

EXTENDING CITYGML 3.0 TO SUPPORT 3D UNDERGROUND LAND ADMINISTRATION

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ABSTRACT:

Rapid development of underground space necessitates the efficient management of underground areas. Data modelling plays an underpinning role in integrating and managing underground physical and legal data. The physical data refers to semantic and spatial data of underground assets such as utilities, tunnels, and basements, while the legal data comprises the ownership information and the extent of underground legal spaces and the semantic and spatial relationships between legal spaces. Current Underground Land Administration (ULA) practices mainly focus on representing only either legal spaces or the physical reality of subsurface objects using fragmented and isolated 2D drawings, leading to ineffective ULA. A complete and accurate 3D representation of underground legal spaces integrated with the 3D model of their physical counterparts can support different use cases of ULA beyond underground land registration, such as planning, design and construction of underground assets (e.g. tunnels and train stations), utility management and excavation. CityGML is a prominent semantic data model to represent 3D urban objects at a city scale, making it a good choice for underground because underground assets such as tunnels and utilities are often modelled at city scales. However, CityGML, in its current version, does not support legal information. This research aims to develop an Application Domain Extension (ADE) for CityGML to support 3D ULA based on the requirements defined in the Victorian state of Australia. These requirements include primary underground parcels and secondary underground interests. This work extends CityGML 3.0, which is the new version of this model. In CityGML 3.0, UML conceptual models as platform-independent models are suggested to express ADEs. Thus, the ADE proposed in this study will be based on UML. The findings of this study show that extending CityGML to support legal information can be a viable solution to meet the requirements of a 3D integrated model for ULA. The CityGML ADE proposed in this study can potentially provide a new solution for 3D digital management of underground ownership rights in Victoria, and it can be used to implement an integrated 3D digital data environment for ULA.

1. INTRODUCTION

The rapid urbanisation in recent years has increased the development and use of underground spaces in urban areas. Currently, underground spaces are used for various purposes, which necessitates the efficient management of this environment. Underground Land Administration (ULA) is concerned with legal ownership of subdividing, registering and managing underground assets. A modernised ULA system should provide a reliable and data-rich digital model that represents ownership boundaries and rights, restrictions and responsibilities (RRRs) associated with underground assets.

To address the issues of current isolated and fragmented 2D approaches, 3D digital models provide a great potential to modernise ULA. A complete and accurate 3D representation of underground legal spaces integrated with the 3D model of their physical counterparts can support different use cases of ULA beyond underground land registration, such as planning, design and construction of underground assets (e.g. tunnels and train stations), utility management and excavation.

Current research mainly focuses on representing only either legal spaces or the physical reality of subsurface objects. A few studies identified potential solutions to address the integration of physical and legal datasets for underground environments (Aien et al., 2013; Aien et al., 2015; Atazadeh et al., 2017). However, these studies aimed to link ownership objects and the physical elements that define the legal spaces. For example, a wall whose interior/median/exterior face defines a legal boundary. These solutions cannot provide a fully integrated 3D representation of underground physical and legal objects. The physical reality of some underground assets such as utilities is not included in 2D plans applied for land registration (cadastre) in some jurisdictions (e.g. Victoria, Australia). However, the integrated 3D underground data model should include them to support different use cases of ULA (Saeidian et al., 2022). For instance, to plan and design a large-scale underground construction such as a train station, it is necessary to investigate both legal and physical data.

Saeidian et al. (2021) discussed the approaches for developing 3D data models to support ULA. Extending a physical data model that provides a wide range of entities addressing both

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spatial and semantic elements of underground areas is proposed to support ULA in the jurisdictions where both legal and physical objects are needed. Although BIM is a prominent physical model at the building scale, the ULA data model needs to support city-scale modelling since underground assets such as tunnels and utilities are often modelled at city scales. CityGML can effectively create a 3D digital cadastral model for an entire jurisdiction (Atazadeh et al., 2022). CityGML is a prominent semantic data model to represent 3D urban objects. However, in the context of cadastral requirements, including underground cadastre, CityGML does not have any features to cover and describe the legal information of assets (Dimopoulou et al., 2018; Gózdź et al., 2014).

This research aims to develop an Application Domain Extension (ADE) for CityGML to support 3D ULA based on the ULA requirements in Victoria jurisdiction. This work extends CityGML 3.0, the new version of this model, to support ULA requirements in Victoria. CityGML 3.0 has some new features such as a new concept of LoD, special classes for facilitating conversion to IFC, the option for introducing a logical space as a complement to a physical space and so on (Noardo et al., 2020). In CityGML 3.0, UML conceptual models as platform-independent models are suggested to express ADEs. Thus, the ADE suggested in this study will be based on UML.

The next section will provide an overview of studies in the ULA domain and CityGML for land administration purposes and summarise the research gaps in the studies. Then, Section 3 will describe underground legal spaces in Victoria. The developed ADE will be presented in Section 4. The last section will provide a discussion and conclusions.

2. LITERATURE REVIEW

This section will firstly provide an overview of ULA and the studies on data modelling in this domain. As described in the introduction, CityGML is chosen to be extended in this research for ULA. Therefore, the second part of this section will review this data model and the studies worked on extending this data model for land administration purposes.

2.1 Underground Land Administration

Underground space refers to areas below ground level. In general, the ground level is the natural elevation of the ground surface, which may be raised or lowered artificially (Rönkä et al., 1998). Underground Land Administration (ULA), as a part of land administration, refers to the processes and information required for subdivision, registration, and management of ownership boundaries and rights associated with assets located in underground space (Saeidian et al., 2021). Most efforts in 3D land administration have focused on implementing 3D above-ground cadastral systems. Underground objects are often neglected (Den Duijn et al., 2018). Therefore, the data models are not well customised to support underground (Kim and Heo, 2019).

Managing underground space and integrating physical and legal data rely on the data model. A few studies have focused on developing cadastral data models for underground. These studies are limited to asset types such as utility networks (Radulović et al., 2018; Radulović et al., 2019; Silva and Carneiro, 2020; Yan et al., 2019a; Yan et al., 2019b; Yan et al., 2019c; Yan et al., 2021), underground buildings (Kim and Heo, 2017), and wine cellar (Janečka and Bobíková, 2018). These studies were conducted based on the requirements in different

jurisdictions such as Singapore (Yan et al., 2019a; Yan et al., 2019b; Yan et al., 2019c; Yan et al., 2021), Korea (Kim and Heo, 2017), Czech Republic (Janečka and Bobíková, 2018), Brazil (Silva and Carneiro, 2020), and Serbia (Radulović et al., 2018; Radulović et al., 2019). On the other side, most of these studies used the LADM data model, which is a conceptual legal data model. It uses two classes to describe underground utility networks, but these classes are not adequate to define the structure, geometric and topological information of utilities (Janečka and Bobíková, 2018; Yan et al., 2019a; Yan et al., 2019b; Yan et al., 2019c). Therefore, LADM, in its current form, cannot support the requirements of ULA, especially related to physical aspects (the spatial and semantic information of underground assets).

In order to manage the physical reality and legal extent of all underground assets, a 3D integrated data environment is critically needed. A fully integrated 3D view of underground environments can assist in registering different underground assets and defining ownership of underground areas.

Data model plays a key role in 3D underground land administration. It enables the acquisition, manipulation, visualisation and query and analysis of 3D land RRRs (Aien et al., 2011). Therefore, developing an integral data model to identify 3D underground objects, their relationships and RRRs associated with them is necessary. In this research, a CityGML-based 3D data model with comprehensive geometry and semantics will be developed to integrate physical and legal data of different underground assets.

2.2 CityGML

CityGML is a prominent semantic data model to represent 3D urban objects. It is an open standardised and geo-referenced model. The concept of LoDs in CityGML is useful for different use cases of ULA. CityGML is a city-scale model that is an appropriate data model for underground space where tunnels and utility networks are distributed on a large scale. It provides 3D city models in the geographic information environment, which plays a fundamental role in various urban applications, especially land administration. CityGML represents the shape and graphical appearance of 3D city features and supports the semantic and thematic properties, taxonomies, and aggregations. This 3D data model also allows the hierarchical specification of geometry and attributes for urban features (Gózdź et al., 2014; Kolbe et al., 2021; Van Oosterom et al., 2018).

CityGML has some useful concepts; for example, *TerrainIntersectionCurve* can be applied to integrate 3D objects with the terrain. The concept of *ClosureSurface* can be used to model the entrances of underground objects (e.g. pedestrian underpasses and tunnels). It can be used to be virtually sealed the objects that are not geometrically modelled as closed solids and be computed their volume. 3D underground objects are often derived from different datasets. The concept of *ExternalReference* can be used to refer to external data sets (Elwannas, 2011; Gózdź et al., 2014; Gröger et al., 2012; Jusuf et al., 2017; Van Oosterom et al., 2018).

Many cities use the CityGML data structure to manage their 3D city models, which serve many purposes, from land use planning to cadastre (Lippold, 2022). Some studies investigated and suggested CityGML for land administration purposes (Çağdaş, 2013; Dsilva et al., 2009; Gózdź et al., 2014; Gürsoy Sürmeneli et al., 2021; Hajji et al., 2021; Li et al., 2016;

RASHIDAN et al., 2021; Rönsdorff et al., 2014; Sun et al., 2019; Surmeneli et al., 2020; Van Oosterom et al., 2018; Vandysheva et al., 2011; Ying et al., 2014). However, CityGML does not have any features to define the legal information of assets (Dimopoulou et al., 2018; Gózdź et al., 2014). Also, the studies mainly focused on above the ground. There are different assets in underground space such as utility networks, tunnels, and train stations with complex geometries and topologies that can differ from those of land parcels.

Therefore, the aim of this research is to develop a 3D CityGML-based underground data model to enable integrated management of underground assets by linking legal spaces to the physical reality.

3. UNDERGROUND LEGAL SPACES IN VICTORIA

This section provides the requirements identified using current practice (survey plans) and literature review. There are two types of underground legal spaces in Victoria: primary underground parcels and secondary underground interests.

3.1 Primary underground parcels

Primary underground parcels refer to base-level parcels for forming the continuous cadastral fabric. There is no overlap and gaps between these parcels. In the current 2D survey plans, cross-sectional diagrams and upper and lower limits of parcels are used to represent underground primary parcels in 3D. In 3D,

the spatial extent of these parcels should be a closed volume (volumetric legal spaces). Underground primary parcels include:

- **Underground lot:** this parcel is owned by an individual or private owner (e.g. underground shopping malls, basements, storage spaces, private parking spaces, wine cellars, etc.).
- **Underground stage lot:** it is used to subdivide underground land into stages.
- **Underground crown:** these parcels are owned by the government (e.g. underground train stations, walkways, tunnels, public parking, etc.). There are two types of crown lands, including crown allotment and crown portion.
- **Underground common property:** it is for the benefit and use of some/all lot owners (e.g. elevators, entrances, etc.). Common property is divided into two types: Limited and Unlimited. A limited common property refers to the legal space for the benefit of some lot owners, while unlimited is for the benefit of all lot owners.
- **Underground reserve:** these land parcels are owned by city councils and are for the benefit and use of the public.

Figure 1 shows some examples of different types of primary underground parcels.

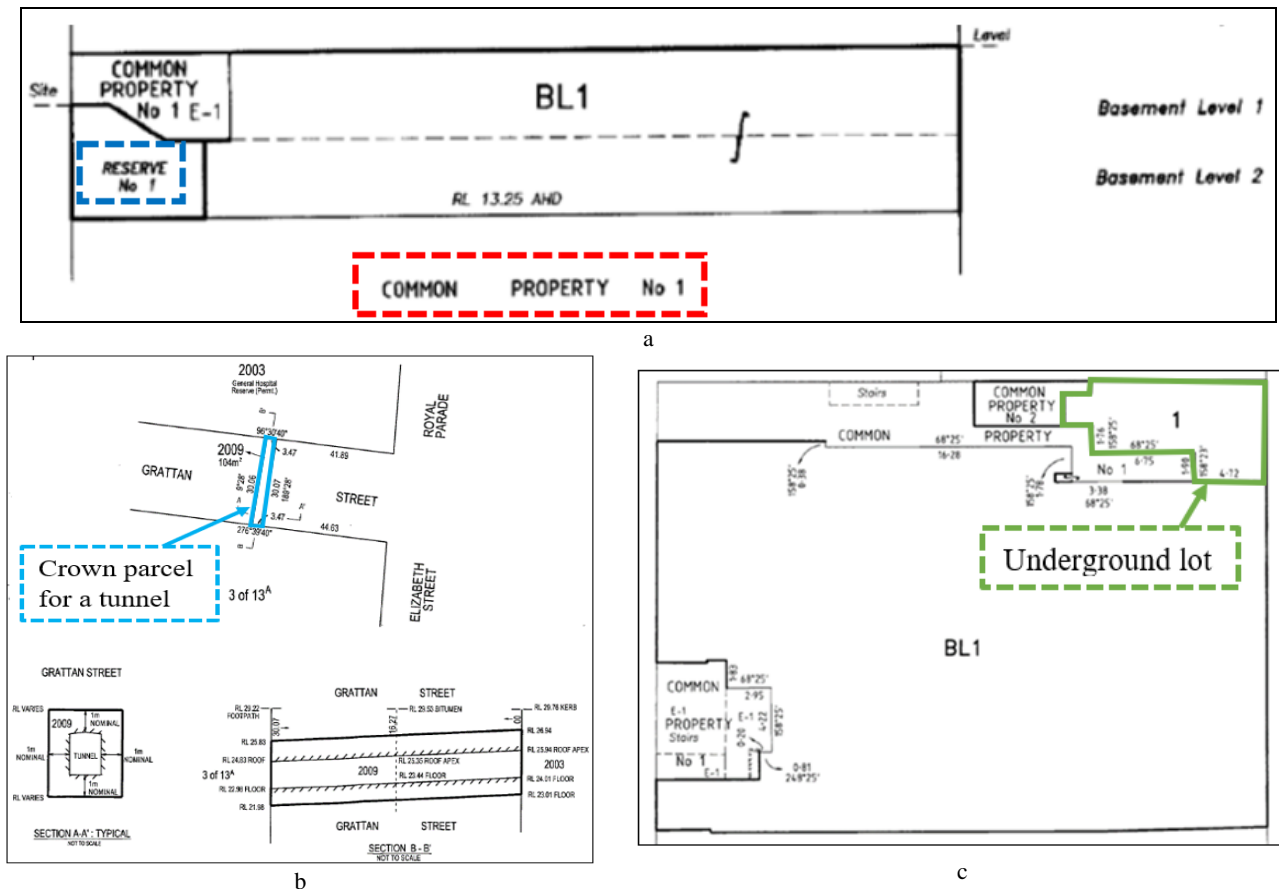


Figure 1. Examples of underground primary parcels: a) common property and reserve; b) crown parcel; c) underground lot

3.2 Underground secondary interests

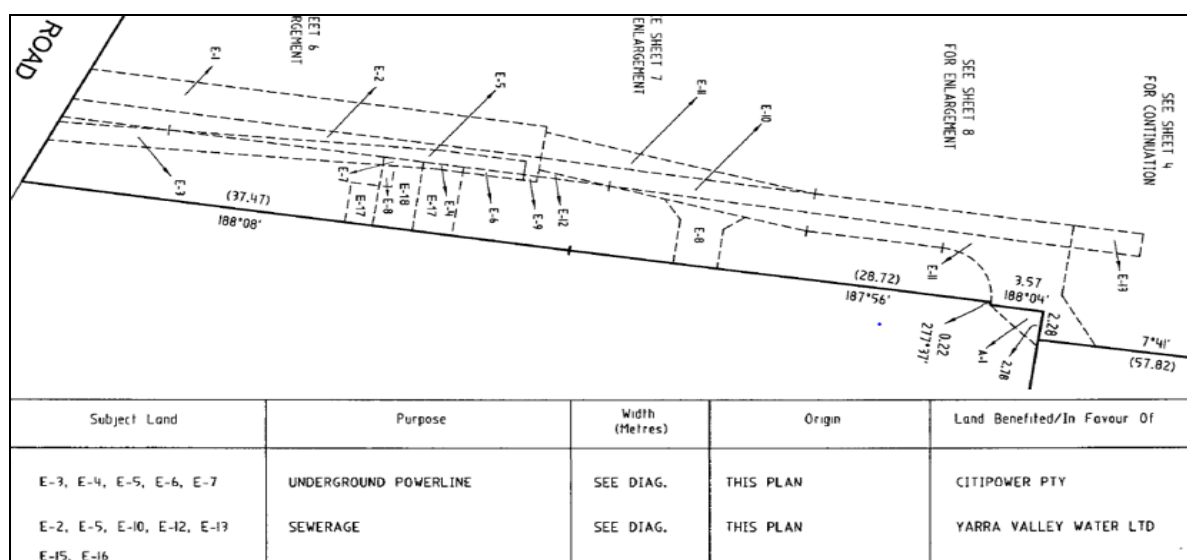
Underground secondary interests provide benefits and/or pose restrictions on primary parcels. These legal interests can overlap any primary parcels or other secondary parcels. There are two types of relationships between primary underground parcels and secondary underground interests: 1. each secondary underground interest has a semantic relationship with at least one primary parcel for which the benefits are provided, or the restrictions are posed; 2. secondary underground interests need to be fixed to a primary parcel (spatial relationships). Like underground primary parcels, in 3D, the spatial extent of these parcels should be a closed volume (volumetric legal spaces). Underground secondary interests include:

- **Easement:** it is a property right held by someone or public authority to use part of the land belonging to someone else for a specific purpose (e.g. drainage,

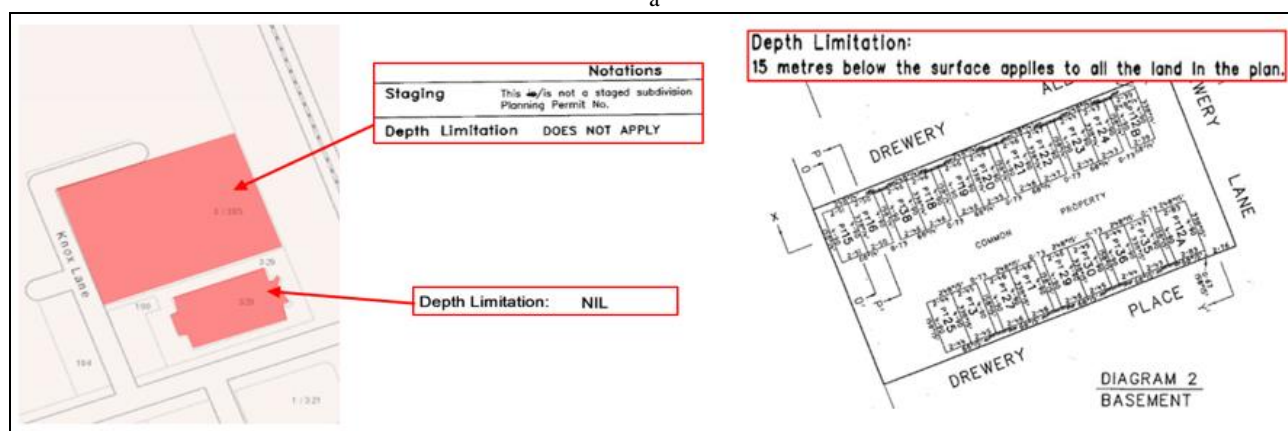
sewerage, and carriageway easements, entrances to underground structures such as train stations, etc.).

- **Depth limitation:** it is captured as a notation on plans, but in ePlan, it is captured as a non-spatial parcel (LandVictoria, 2019). In the 3D underground model, depth limitations need to be spatially represented in 3D as underground volumetric spaces. In some cases, unbounded underground parcels are defined that must be considered.
- **Restriction:** defines an area or space on one or more lots where limitations on the use of land apply. The benefited land(s) can be lots and stage lots, and the burdened land(s) can be lots, stage lots and common properties.

Figure 2 shows some examples of different types of underground secondary interests.



a



b

Figure 2. Examples of underground secondary interests: a) easements; b) depth limitations

4. IMPLEMENTATION

CityGML is a data model to support generic domain-independent information at a city scale. It provides 3D models for the most important types of city objects, which are useful for a wide range of applications. This data model is modular, including the Core module (green colour in Figure 3), 11 thematic modules (red colour in Figure 3) and five extension

modules to add specific modelling aspects (blue colour in Figure 3). Each application can use one or more of the thematic and extension modules, but all applications must implement the Core module. In other words, implementations may use specific subsets of the CityGML Conceptual Model (CM) depending on the information needs. Therefore, implementations are not required to support the complete CityGML model in order to be conformant to the standard. In

this respect, modularisation is applied to the CityGML CM (Kolbe et al., 2021).

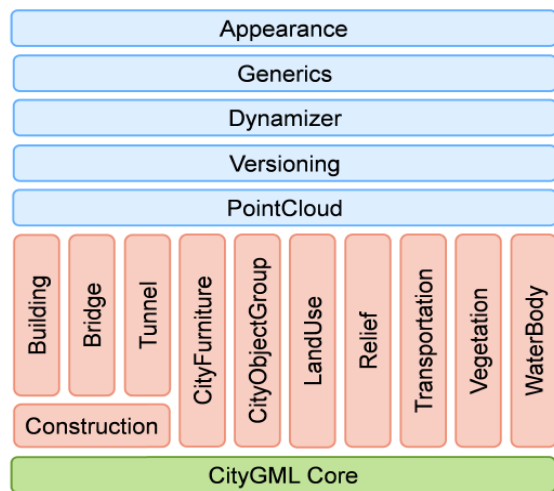


Figure 3. CityGML 3.0 module overview (Kolbe et al., 2021)

CityGML CM most likely needs to be extended to contain attributes that are not explicitly modelled and/or 3D objects which are not covered for specific applications and use cases. CityGML provides three different approaches in this regard (Kolbe et al., 2021):

- Generic objects and attributes,
- Application Domain Extensions (ADEs), and
- Code lists

ADEs are formal and systematic extensions of CityGML CM for specific applications or domains. An ADE typically extends CityGML CM by adding new feature types and additional content such as code lists, enumerations, and data types to support the application or domain area. The ADE mechanism was traditionally defined in CityGML only at the level of XML Schema encoding (Kolbe et al., 2021). Therefore, some studies investigated the extension of this data model using UML. For example, Van den Brink et al. (2013) compared six alternatives for modelling CityGML ADEs in UML. In the new version of CityGML (version 3.0), ADEs need to be expressed in UML and then encoded in other languages. Users can create additional UML models to extend this model as ADEs. Therefore, CityGML 3.0 allows ADE models to be mapped to multiple and different target encodings from a conceptual level, regardless of the platform (Kolbe et al., 2021). Therefore, UML is selected as a formal modelling language to represent classes, attributes, code lists, and relationships in this study. UML has several advantages: (Van den Brink et al., 2013):

- As a result of the visual representation, communication with stakeholders is simple.
- As an international standard and a formal modelling language, it can unambiguously explain the structure and rules of information models.
- XML schema and documentation can be generated directly and automatically from UML models.

Identifying relevant features in CityGML is essential for extending this data model. There are two options to define the features: 1- features that can be mapped to the existing features of the CityGML standard data model; 2- features that need to be defined as new features by an ADE (Biljecki et al., 2021).

According to the requirements, it is necessary to model the legal spaces along with physical objects. As seen in Figure 3, CityGML provides some modules and classes to support underground assets such as Building and Construction modules (for underground basements, train stations, walkways, etc.), Tunnel module, and so on. Although these modules need to be extended to cover all underground assets, this study focuses on legal aspects. CityGML 3.0 does not provide any classes to define legal spaces in the current form.

CityGML 3.0 defines two types of spaces: physical spaces and logical spaces. Physical spaces are fully or partially enclosed by physical objects (e.g. a building or room bounded by walls and slabs), while logical spaces are defined according to thematic considerations and are not necessarily bounded by physical objects. Logical spaces can also be bounded by non-physical/virtual boundaries (Kolbe et al., 2021). Therefore, legal spaces, including primary parcels and secondary interests, can be defined as logical spaces in CityGML. CityGML 3.0 CM also defines all geometric representations in the Core module (Kolbe et al., 2021). According to the CityGML space concept, features representing spaces shall be derived directly/indirectly from Core::AbstractSpace (Kolbe et al., 2021).

Figure 4 shows the developed ADE (CityGML VicULA ADE) for legal spaces in Victoria based on the requirements described in the previous section. The feature classes and code lists of the VicULA ADE are marked in green, and the CityGML CM feature classes are highlighted in yellow. The primary parcels and secondary interests are subsets of the abstract class named *UndergroundLegalParcel*.

Legal objects have unique names in Victoria (e.g. 1\PS246521 for a lot and EAS1\PS236435 for an easement). All classes of the VicULA ADE inherit the properties of the *CityObjectGroup*, *AbstractSpace*, *AbstractCityObject*, *AbstractFeatureWithLifespan*, and *AbstractFeature* classes of the CityGML CM. Therefore, these unique names can be mapped via the property of the *AbstractFeature* class.

Legal objects are captured as "single", "part", or "multipart" parcels. Therefore, the spatial extent of underground primary parcels and secondary interests can consist of one part or multiple parts. Parcels with multiple closed polygons are known as multipart parcels. The enumeration named "ParcelType" is created in this regard. On the other side, CityGML provides user-definable grouping using the *CityObjectGroup* thematic module. This module can be used to define multipart legal objects.

The state of legal objects can be created, extinguished, affected, and existing. The "ParcelState" enumeration defines the list of this property of the *UndergroundLegalParcel* class. It is also necessary to define the measured area of legal objects. As all classes inherit the property of the *AbstractSpace* class, the area and volume of legal spaces can be defined via the area and volume attributes of the *AbstractSpace* class.

Each restriction can have an expiry date. The *Restriction* feature class inherits it from the *AbstractFeatureWithLifespan* class. As seen in Figure 4, there are two types of relationships between primary and secondary spaces: spatial and semantic relationships. Every secondary underground parcel needs to be fixed by a primary parcel (spatial relationship). Every secondary underground parcel provides benefits and/or poses restrictions on primary parcels (semantic relationship).

The *AbstractSpace* class has an association relationship with the *AbstractSpaceBoundary* class. Therefore, its subclasses (*PrimaryUndergroundParcel* and *SecondaryUndergroundInterest*) inherit this association as well. Consequently, it is possible to define boundaries using this relationship.

Underground primary parcels and secondary interests have a “description” attribute. This attribute is optional for some types

of legal parcels, but is required for others (e.g. restriction description for the *Restriction* feature class). This attribute is inherited from the *AbstractFeature* class of the Core module of CityGML. Finally, it should be mentioned that the “parcelUse” property of the *UndergroundLegalParcel* feature class can be used to define the land use of primary parcels or the purpose of easements.

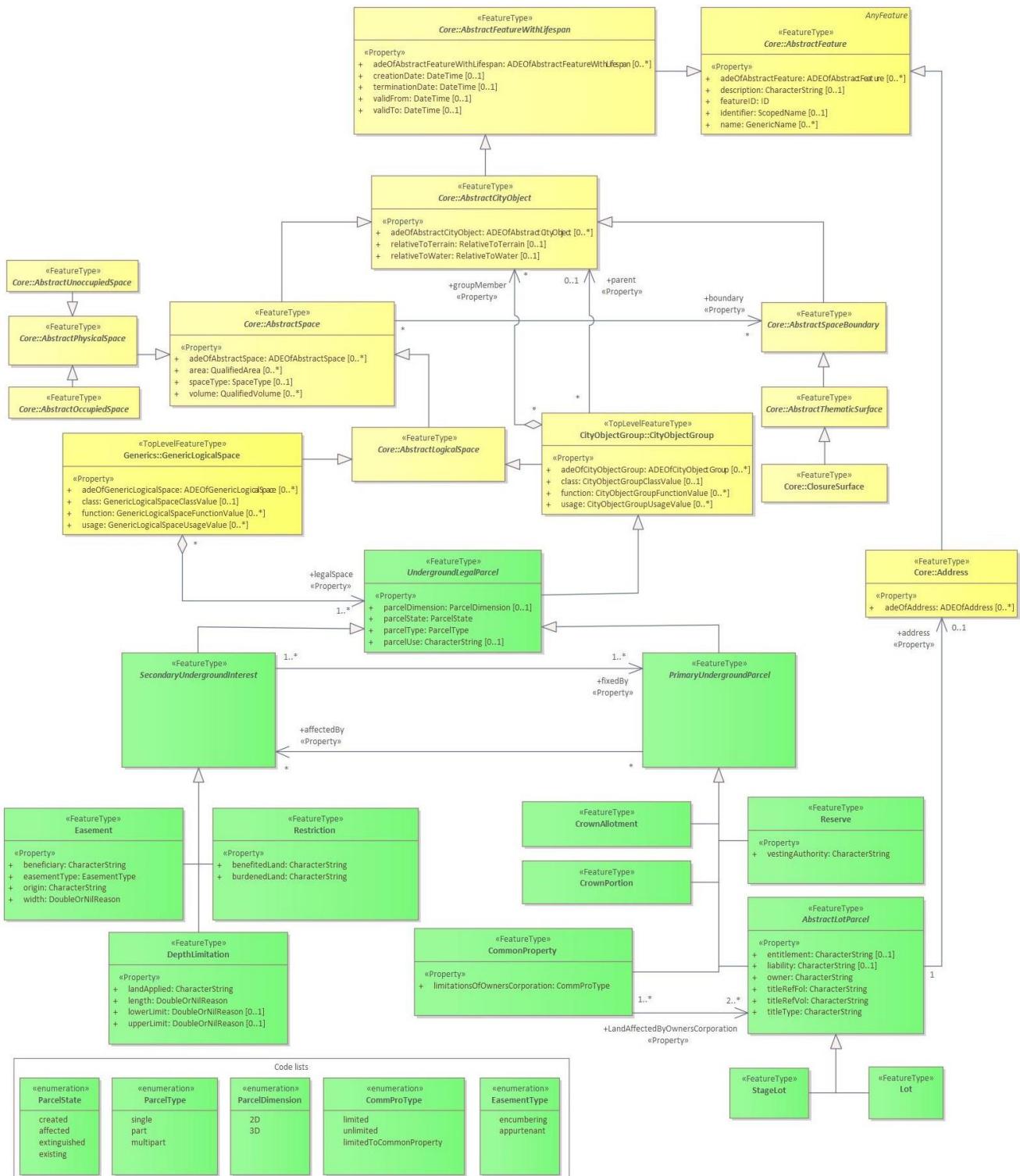


Figure 4. The UML diagram of the developed CityGML VicULA ADE (the added features are in green, and the features from the CityGML CM are in yellow).

5. DISCUSSION AND CONCLUSIONS

The CityGML ADE proposed in this study can potentially provide a new solution for 3D digital management of underground ownership rights in Victoria. It can be used to upgrade ULA using an integrated 3D digital model. While the 3D data model developed in this study was based on the requirements in Victoria, our proposed approach can be used as a general guideline for other jurisdictions. The method suggested in this study can be a viable approach to replicate elsewhere.

CityGML can be used to create 3D digital property maps across an entire city, jurisdiction, or country. It can also be used in national systems to exchange property data. In current property maps, only 2D parcels are displayed. However, underground assets such as underground shopping malls, tunnels, utility networks, and car parks are usually built vertically. Therefore, these property maps fail to represent these assets' spatial and ownership data in 3D. Extending CityGML to support legal information would be a key step towards realising 3D property maps with fully integrated representations of underground RRRs. The findings of this study show that extending CityGML to support legal information can be a viable solution to meet the requirements of a 3D integrated model for ULA. Based on the findings, the logical space concept of the new version of CityGML is useful and applicable for cadastral data modelling.

The VicULA ADE extends CityGML 3.0 and defines a specialised model for underground land administration at the conceptual level. There are different encoding specifications supported by CityGML, such as GML and JSON (Kolbe et al., 2021). The future study will investigate these encoding specifications for the developed ADE. Future work will also focus on testing the ADE with real-world case studies and use cases to demonstrate the model's applicability. In addition, it is necessary to investigate geometry and Levels of Detail (LOD) for the ADE.

This research did not investigate legal boundaries, survey elements, and administrative elements. Based on the investigation, there are different types of legal boundaries (general and fixed boundaries) in Victoria. The interior, exterior or median faces of some building elements such as walls, doors, floors, and ceilings can define legal spaces. CityGML defines the interior and exterior faces of some elements and can be useful in this regard. Also, there are different types of survey points and lines in Victoria. Therefore, it is necessary to define relevant code lists in CityGML to support these elements. Finally, CityGML does not provide explicit attributes or classes for administrative elements, including legal documents and actors such as the owner of a right (Atazadeh et al., 2022). All these aspects need to be investigated in detail in future studies.

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