.ee

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Abstract

The rapid growth of urban areas underscores the need for developing semantically rich 3D city models representing a variety of urban objects and integrating the results from the analysis and simulation of urban processes and environment. Adhering to standards such as CityGML, these 3D city models offer immense value in urban planning, development, and management. By encoding the spatial, functional, and thematic information in a standardized way, they provide a comprehensive digital representation of cities. This enables city authorities to evaluate the impact of proposed developments and thereby make informed decisions. CityGML-based city models facilitate the progression towards smarter, more efficient, and more sustainable cities by supporting interoperability across different systems and platforms. This fosters collaboration and data exchange among diverse stakeholders.

This paper contributes to the development of semantically rich and interoperable 3D city models by proposing a conceptual model for Application Domain Extension (ADE) of the CityGML 3.0 Vegetation module. The ADE enhances the *SolitaryVegetationObject* and *PlantCover* feature types with additional properties by leveraging the new "hook" mechanism available in CityGML 3.0. Furthermore, it considers the dynamics of vegetation in terms of growth and management through modelling of dynamic data based on the *Dynamizer* module. Additionally, new data types, code lists and enumerations appropriate to the ADE domain are defined, providing a unified description of the vegetation's specific characteristics that are comprehensive across different platforms and disciplines. The Vegetation ADE' conceptual model opens several avenues for future research, including development of more accurate vegetation simulations and analyses, investigation of urban heat island effect or environmental impact assessments.

1. Introduction

The digital replication of cities, in the form of 3D models and urban digital twins, is increasingly prevalent. In evaluating the progress of digitalisation across various aspects of these replicas, it is observed that advancements in green infrastructures, particularly vegetation, lag behind those of human-made objects, such as buildings. The modelling of urban vegetation presents challenges due to its dynamic nature and diverse systems. These challenges encompass the collection and management of fundamental data on vegetation, its intrinsic changes and its maintenance. It is crucial to acknowledge the widespread collection and storage of urban vegetation data globally, often conducted without adherence to standards for semantic representation and interoperability. On this note, the absence of comprehensive and systematically organized data complicates decision-making, planning, and budget allocation.

CityGML is a widely adopted open standard for modelling both the geometry and semantics of urban environments. To provide a more comprehensive depiction of urban landscapes, it enables the development of Application Domain Extensions (ADEs), thereby extending its applicability in different domains and use cases. (Kolbe, 2009) Since the ADE concept was introduced in 2007, numerous extensions have been proposed.

This study proposes a conceptual model for a Vegetation ADE of CityGML 3.0. It serves as a foundation for vegetation data modelling, overcoming the limitations of the standard in supporting routine vegetation information, management, maintenance, etc. The proposed ADE covers top-level feature types, namely *SolitaryVegetationObject* and *PlantCover*. By extending them, it aimed to enhance the semantic richness and modelling capabilities of CityGML 3.0 in capturing the complexity of urban vegetation. Thus, a more holistic representation of urban environments is achieved by encapsulating the relationships between vegetation and the built environment. This enhancement aligns with the overarching goal of CityGML to facilitate the creation, sharing, and utilisation of semantic 3D city models.

The rest of the paper is organized as follows: Section 2 overviews the relevant related work. Section 3 outlines the methodology employed in the development of the ADE. Section 4 provides a detailed account of the ADE's implementation. Section 5 discusses the implications and results derived from the study. Finally, Section 6 concludes the paper.

2. Related Work

2.1 CityGML Development

While the City GML standard aims to provide a universal and non-biased geographical information model, the popularity of the standard throughout the years has created the need for additional domain-specific add-ons that would be able to meet the requirements of a wide range of applications. To address those initial shortcomings without disrupting and overcomplicating the base model, the Application Domain Extension (ADE) has been introduced. The ADE concept is part of the model from the early stages of its development or, more superficially, in May 2007 with the deployment of version 0.4 of the standard. It allows for extending the existing CityGML schema and opens the opportunity for many domain and field experts to adapt and utilise CityGML in serving their own case specific scenarios, applications or projects. ADEs enable users to define additional attributes, new feature classes, and relationships.

CityGML has been developed since 2002 by the members of the Special Interest Group 3D (SIG 3D) of the Open Geospatial Consortium (Gröger et al., 2008). Since the publication of CityGML 1.0 in 2008, it has undergone several further improvements, which have resulted in the publication of CityGML 2.0 in March 2012 (Gröger et al., 2012). Additional change requests for version 2.0 since its publication have been considered and the standard has been further developed to version 3.0. The transition from CityGML 2.0 to CityGML 3.0 in the year 2020 introduced several significant enhancements and changes aiming to reflect the increasing need for better interoperability with other relevant standards (Kutzner, et al., 2020). A revision of the existing modules *Core*, *Generics*, *Building*, and *Transportation* is performed as well as new modules *Dynamizer*, *Versioning*, *PointCloud*, and *Construction* are added. The Vegetation module has not been revised, which further motivates the work in this study on implementation of Vegetation ADE.

In CityGML 3.0, all city objects are mapped to the onto the semantic concepts of spaces and space boundaries (Kutzner et al., 2020). The spaces are further subdivided into logical spaces and physical spaces, which in turn can be occupied and unoccupied. Nearly all geometry representations are moved from the thematic modules to the Core module and are associated with the semantic concepts of spaces and space boundaries. Thus, the redundancies in some modules such as Buildings and Tunnels are overcome. 3D point clouds can be used to represent the geometries of physical spaces and space boundaries through the new *PointCloud* module. The dynamic variations of the objects' properties are handled by the *Dynamizer* module and bitemporal timestamps for those objects are introduced by the Versioning module.

The Unified Modelling Language (UML) semantic data models in the geographic information system (GIS) domain typically conform to relevant standards from the ISO 191xx series of geographic information standards. The data model of CityGML 3.0 also adheres to these established standards. Applying ISO-compliant transformation rules to CityGML 3.0 results in changes to the XML encoding, altering it from that of CityGML 2.0 and 1.0. Although the conceptual model remains the same as in CityGML 2.0, the encoding differences require converting datasets and adapting CityGML 2.0 software for compatibility with version 3.0. However, all updates in CityGML 3.0 are designed to maintain backward compatibility with versions 1.0 and 2.0, allowing for dataset transformation through syntactical adjustments only. This backward compatibility is crucial to preserve existing investments in CityGML tools, datasets, and extensions.

2.2 CityGML ADEs

An overview of the CityGML 2.0 ADE developments has been published by Biljecki et al. in 2018. The existing Noise ADE previously conceptualised by Gröger et al. in 2012, is further extended by Kumar et al, 2017. The enhancements cover Transportation, Building, and City Furniture modules. The modifications have been designed to incorporate noise data seamlessly into the CityGML framework.

The CityGML Utility Network ADE proposes a unified data model for depicting various supply and disposal networks, including those for electricity, freshwater, wastewater, gas, oil, district heating, and telecommunications (Kolbe et al., 2018). It supports advanced analyses and simulations by providing a cohesive perspective of 3D city models alongside supply infrastructures.

The CityGML Indoor ADE is specially designed for management of indoor spaces and facilities (Kim et al., 2014). It consists of two feature models: one for representing the characteristics of indoor spaces, known as the indoor space feature model, and another for depicting indoor facilities within these spaces, referred to as the indoor facility feature model.

Another study is acknowledging the rise and need for workflows and technologies for translating BIM to CityGML (Lim et al., 2020). It presents an approach that uses a combination of generic rules to extract information from both standard CityGML and ADEs. A flexible web interface is developed for visualization of the CityGML ADE-enabled models, contributing to their usability.

The number of published works on ADEs of the new version of the standard, CityGML 3.0, is limited. Underground Land Administration ADE, called VicULA, is proposed at the conceptual level (Saeidian et al., 2023). The VicULA ADE aims at managing subterranean data through a unified 3D model that integrates legal and physical aspects on an urban scale. It introduces semantic entities for subterranean legal domains, thereby facilitating the delineation of spatial and semantic linkages among various categories of legal spaces.

Efforts are made towards mapping the existing Energy ADE to CityGML 3.0 (Bachert, 2023). The Energy ADE version 1.0 is built upon CityGML 2.0 and extends the Core and Building modules in the context of energy domain. The changes in CityGML 3.0 directly affect the portability of the Energy ADE, leading to the need of its conversion from CityGML 2.0 to CityGML 3.0 (Bachert, 2024). The mapping performed employs a model driven approach and is validated on actual data transformation. Following the current developments of CityGML 3.0, the modelling of floor plans in CityGML is considered and a delineation of multiple variants of indoor LoD0 is proposed (Konde et al., 2018).

3. Methodology Overview

The methodology employed for the implementation of the ADE adapts the model-driven framework designed for CityGML ADE developments as described by Van den Brink et al. (2013). It also adheres to the guidelines for ADEs, defined in the CityGML Conceptual Model Standard by Kolbe et al. (2021). This methodology consists of the following steps.

3.1 Selection of Formal Modelling Language

A formal modelling language to represent the ADE classes should be selected. In this study, the UML is chosen for several reasons. First, according to the CityGML 3.0 standard, ADEs should be defined as a UML conceptual model in accordance with the General Feature Model and the rules for creating application schemas in UML, specified in ISO 19109:2015 and the rules and constraints for using UML to model geographic information, specified in ISO 19103:2015 (Kolbe et al., 2021). Since UML provides a visual modelling approach, the ADE conceptual model can be easily communicated with various stakeholders, such as domain experts, software developers, city authorities, etc. As a formal language, UML can unambiguously express the structure and rules of an information model and allows the automatic and direct generation of XML schema and documentation from the model.

3.2 Selection of CityGML Feature Types to be Extended

This step includes the selection of CityGML feature types to be extended and the definition of additional properties appropriate for the ADE domain. For this purpose, a subclass of the corresponding abstract data type associated with the feature type is created. The subclass is defined as data type using the stereotype «DataType». The additional application-specific attributes and associations are modelled as properties of the ADE subclass.

The extension attribute named “adeOfFeatureTypeName” and data type “ADEOfFeatureTypeName”, referred to as the “hook”, is used, where FeatureTypeName corresponds to the class name for which the new properties are defined. The “hook” mechanism enables subclassing a CityGML feature type. The properties are modelled with either simple or complex data types in accordance with the ADE domain.

3.3 Definition of new Feature Types

Defining new feature types appropriate to the application domain is a core step in the ADE implementation. Every feature type in an ADE should be derived from the CityGML root feature type *Core::AbstractFeature*. This can be done directly or indirectly or, depending on its type and properties, from a more suitable subclass thereof. The object types and data types are not required to be derived from a predefined CityGML class. The stereotype used to represent the new feature types is «FeatureType». It represents an abstraction of a real-world phenomenon, having an identity.

3.4 Relationship Definition between Feature Types

The definition of relations between CityGML and ADE feature types follows UML notations for association, aggregation and composition between classes as well as class inheritance.

3.5 Definition of Additional Content

The definition of additional content includes the specification of data types, code lists and enumerations appropriate to the ADE domain. The stereotypes used for implementation are as follows:

- «DataType», used for holding information and defining a set of properties that lack identity.
- «CodeList», used for enumeration of an open list with valid attribute values.
- «Enumeration», used for enumeration of a fixed list with valid literal values.

3.6 Definition of Geometry Representation

The definition of geometry representation for ADE feature types is optional. It is applied when the new feature type represents a real-world object with geometry. In such a case, the new feature type should be derived directly or indirectly from *Core::AbstractSpace* or *Core::AbstractSpaceBoundary*. In the current study, this step is omitted since the proposed ADE extends only semantically the CityGML Vegetation module.

3.7 Decide on LOD

The last step requires deciding on which Level of Detail (LOD) should be topologically correct. The existing CityGML 3.0 geometries are reused instead of explicitly defining them in the ADE classes themselves. Thus, a multi-geometry representation in different LODs of the ADE classes is possible.

4. Implementation

The Vegetation module of CityGML 3.0 represents vegetation objects with vegetation-specific thematic classes. Additional properties are added to the top-level feature types *SolitaryVegetationObject* and *PlantCover* via the ADE “hook” mechanism. Additionally, new feature types are defined according to the ADE domain.

4.1 SolitaryVegetationObject Properties

The *SolitaryVegetationObject* feature type represents single vegetation objects like bushes or trees. The new data type *SolitaryVegetationObjectProperties* is derived from the *ADEOfSolitaryVegetationObject* and is used to add the corresponding Vegetation ADE properties, including planting and extermination years, protection status, classification, ownership, etc. (Figure 1). Since the vegetation objects consist of three main parts, crown, trunk and root, new classes are defined and derived from *AbstractFeatureWithLifespan* to describe the specific characteristics of these parts. The *Crown* feature type represents the crown of the tree and is described with properties representing the diameter, type, density, clearance and leaf texture. The crown type and density are defined using code lists to enable extensibility. The leaf texture is supposed to be read from a URI, providing a resource which is useful for visualization purposes. The *Trunk* feature type corresponds to the trunk of the tree and is described with properties for diameter, height, type and texture. Similarly to the crown type, the trunk type is defined using a code list and the trunk texture is available from a URI. The *Root* feature type represents the roots of the tree, having properties of diameter and root ball depth.

The solitary trees have specific crown shapes, which are not affected by neighboring trees or buildings. According to the literature and urban tree catalogues, the most commonly occurring tree crown shapes are pyramidal, cylindrical (columnar), spherical (round), oval and half-ellipsoidal (baumportal.de; Franceschi, 2022; GALK, Jinasena, 2023, Liu, 2021; Summit, 1999). Other frequently appeared tree crowns are weeping, umbrella, conical, upright funnel and irregular (Othman, 2014). Based on this, the code list is defined to describe the variability of crown types includes the following items: irregular, conical, cylindrical, spherical, ellipsoidal, oval, umbrella, upright funnel and weeping. Since the code list is extensible, new items can be added for particular requirements.

Since many different patterns of trunk branching have been defined and many of them represent evolutionary adaptations to a given environment or life strategy, three general trunk types are considered. They are related to the original development of a branch or axis. If a given trunk axis is derived from a single meristem, the trunk type is called monopodial. In contrast, if a given axis has multiple branches derived from separate meristems, the trunk type is sympodial. Finally, a rare type of branching is dichotomous, in which a single meristem divides equally into branches (Jinasena et al., 2013). The trunk types are classified in 9 categories by Tarsha Kurdi et al., 2024. The trunks are classified in 3 main classes according to the number of axes – single trunk, multiple trunk and forked trunk. From vertical point of view the trunk types are classified in vertical, oblique and twisted. To avoid complexity and make the conceptual model comprehensive for a diverse group of stakeholders three main trunk types are considered – single, multiple and low-branched. This enables a practical on-site approach in measuring the trunk height when collecting data.

Since many classification systems exist for species and habitats, which are partially inconsistent with each other, the approach applied in the ADE is based on referencing of external classification systems. A new *SolitaryVegetationClassificationSystem* data type is defined, having properties about the name of the classifications system, its unique identifier represented with URI and code, and the exact classification of the object within the classifications system. Such an approach allows several classification systems to be referenced, enabling data interoperability between different databases and registers.

The *AbstractFeatureWithLifespan* is employed as the newly introduced classes, *Crown*, *Trunk*, and *Root* have time-dependent properties. Those encompass among others *crownDiameter* for the *Crown* feature type, *trunkHeight* for the *Trunk* feature type and *RootBallDiameter* for the *Root* feature type. Since the features *Crown*, *Trunk* and *Root* are not derived from the *AbstractCityObject*, they do not inherit the relation to *AbstractDynamizer*. Therefore, a new relation is modelled through a new *SolitaryVegetationObjectGrowth* class to *AbstractDynamizer*.

4.2 SolitaryVegetationObjectGrowth Feature Type

The growth of single trees is handled by a new *SolitaryVegetationObjectGrowth* class, inheriting *AbstractDynamizer*. The growth is described with the following properties:
growthType, corresponding to the characteristic of the tree, which is measured, e.g. trunk height, crown diameter, etc.
growthValue, specifying the value of the respective characteristic.

- *aquisitionMethod*, defining how the measured value is obtained, such as estimation, measurement, simulation, calibrated simulation, etc.
- *healthStatus*, representing the health status at the time of recording the value of the characteristic.

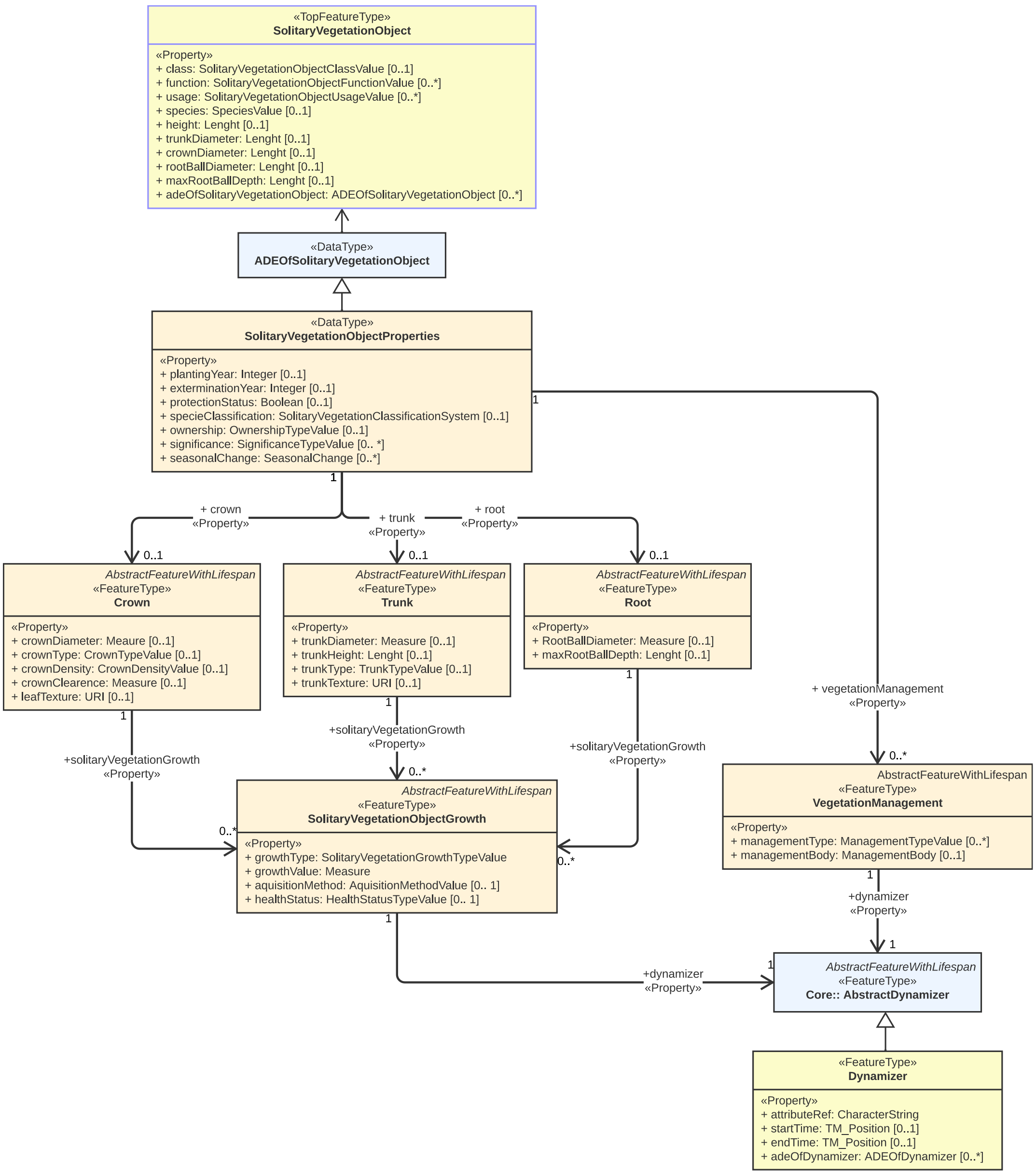

Figure 1. SolitaryVegetationObject ADE Module.

4.3 PlantCover Properties

The *PlantCover* feature type represents a space covered by vegetation. The new data type *PlantCoverProperties* is derived from the *ADEOfPlantCover*. It adds the corresponding Vegetation ADE properties, including planting year, protection status, species richness and relative abundance, ownership, etc. (Figure 2). A new *PlantCoverClassificationSystem* data type is defined, featuring properties about the name of the classifications system, its unique identifier represented with URI and code, the exact classification of the object within the classifications system, and relative abundance. In contrast to the *specieClassification* property of the *SolitaryVegetationObject* feature type, where only one value is allowed, the *habitatClassification* property of the *PlantCover* feature type can have a list of values, representing the ratio of the various habitats available in the plant cover.

4.3.1 PlantCoverGrowth Feature Type

The growth of the plant cover is handled by a new *PlantCoverGrowth* class, inheriting *AbstractDynamizer*. The properties of this class are like those of the *SolitaryVegetationObjectGrowth* class.

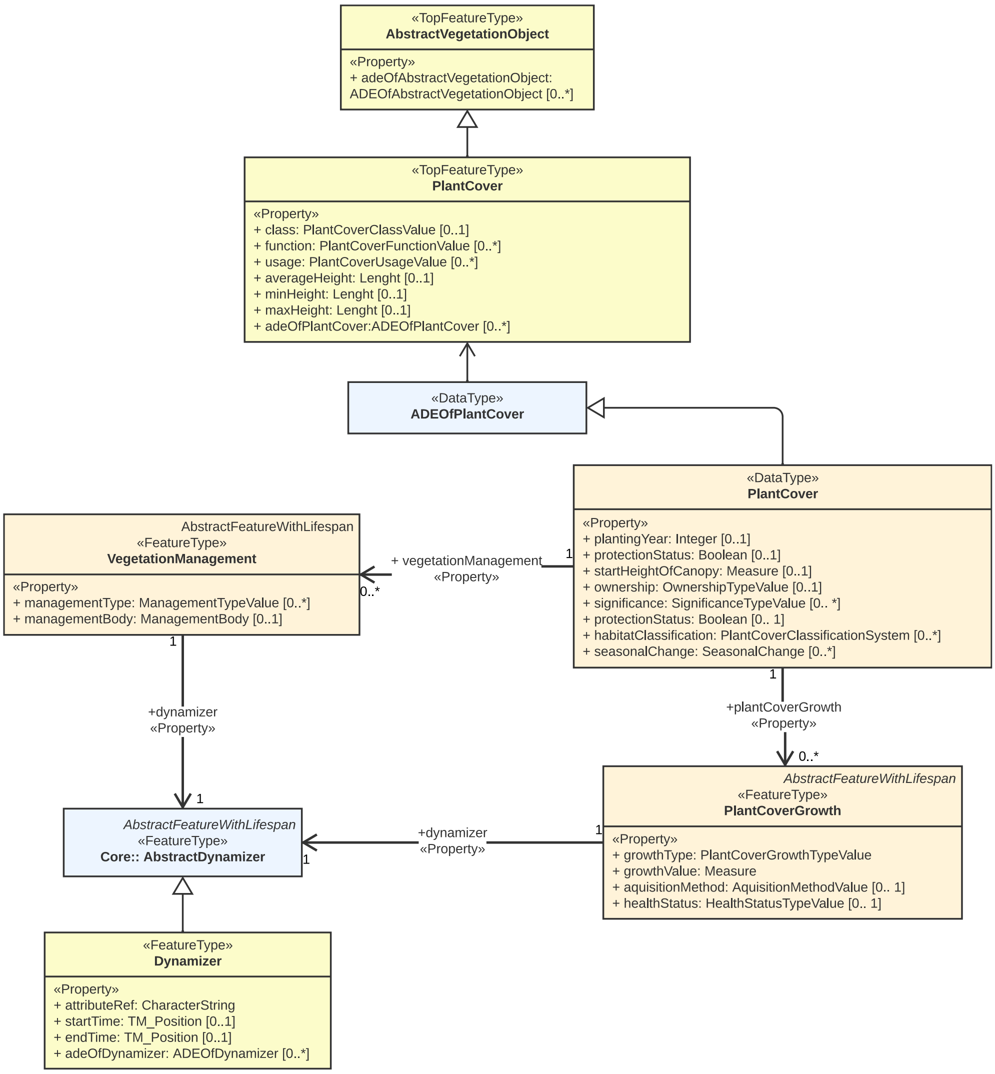

Figure 2. PlantCover ADE Module.

4.4 VegetationManagement Feature Type

The management of both solitary vegetation and plant covers are modelled by a new *VegetationManagementClass*, introducing an additional ADE property like *SolitaryVegetationObjectGrowth* and *PlantCoverGrowth*. A special *ManagementTypeValue* enumeration is defined for the management type, including values related to hazardous tree removal, tree bending, pruning, fertilisation, herbicide application, watering, etc. The management body is defined with a new *ManagementBody* data type with properties for name, type and address.

5. Discussion

Today, the modelling of vegetation data in a meaningful and comprehensive way meets many challenges which cities around the world face. Data heterogeneity and quality, integration complexity and lack of unified data models complicate the collaboration of stakeholders working in the urban vegetation domain. The CityGML standard has been conceived to overcome those challenges, yet the Vegetation module has not been revised from CityGML 2.0 to 3.0 (Kutzner, T., 2020). In consequence, the representation of vegetation in city models still lacks important properties and is less comprehensive than that of the built environment. Thereby, the accurate representation of

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vegetation in 3D city models not only aims to depict the urban environment as realistically as possible, but also fosters a deeper understanding of cities through adding additional semantics. The proposed CityGML Vegetation ADE conceptual model therefore addresses this gap by extending the vegetation representation with both descriptive and dynamic characteristics. This is pivotal for simulating, managing, and analyzing urban environments in a way that handles the environment's complexity and change over time. The fact that vegetation is diverse and exhibits variegated forms and peculiarities all around the globe motivated the work on the ADE. During its implementation, especially while defining e.g. enumerations and code lists, the diversity and intricacies of vegetation posed challenges for unified representation. This issue is particularly apparent in habitat classifications, where, to date, there is no uniform global system in use that accommodates the peculiarities of locally used habitat classifications. To overcome this challenge the ADE allows reference to external classification systems based on URI, thus enabling interoperability between the systems and applications. By allowing local classifications to be introduced in the CityGML models, the flexibility of the ADE is achieved, which is a prerequisite for wide adoption.

Furthermore, different urban stakeholders have varying requirements when it comes to the representation of vegetation, which handling in the ADE could lead to increased complexity. That is why a balance between level of detail and usability is provided and therefore the broad application of ADE is encouraged. This approach opens possibilities for further improvements. Future developments of the ADE coul54d incorporate more properties and include for instance various indices of vegetation such as the Normalized Difference Vegetation Index (NDVI), Leaf Area Index (LAI) or the Normalized Difference Water Index (NDWI). Moreover, the representation of subterranean vegetation parts could be enhanced. A more intricate depiction of underground vegetation structure, along with a comprehensive model of the subsurface environment – including potentially soil quality and biota – would broaden applications towards e.g. urban ecological models. For this purpose, a future investigation of the conceptual model for underground objects, called MUDDI (Model for Underground Data Definition and Integration) to standardize the representation of geospatial data related to the Earth's subsurface is intended.

To refine the ADE conceptual model, feedback from various stakeholders working in the urban vegetation domain, such as landscape architects, urban planners, ecologists, biologists etc., is scheduled to be collected through an online survey and expert interviews. This step aims at collecting more insights from different professionals globally to improve the representation of vegetation and to prove the ADE's applicability and usefulness.

The ADE conceptual model will be employed in the implementation of the in the City Digital Twin Pilot of Sofia, Bulgaria and Green Digital Twin of Tallinn, Estonia. Additionally, the proposed conceptual model will be applied for unified representation of the vegetation data stored in the online web-based tree mapping platform, named "OneTree". It is a citizen-science oriented GIS solution specifically designed for gathering the general information about the trees. The ADE conceptual model aligns with the specific data model behind the OneTree platform, where tree attributes are stored in a consistent manner starting with the base tree attributes like tree height, crown and trunk sizes, followed by more specific characteristics such as damages, health problems, maintenance needs and more. A very rich knowledge base has been developed, providing for deeper species level characteristics and validation.

The Vegetation ADE contributes to the research community by opening several avenues for future research, including the development of more accurate simulations, analysis and visualizations, urban heat island effect investigation or environmental impact assessments. These directions not only promise to expand the adoption of CityGML but also offer a path towards a more integrated and holistic approach to urban modeling, reflecting the complex interdependencies of the urban ecosystems.

6. Conclusion

This paper proposes a Vegetation ADE conceptual model of the CityGML 3.0, designed to provide a more detailed and dynamic representation of vegetation. Additional properties and classes are incorporated to the existing vegetation module based on the ADE hook mechanism. The dynamic changes related to growth and management of the vegetation are addressed through the *Dynamizer* module. The ADE is defined at a conceptual level, allowing for consideration of different encoding specifications such as GML, JSON, etc. Future work includes refining the ADE by obtaining feedback from diverse stakeholders, working in different fields including urban planning, landscape engineering and architecture, ecology, and others, as well as applying the ADE to real case studies.

In summary, the proposed CityGML Vegetation ADE conceptual model marks a significant step forward in the standardized representation of urban vegetation within 3D city models and urban digital twins. While acknowledging its current limitations, we envision its evolution as an essential component of future representations of cities, aiding data interoperability and overall contributing to the data-driven development, maintenance, and management of urban landscapes.

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