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Development of an LADM-based Conceptual Data Model for 3D Underground Land Administration in Victoria

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Key words: Underground land administration, 3D cadastral data model, LADM, Underground space management, Victoria

SUMMARY

Currently, many cities around the world use underground space for different applications such as tunnels, utility networks, parking, walkways, and shopping malls. Due to the increasing use of underground areas, management of this space is very important for decision-makers and stakeholders. A 3D Underground Land Administration (ULA) data model has an underpinning role in the management of spatial and semantic information of underground physical structures (physical aspects) as well as the ownership attributes and the extent of legal spaces in underground (legal aspects). Current data models focus on either physical or legal aspects and are mostly based on 2D approaches. The Land Administration Domain Model (LADM), as an ISO standard (ISO 19152), is a prominent legal 3D model adopted for land administration. Several studies and countries have used this data model for land administration purposes. However, LADM has not been fully implemented for modelling underground assets. In addition, it does not consider the physical aspects of underground objects. Physical structures have significant roles in defining the ownership extent of underground assets in some jurisdictions such as Victoria, Australia. On the other hand, LADM-based data models developed by different studies are based on the current requirements and legislative of different jurisdictions. Although these solutions can be helpful, a comprehensive underground data model customised for Victoria is needed. This research aims to develop an LADM-based conceptual data model for 3D ULA to enable integrated management of underground assets by interlinking legal and physical aspects. It is based on the requirements and legislative of Victoria jurisdiction. These requirements include underground legal objects and boundaries and underground physical objects. The data model developed in this study is one of the first and crucial steps to enable 3D digital management of underground rights, restrictions and responsibilities (RRRs) in Victoria.

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1. INTRODUCTION

In recent decades, the development and use of underground areas have been increased. For example, in Australia, 740,000 km of infrastructure is located in underground, which is valued at more than $340 billion (AADBYDS 2019). Therefore, management of this space is very important for decision-makers and stakeholders. Unregistered underground assets and unclear localisation of them result in several issues such as underground strikes, loss of services due to utility strikes, wasted time and resources and safety hazards during excavations (DEEP DIG 2016, Phillips, Arancibia et al. 2018). Moreover, the necessity of a clear and accurate definition of legal rights associated with underground infrastructure assets is vital. There are different rights, restrictions and responsibilities (RRRs) in underground areas. A reliable and complete representation of legal spaces can prevent unnecessary costs, delays and disruptions in many projects (Rajabifard, Atazadeh et al. 2019).

Current practices cannot effectively communicate underground ownership boundaries and RRRs in complex situations such as intersecting underground utility networks. They based on silo-based and fragmented 2D approaches, which cannot provide a reliable, unambiguous and coordinated representation of the legal extent of subsurface areas. 2D survey plans often create spatial problems and unclear representation of complex RRRs within subterranean environments, leading to ineffective management. On the other side, in some jurisdictions (e.g. Victoria, Australia), physical and semantic data such as walls and ceilings are necessary to define legal spaces. Therefore, integrating physical data (semantic and spatial extent of underground physical objects) with legal data (ownership information and the extent of legal spaces) in a 3D integrated data environment is essential. Most efforts in 3D land administration have focused on implementing 3D above ground cadastral systems; therefore, they are not well customised to support underground (Kim and Heo 2019).

Compared to above ground, underground areas have unique characteristics and require special considerations. This space has different assets such as basements, utility networks, tunnels, train stations, and walkways with complex geometries and topologies. For example, survey plans of some underground assets such as underground tunnels can be more complex than land parcels. They are very long and represent different shapes (because of limitations such as excavation limitations in underground areas (the surrounding soils and rocks). Data acquisition of buried objects is also different from above ground. Geometric and semantic validation of underground legal and physical objects and 3D visualisation of them also need special concerns. Underground areas have specific laws and regulations and use cases such as excavation, construction of an underground tunnel, and utility management. Finally, various stakeholders, both private and public, have interests and benefits in underground which create complex institutional arrangements (Saeidian, Rajabifard et al. 2021).

A fully-integrated physical and legal view of underground environments can assist to register different underground assets and define ownership of underground areas. Data model plays an underpinning role in integrating physical and legal data and managing underground space. Effective management and use of underground data depend on models and schemas to organise them (Lieberman and Roensdorf 2020). Data modelling enables the acquisition, manipulation, visualisation, and query and analysis of 3D land RRRs (Aien, Rajabifard et al. 2011). Several studies have focused on modelling above ground assets; however, underground objects are often neglected (Den Duijn, Agugiaro et al. 2018).

Land Administration Domain Model (LADM) is a prominent legal 3D model adopted for land administration at the international level (Lemmen, Van Oosterom et al. 2015). However, LADM has not been fully implemented for modelling underground assets. In addition, it does not consider the physical aspects of underground objects. In some cases, physical elements define the legal extent of objects in the form of a boundary (Van Oosterom, Lemmen et al. 2018, Darin 2019, Knoth, Atazadeh et al. 2020); Therefore, LADM's major issue is the inefficient communication of ownership boundaries referencing the physical location of underground assets. There is a significant research gap in developing a 3D integrated data environment to manage the physical reality and legal extent of underground assets. Therefore, it is necessary to develop an integral data model to identify 3D underground objects, their relationships, and RRRs associated with them. On the other hand, LADM-based data models developed in different studies are based on the current requirements and legislative of different jurisdictions. Although these solutions can be helpful, a comprehensive underground data model customised for Victoria is needed. This research aims to develop an LADM-based conceptual data model for 3D underground land administration to enable integrated management of underground assets by interlinking legal and physical aspects. It is based on the requirements and legislative of Victoria jurisdiction.

The following section will present related works. Then, the methodology of doing this research will be described in Section 3. In Section 4, data model requirements will be provided based on Victoria jurisdiction. Then, Section 5 presents the LADM conceptual data model and the developed LADM-based conceptual data model based on the requirements. The final section of this research will provide conclusions and recommendations for next works.

2. LITERATURE REVIEW

LADM is one of the prominent legal 3D models adopted for land and property management. Several studies and countries have used this data model for land administration purposes. Yan, Jaw et al. (2019) developed a data model for modelling 3D geometric and spatial information of underground utilities in Singapore. They used LADM to connect the developed data model to cadastral parcels for land administration purposes. In similar studies, Yan, Jaw et al. (2019) and Yan, Soon et al. (2019) presented an LADM-based 3D underground utility data model in Singapore. Kim and Heo (2017) also proposed a 3D underground cadastral data model based on LADM. This model was associated and integrated with classes in LADM. The authors noted that this data model is not applicable for other jurisdictions, as it is only compatible with the current cadastral law and cadastral administration in Korea (Kim and Heo 2017). Janečka and Bobíková (2018) focused on underground data capturing, storing and visualising for a specific case study (a wine cellar in Slovakia). They used the LADM boundary face concept with topological encoding for modelling the 3D underground parcels. Silva and Carneiro (2020) developed a data model of subsurface water utility networks based on the standard proposed by LADM. Radulović, Sladić et al. (2018) and Radulović, Sladić et al. (2019) proposed LADM-based data models for utility network cadastre in Serbia. Most recently, Yan, Van Son et al. (2021) proposed a 3D data model for underground utility networks based on the current requirements in Singapore. In this model, some packages and classes of LADM are inherited in order to define geometries. Additionally, the model provides 2D parcels, but it does not define the ownership extent of underground utilities.

Following research gaps are identified in the previous studies:

- There are research gaps in developing a 3D integrated data environment for managing the physical reality and legal extent of underground assets.

- The land administration data models mentioned above for underground assets covered a specific underground asset such as utility networks (Radulović, Sladić et al. 2018, Radulović, Sladić et al. 2019, Yan, Jaw et al. 2019, Yan, Jaw et al. 2019, Yan, Soon et al. 2019, Silva and Carneiro 2020, Yan, Van Son et al. 2021), underground buildings (Kim and Heo 2017), and wine cellar (Janečka and Bobíková 2018). A 3D land administration data model needs to eventually be extended to cover all underground assets (Yan, Jaw et al. 2018).

- Land administration requirements vary in different jurisdictions (Aien, Kalantari et al. 2011, Kim and Heo 2017, Rajabifard, Atazadeh et al. 2018). On the other side, the integral solution should be developed according to the legislative (Yan, Jaw et al. 2019). The land administration data models mentioned above for underground assets are based on the current requirements and legislative of different jurisdictions such as Singapore (Yan, Jaw et al. 2019, Yan, Jaw et al. 2019, Yan, Soon et al. 2019, Yan, Van Son et al. 2021), Korea (Kim and Heo 2017), Czech Republic (Janečka and Bobíková 2018), Brazil (Silva and Carneiro 2020), and Serbia (Radulović, Sladić et al. 2018, Radulović, Sladić et al. 2019). These solutions can be helpful; however, a comprehensive underground data model customised for Victoria is needed.

This research aims to address the above research gaps. An LADM-based conceptual 3D data model will be developed to integrate physical and legal data of different underground assets based on the requirement and legislation of Victoria.

3. METHODOLOGY

The conceptual framework of this research is underpinned by the design science research methodology (Figure 1). In line with design science, the conceptual framework of this research comprises three major activities: foundation, identification of the requirements, and design and development of an artefact.

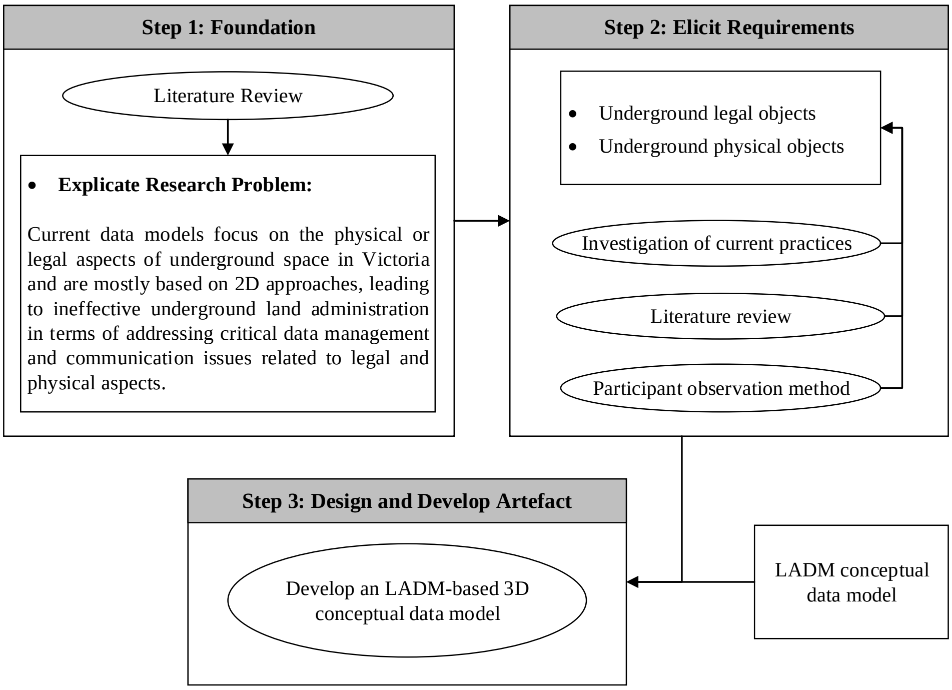


Figure 1. Overall research method

In step 2, a set of requirements that should be considered in designing an underground 3D data model will be identified. Investigation of current practices, literature review, and participant observation methods such as visiting related companies can help to elicit the requirements. The set of requirements should provide elements needed to manage, model and communicate underground legal and physical data. The third step is designing and developing an LADM-based 3D data model to meet underground land administration requirements identified in the previous stage. The conceptual 3D underground data model will include main concepts and their relationships. Unified Modelling Language (UML) diagrams will be created to visually represent the different entities and their logical relationships in the conceptual 3D underground data model.

4. REQUIREMENTS BASED ON VICTORIA JURISDICTION

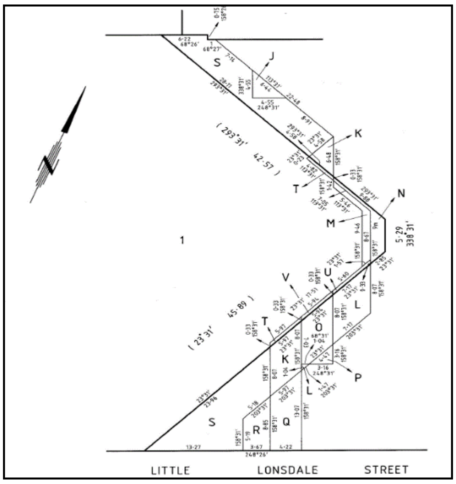
In this part, a set of requirements that should be considered in an underground 3D data model will be provided based on Victoria jurisdiction. The knowledge acquired from the investigation of current practices for ULA and literature review are used to define requirements. Visiting surveying companies and land registry organisations in Victoria is another valuable method to identify a comprehensive range of data requirements for ULA. By investigating the resources, two important categories of requirements are identified: underground legal objects and underground physical objects.

4.1 Underground Legal Objects

In Victoria, each underground asset has legal ownership specified by legally defined objects. In this research, underground legal objects are categorised into three common types of categories: primary underground parcels, secondary underground interests and underground legal boundaries.

4.1.1 <u>Primary underground parcels</u>

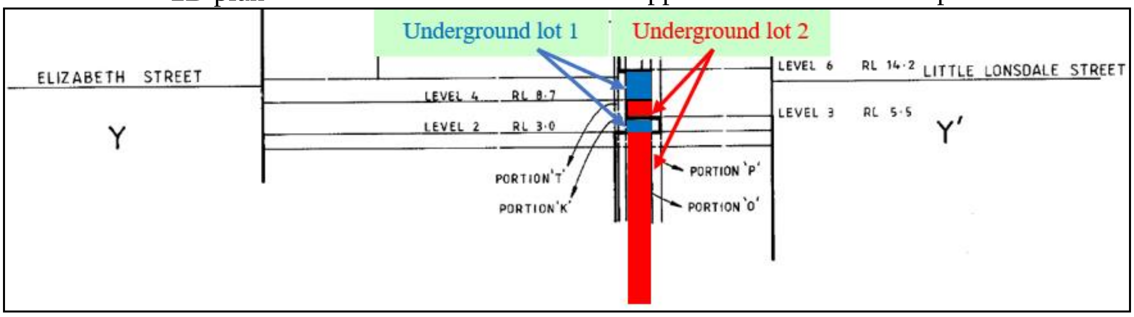
In Victoria, base-level parcels for forming the continuous cadastral fabric are primary parcels. There is no overlap and gaps between primary parcels (LandVictoria 2019). The primary legal parcels used in underground subdivisions include lot, stage lot, crown allotment, crown portion, common property and reserve.



2D plan

PORTION	LOT 1	LOT 2
I	BELOW RL = 19.4m	ABOVE RL = 19.4m
J	BELOW RL = 3.0m AND BETWEEN RL = 8.7m AND RL = 14.2m	BETWEEN RL = 3.0m AND RL = 8.7m AND ABOVE RL = 14.2m
K	BETWEEN RL = 3.0m AND RL = 14.2m	BELOW RL = 3.0m AND ABOVE RL = 14.2m
L	BETWEEN RL = 8.7m AND RL = 14.2m	BELOW RL = 8.7m AND ABOVE RL = 14.2m
M	BELOW RL = 3.0m AND ABOVE RL = 8.7m	BETWEEN RL = 3.0m AND RL = 8.7m
N	ABOVE RL = 13.2m	BELOW RL = 13.2m
O	BETWEEN RL = 3.0m AND RL = 5.5m AND BETWEEN RL = 8.7m AND RL = 14.2m	BELOW RL = 3.0m AND BETWEEN RL = 5.5m AND RL = 8.7m AND ABOVE RL = 14.2m
P	BETWEEN RL = 3.0m AND RL = 5.5m	BELOW RL = 3.0m AND ABOVE RL = 5.5m
Q	BETWEEN RL = 3.0m AND RL = 8.7m	BELOW RL = 3.0m AND ABOVE RL = 8.7m
R	BELOW RL = 8.7m	ABOVE RL = 8.7m
S	BELOW RL = 14.2m	ABOVE RL = 14.2m
T	ABOVE RL = 3.0m	BELOW RL = 3.0m
U	ABOVE RL = 8.7m	BELOW RL = 8.7m
V	BETWEEN RL = 3.0m AND RL = 5.5m AND ABOVE RL = 8.7m	BELOW RL = 3.0m AND BETWEEN RL = 5.5m AND RL = 8.7m

Upper and lower limits of parcels



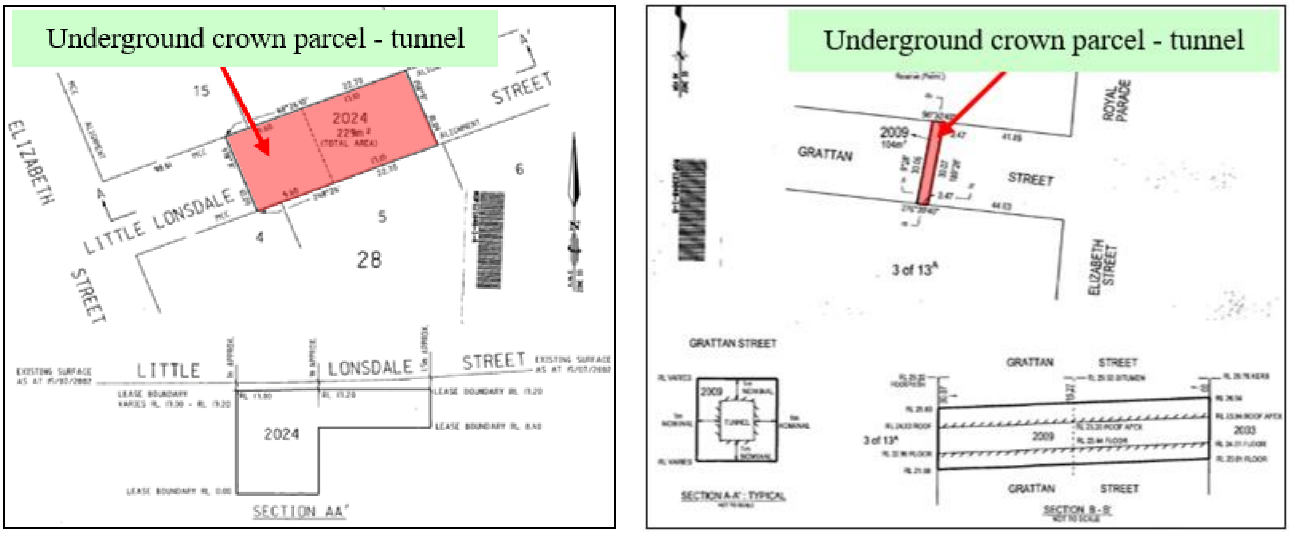
Cross-sectional diagram

Figure 2. Examples of underground lots, 2D cross-sectional diagrams and upper and lower limits

- Underground lot: it refers to underground spaces which are allocated to an individual or private owner. Examples of such spaces can be underground shopping malls, basements, storage spaces, parking spaces, and wine cellars. In 3D, the spatial extent of lots should be a closed volume; therefore, it can be represented spatially by volumetric legal spaces. An underground lot can be captured as "single", "part", or "multipart" parcel. Multipart parcels are used where the spatial description contains multiple closed polygons. In subdivision plans, 2D cross-sectional diagrams and upper and lower limits of parcels are used to represent underground lots in 3D. Figure 2 shows a few examples of cross-sectional diagrams and upper and lower limits of underground parcels to represent different portions of underground lots in 3D. The blue and red colours indicate the spatial extent of portion “O” in lots 1 and 2 based on the upper and lower limits. Each portion of this area has upper and lower limits, making this underground area very complex.

- **Stage lot:** a staged subdivision is a scheme for subdividing land in stages (Surveyors Registration Board of Victoria 1997). Stage lots can be captured in Staged Subdivisions similar to underground lots. Staged subdivision has a master plan which specifies the lots in the first stage and the prescribed information; and plans for the second or subsequent stages which contain the prescribed information (Victorian Legislation 2020).

- **Underground crown:** in Victoria, most underground areas are crown. Crown land parcels are owned by the government and refer to crown allotments and crown portions. When crown parcels are subdivided, they follow the same rules as lots; for example, they must contain a closed geometry (LandVictoria 2019). Therefore, they must be a closed volume in 3D. These spaces are used for different purposes, such as underground train stations, walkways, tunnels, and parking. Figure 3 shows two crown plans for underground constructions located under the roads. In some cases (e.g. Figure 3b), both an underground tunnel (physical object) and its safety zone (legal space) are represented. Cross-sectional diagrams are used to represent the underground crown parcels in 3D. Upper and lower limits may also be used for crown parcels to give some extra information about 3D.



a b

Figure 3. Examples of underground crown parcels

- **Underground common property:** it is for the benefit and use of some/all lot owners and is defined for those spaces which are not lots and reserves. It must be complemented by an Owners Corporation. A common property parcel can be "single", “part”, or "multipart". Like other primary parcels cross-sectional diagrams can be used to represent the common property in 3D.

- Underground reserve: these legal parcels include the land parcels owned by city councils and are for the benefit and use of the public. Similar to other primary parcels, a reserve parcel can be "single", “part”, or "multipart" parcel. A reserve owner (vesting authority) is presented as notation in the subdivision plans (LandVictoria 2019).

4.1.2 Secondary underground interests

Secondary interests provide benefits and/or pose restrictions on primary parcels. These legal interests can overlap any primary parcels or other secondary interests (LandVictoria 2019). The secondary legal interests in underground space include easements, depth limitation, and restriction. All secondary underground interests, except depth limitation float over primary parcels. These legal objects have relationships with at least one primary parcel for which the benefits are provided, restrictions are posed and/or depth limitations are applied. In addition to these semantic relationships, there are some spatial relationships between secondary underground interests, except depth limitation, and primary parcels. Each secondary underground interest needs to be fixed to a primary parcel. All these relationships need to be defined in the integrated data model in 3D space.

- Underground 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. Easement can be used to define the legal extent of underground assets especially utility networks. Common examples of easements are drainage, sewerage, and carriageway easements (DELWP 2020). Figure 4 shows some easements defined for a few underground assets such as underground utilities. As shown in Figure 4, the information presented in plans include 2D spatial extent (geometry) of easements and a standard table that describes attributes such as width, the owner of each unique combination of “purpose/origin/land benefitted”, and the references to the geometry segments (LandVictoria 2019). In this way, parcels above the underground assets are known, and the physical elements are not registered. The depths of underground objects are not also specified. In Figure 4, there are easements intersecting each other, making it challenging to understand the legal ownership of assets associated with these easements without depth information. It is almost impossible to query these underground objects themselves as they do not have a cadastral identity (Ploeger and Stoter 2004).

Easements can be "Single", "Multipart" or "Part" parcels. In 2D plans, easements must be captured as closed polygons. Therefore, in 3D, they must be a closed volume and be represented based on their depth/height. Easements can be defined for a single purpose or multiple purposes. Some spatial and non-spatial information about easements (e.g. depth/height limitations) can be represented as attributes in the standard table of easements or as a note in “Notation” section of the plan. Interpretation of such information can be complicated. The 3D data model should consider these spatial data as well. In some cases, some extra information about easements such as rights and restrictions associated with them can be given as ‘Easement Information’ in plans. These data should also be considered in the 3D underground data model. Most easements are defined in 2D, but in a few plans, cross-sectional diagrams of easements are also available. Accessibility to underground areas is another data requirement that needs to be considered. In some countries, entrances to underground structures such as train stations are registered and represented by polygons on cadastral maps. In Victoria jurisdiction, entrances to underground spaces can be defined as easements in the subdivision plans of surface parcels.

EASEMENT INFORMATION

LEGEND: A - APPURTENANT EASEMENT E - ENCUMBERING EASEMENT R - ENCUMBERING EASEMENT (ROAD)

EASEMENT REFERENCE	PURPOSE	WIDTH (METRES)	ORIGIN	LAND BENEFITED /IN FAVOUR OF
E-5, E-8	PIPELINES OR ANCILLARY PURPOSES	SEE DIAG.	PS 747682D SEC. 136 WATER ACT 1989	BARWON REGION WATER CORPORATION
E-9	PIPELINES OR ANCILLARY PURPOSES	SEE DIAG.	PS 800324 SEC. 136 WATER ACT 1989	BARWON REGION WATER CORPORATION
E-8, E-9	DRAINAGE	SEE DIAG.	PS 747682D	SURF COAST SHIRE COUNCIL
E-15	DRAINAGE	SEE DIAG.	PS 804773K	SURF COAST SHIRE COUNCIL

Figure 4. Example of presenting underground objects as easements

- Depth limitation: it is a kind of restriction that originates from the original crown grant. It is captured as a notation on plans, but in ePlan, it is captured as a non-spatial parcel (LandVictoria 2019). Figure 5a shows some depth limitations in plans. It is possible to have different depth limitations for different (parts of) lots and/or other parcels. Underground lots can also have depth limitations for beneath spaces. In some cases, unbounded underground parcels are defined. Figure 5b shows some underground unbounded parcels. In the 3D underground model, depth limitations need to be spatially represented in 3D as underground volumetric spaces. It is also necessary to consider and investigate unbounded underground parcels.

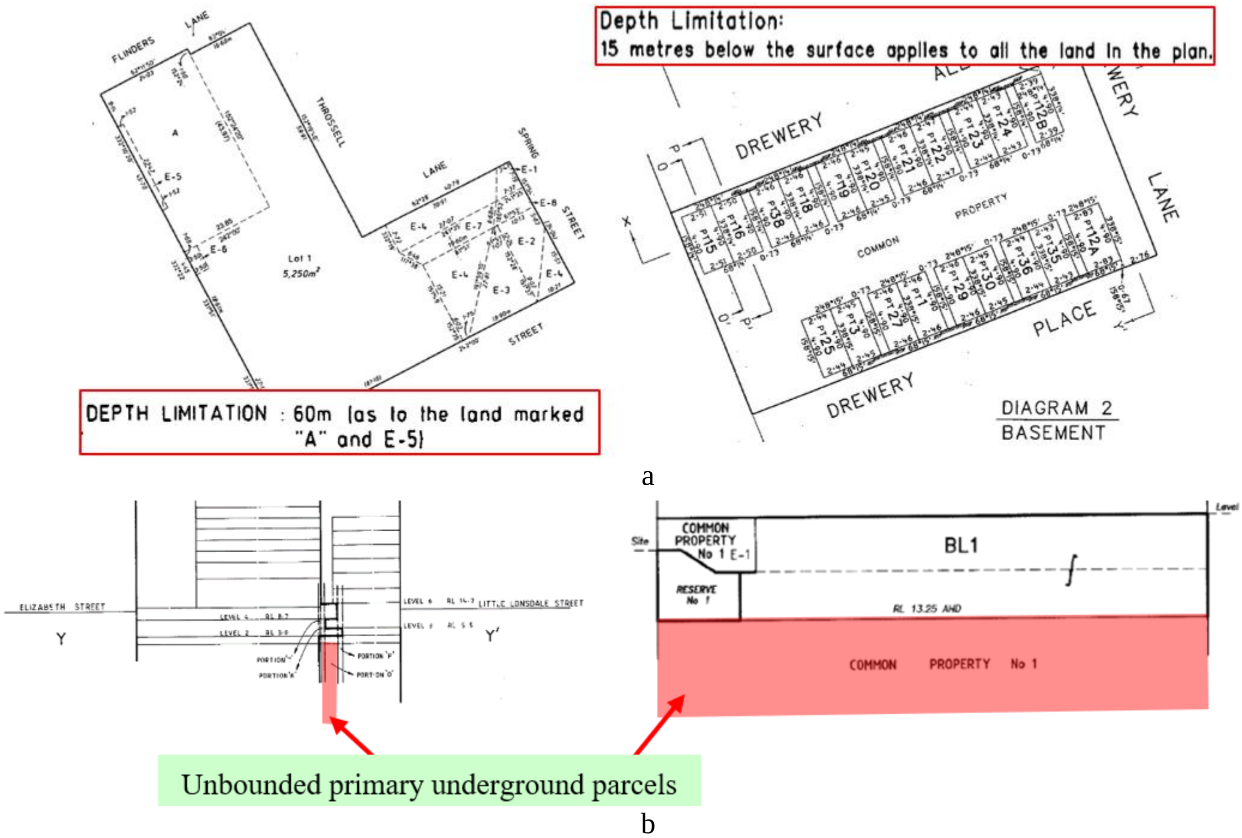


Figure 5. Examples of depth limitation: **a)** a specific depth; **b)** unbounded underground parcels

- Restriction: it is a form of covenant that defines an area or space on one or more lots where limitations on the use of land apply. In subdivision plans, three components are used to define a restriction in underground areas, including benefit and burdened land(s), textual description, and the spatial extent of the restriction (LandVictoria 2019). Restriction benefits can only be lots and stage lots, while restriction burdens can only be lots, stage lots and common properties. These relationships need to be defined in the integrated data model in 3D space. Geometry of restrictions can be “single”, “multipart” or “part”. In the case of multipart restrictions, benefits and burdens can be allocated to individual "part" parcels. Restrictions can have an expiry date that is stored as an annotation (LandVictoria 2019).

4.1.3 Underground legal boundaries

The spatial extent of underground ownership spaces is delineated using a wide range of legal boundaries. By investigating the current underground subdivision practices, this research has developed a new taxonomy of legal boundaries defined in underground environments. Various survey plans have been investigated to elicit the requirements for delineating each legal boundary type. Figure 6 shows the developed taxonomy of legal boundaries used to define underground parcels in Victoria. They are classified into four main categories: surveyed boundaries, building boundaries, projected boundaries, and unsurveyed (computed) boundaries.

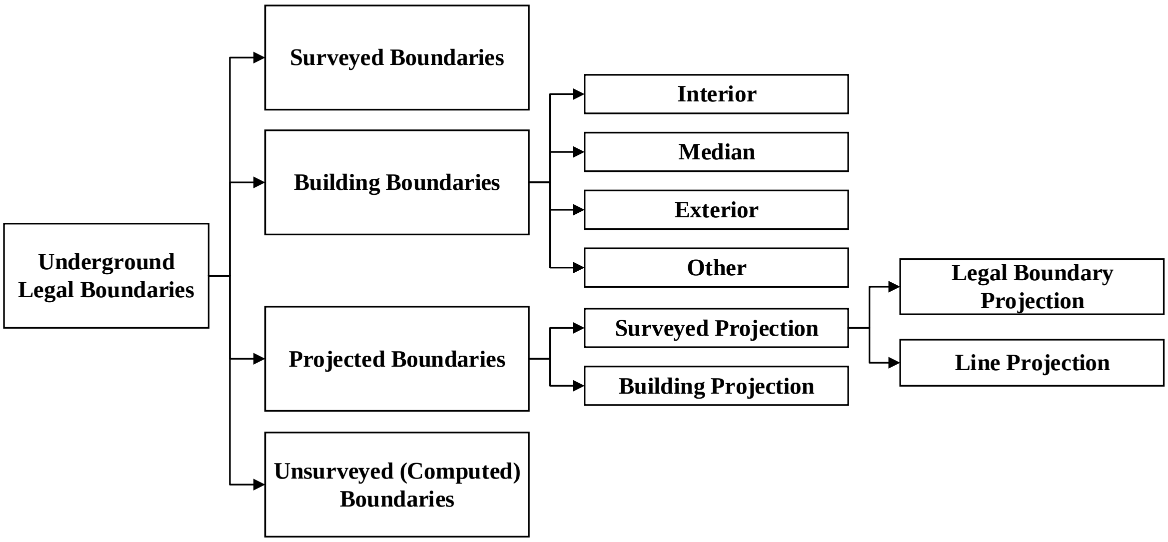
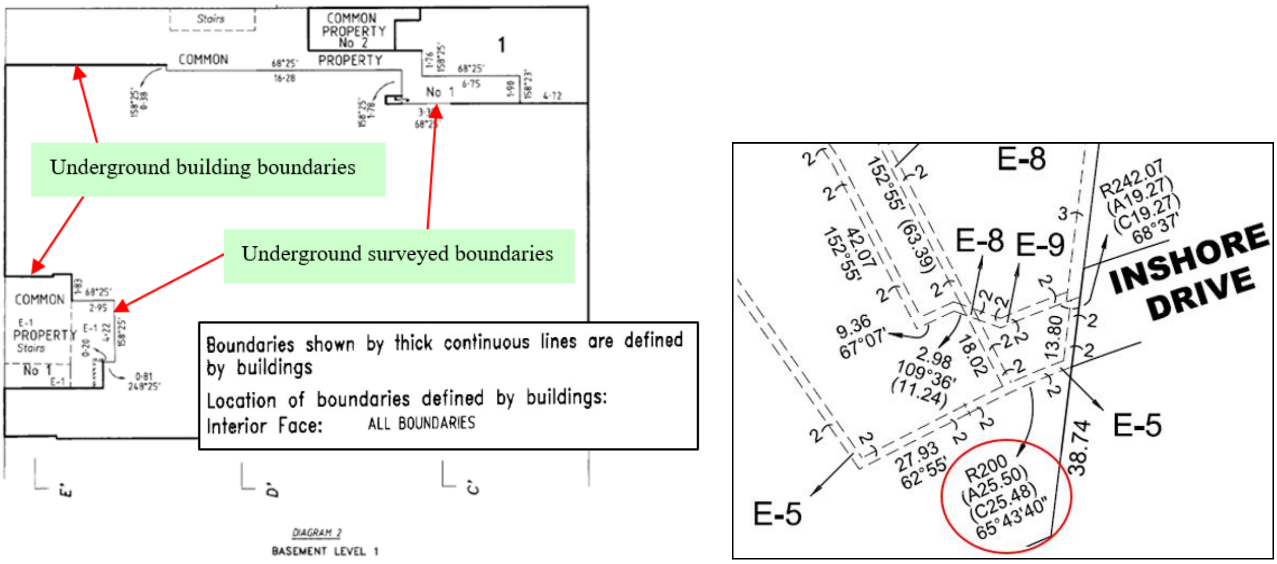


Figure 6. Classification of legal boundaries for defining underground legal objects

- Underground surveyed boundaries: they are defined based on surveying measurements. In 2D, they are delineated by specifying distance and bearing for lines and radius, chord, etc. for curves, especially for tunnels and utilities (easements). Figure 7 shows some surveyed boundaries. In 3D, face and curved face can be used for the geometric representation of legal boundaries. The measurements mentioned are for horizontal boundaries. In 2D subdivision plans, underground vertical boundaries are specified by cross-sectional diagrams, upper and lower limits or notations in subdivision plans. Underground vertical boundaries only include distance (i.e. vertical distance) and no bearing. It can be challenging when a vertical boundary is not straight, and we have an oblique boundary with a slope (e.g. underground parking ramp).

- Underground building boundaries: they are specified by physical objects, which are tangible spatial objects and can be observed in real world. The majority of boundaries in developed areas are marked by actual physical objects (Surveyors Registration Board of Victoria 1997). In Figure 7a, boundaries shown by thick continuous lines are defined by building structures. In this case, boundaries can be the interior face or exterior faces, median surface, or any other locations of building elements. It is specified as a notation in subdivision plans. Underground building boundaries can be extended in vertical direction (walls, doors and columns) or horizontal direction (ceilings and floors).



a b

Figure 7. Examples of underground boundaries: **a)** building and surveyed boundaries (bearing and distance); **b)** surveyed boundaries (curve)

- Underground projected boundaries: they are delineated through projecting a building element, another surveyed boundary or a surveyed line such as a tunnel centreline. The projection can be in vertical or horizontal directions. Figure 8 shows the subdivision plan of an underground tunnel. As noted in the Notations section of the plan, the highway centreline is used to delineate the legal boundaries of this crown allotment. As seen, the legal boundaries of this underground crown allotment are mostly curves.

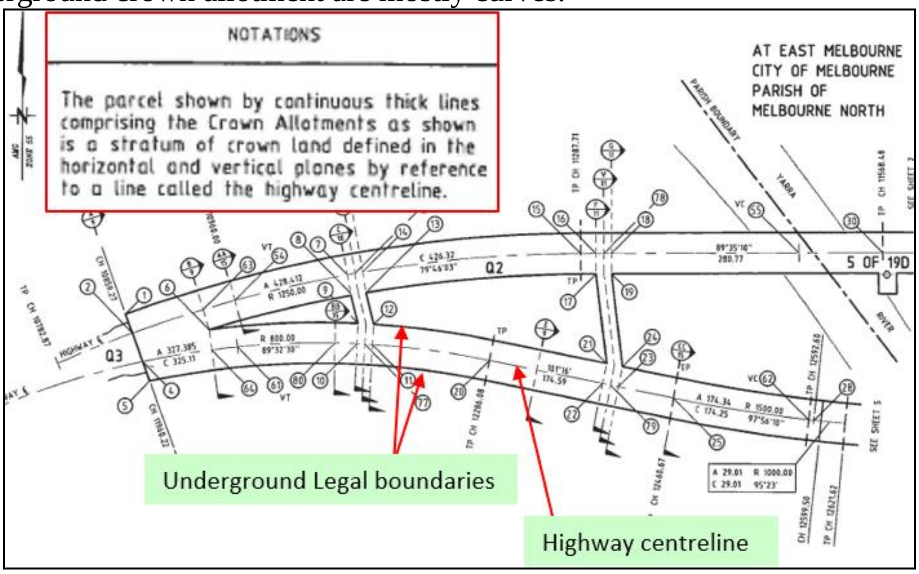


Figure 8. Legal boundaries of a tunnel defined by the centreline of the highway

- Unsurveyed boundaries: the last class of legal boundaries is unsurveyed boundaries. In 2D subdivision plans, these boundaries are displayed as underlined dimensions. For example, in some cases, a line through a building can define a legal boundary. It is not always possible to directly obtain exact measurements of this kind of line, such as those along an underground cliff edges (faces) where these are boundaries. They need to be determined indirectly (Surveyors Registration Board of Victoria 1997).

4.2 Underground Physical Objects

The requirements presented in the previous sections (legal objects) are necessary for land registration which is the first and the most important use case of ULA. Underground land administration has four functions, including land tenure, land value, land use, and land development (Enemark, Williamson et al. 2005, Rajabifard, Atazadeh et al. 2019). Based on these functions, ULA can have different use cases such as underground land registration, planning, design and construction of underground assets, excavation, and utility management. These use cases of ULA require not only legal objects but also some physical objects. Therefore, this research proposes two types of physical information for the 3D integrated ULA model. The first type is the physical objects required to define legal spaces (e.g. building boundaries). An integrated 3D data model should support modelling these physical objects, representing the spatial extent of these objects and defining relationships between the physical objects and boundaries referencing these physical objects.

The second type is the physical information that is not included in 2D survey plans used for land registration, but they are the demands required from an integrated 3D underground data model for different use cases. They can also facilitate the communication of legal objects. Compared to the current practice that provides only 2D spatial extent of legal spaces, the 3D integration model of underground assets and attached legal spaces to them can be more effective for a variety of use cases. A fully combination of the legal and the physical environments into a 3D data model or 3D city model can support the broad functions of a land administration system (Aien, Kalantari et al. 2013). As a result of this approach, it is possible to compare the 3D underground physical objects to the legal rights associated with them and determine if there are any (unwanted) differences; for example, an integrated 3D model with both physical and legal data enables checking the consistency between physical utilities and the legal spaces associated with them including the safety buffer zone around them (Döner, Thompson et al. 2010).

Lieberman (2019) investigated the use cases of an underground physical model and suggested some use cases for Model for Underground Data Definition and Integration (MUDDI). MUDDI is a comprehensive underground information model covering basic geometric representations of underground assets (Lieberman and Roensdorf 2020). However, this model does not support legal objects. Some of these use cases need both legal and physical information. Table 1 presents the use cases of an integrated ULA model based on the use cases presented by (Lieberman 2019) and the author’s experience. This table also lists the physical requirements for each use case.

Table 1. Use cases of an integrated ULA model and the physical requirements of them

Use case	ULA function	Example of underground asset	Physical Requirement
Land Registration (Cadastre)	Land tenure	All underground assets: Private (lots, storage tanks, etc.) and Crown (tunnels, subways, train stations, etc.)	Physical objects that define the spatial arrangements of legal objects (walls, doors, columns, ceilings and floors)
Excavation and Utility Management	Land use Land development	Utilities: Water, drainage, sewerage, telecommunications, electricity (generation, transmission and distribution), gas (transmission and distribution), petrochemical (e.g. oil, petrol and LPG), etc.	Utility type, position (x, y and z-coordinate), the accuracy of the position, size (cable tubes, pits, utility strips), radius, length and number of pipes /cables, date of installation (Bitenc, Dahlberg et al. 2008, Zlatanova and Gorte 2017) Protective areas of utilities, a 'buffer' around the utility (Döner, Thompson et al. 2010)
Planning, design and construction of large-scale building projects	Land tenure Land use Land development	Tunnels: Rail, highways, tram, etc.	The outer surface of physical structures Tunnel protection; Buffer zones to keep the force equilibrium (Peng, Qiao et al. 2021)
		Buildings: Subways, train stations, private buildings, etc.	Same as Land Registration plus the outer surface of buildings
Smart Cities, Digital twins	Land tenure Land value Land use Land development	All underground assets	Physical data integration Data quality and consistency The surface of the lands (ground/site level) / topography

5. THE DEVELOPED LADM-BASED CONCEPTUAL DATA MODEL

LADM intends to provide a generic language for different countries and jurisdictions. Therefore, every jurisdiction needs to customise it based on the requirements. The previous section summarised the requirements for underground land administration in Victoria. This section will present the proposed LADM-based data model to meet these requirements. Three steps should be considered to develop an LADM-based underground data model (Figure 9). In the first step, LADM needs to be investigated and extended to support all underground legal objects in Victoria. In the next step, external classes will be developed to cover underground physical assets. Finally, the relationship between physical and legal objects will be investigated in the third step.

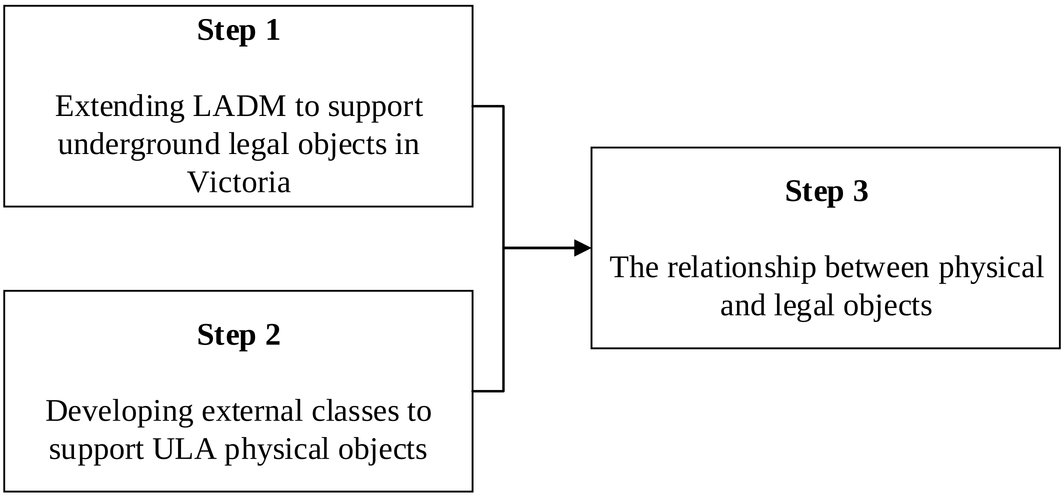


Figure 9. Steps to extend LADM to support ULA in Victoria

Based on the requirements, we developed a general data model. This data model can be a guideline to extend LADM. Figure 10 presents the UML class diagram of this general data model. This data model represents different entities and their logical relationships in the proposed 3D data model.

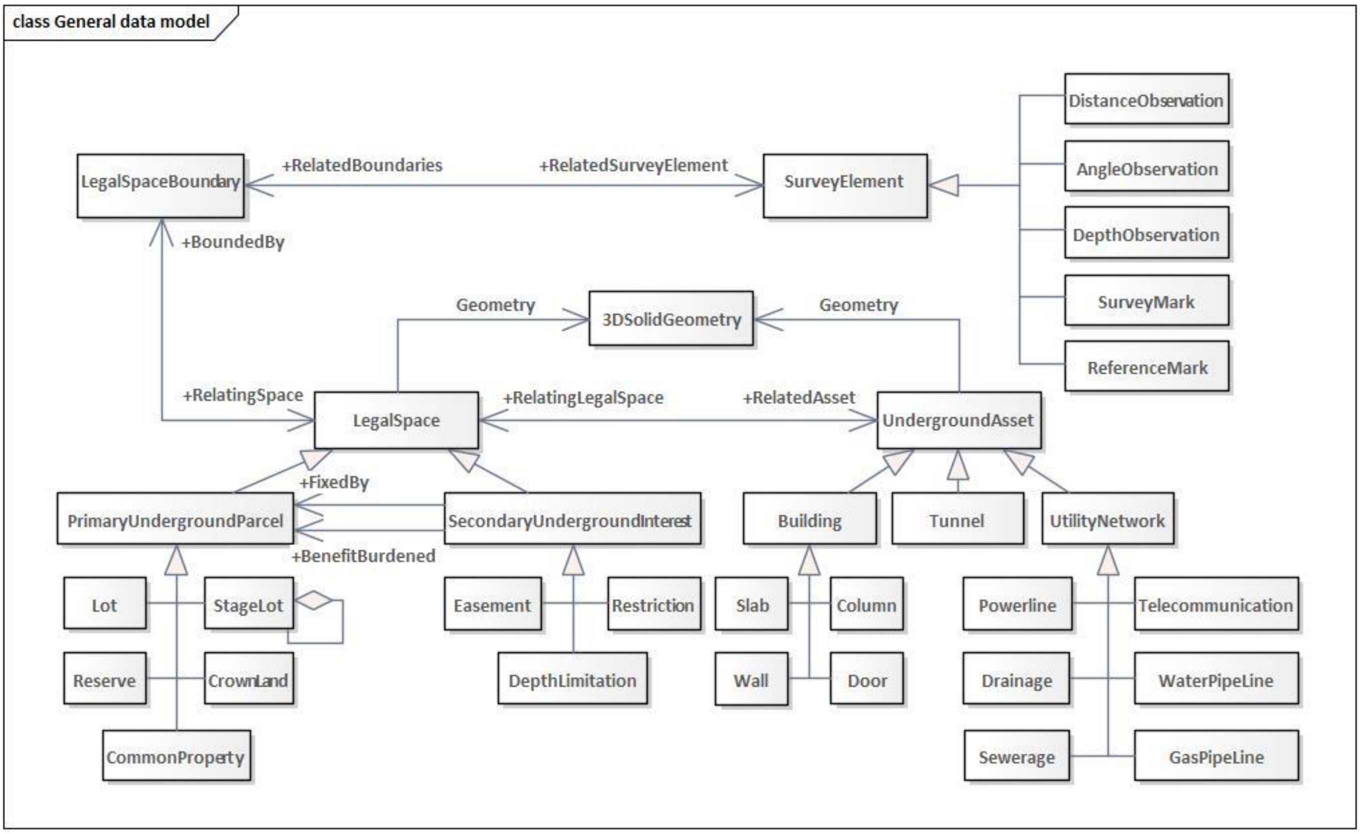


Figure 10. The general data model for underground land administration in Victoria

Figure 11 shows the UML class diagram of LADM. LADM has three packages, including Party (green colour), Administrative package (yellow colour), and Spatial Unit package (blue colour) with its sub package Representation and Survey (red colour) (Lemmen, Van Oosterom et al. 2015). This research focuses on the legal and physical objects, and the Party package and its classes are not investigated. This UML class diagram (Figure 11) focuses on the legal aspects. For the physical aspects, LADM uses external classes.

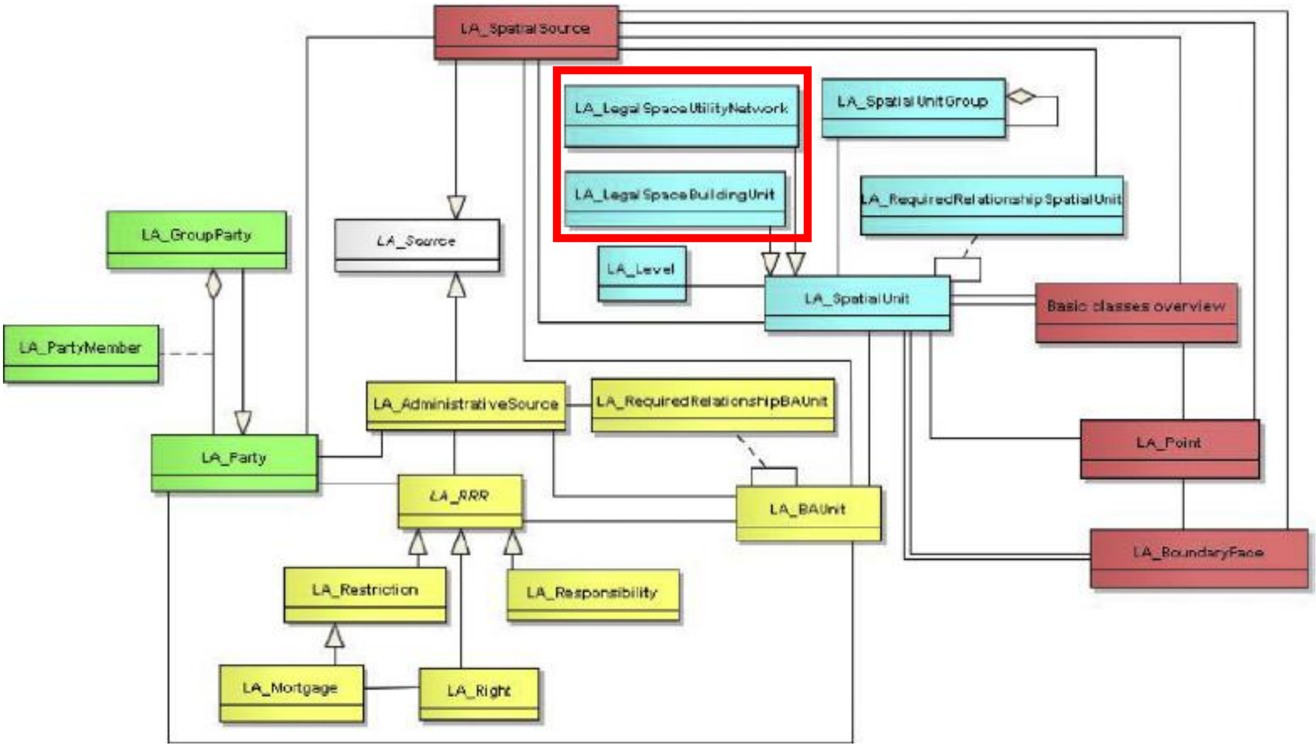


Figure 11. The UML class diagram of LADM (Lemmen, Van Oosterom et al. 2015)

As seen in Figure 11, LADM uses "LA_LegalSpaceUtilityNetwork" and "LA_LegalSpaceBuilding" classes to define legal spaces of underground buildings and utilities. This means that legal spaces are defined based on the asset types. There are some other assets in underground areas such as tunnels. On the other side, based on the requirements in Section 4, in Victoria, legal spaces (legal objects) do not depend on the types of underground assets. In other words, legal spaces are defined independently of the asset types. For example, easements can be defined for utilities and buildings, or crown parcels can be defined for underground buildings (e.g. heritages, walkways, train stations, or shopping malls) and tunnels. It should be mentioned that in the standard table of easements, it is possible to mention the asset type in the purpose field, but it does not mean that the easement depends on the asset type. In Victoria, two types of underground legal spaces are defined: primary and secondary parcels. On the other side, there are relationships between primary underground parcels and secondary underground interests. Section 4.1.2 (secondary underground interests) discussed some of these relationships. Figure 12 shows the proposed LADM-based data model to support legal objects in Victoria. "VIC_" is the prefix for the Victoria country profile.

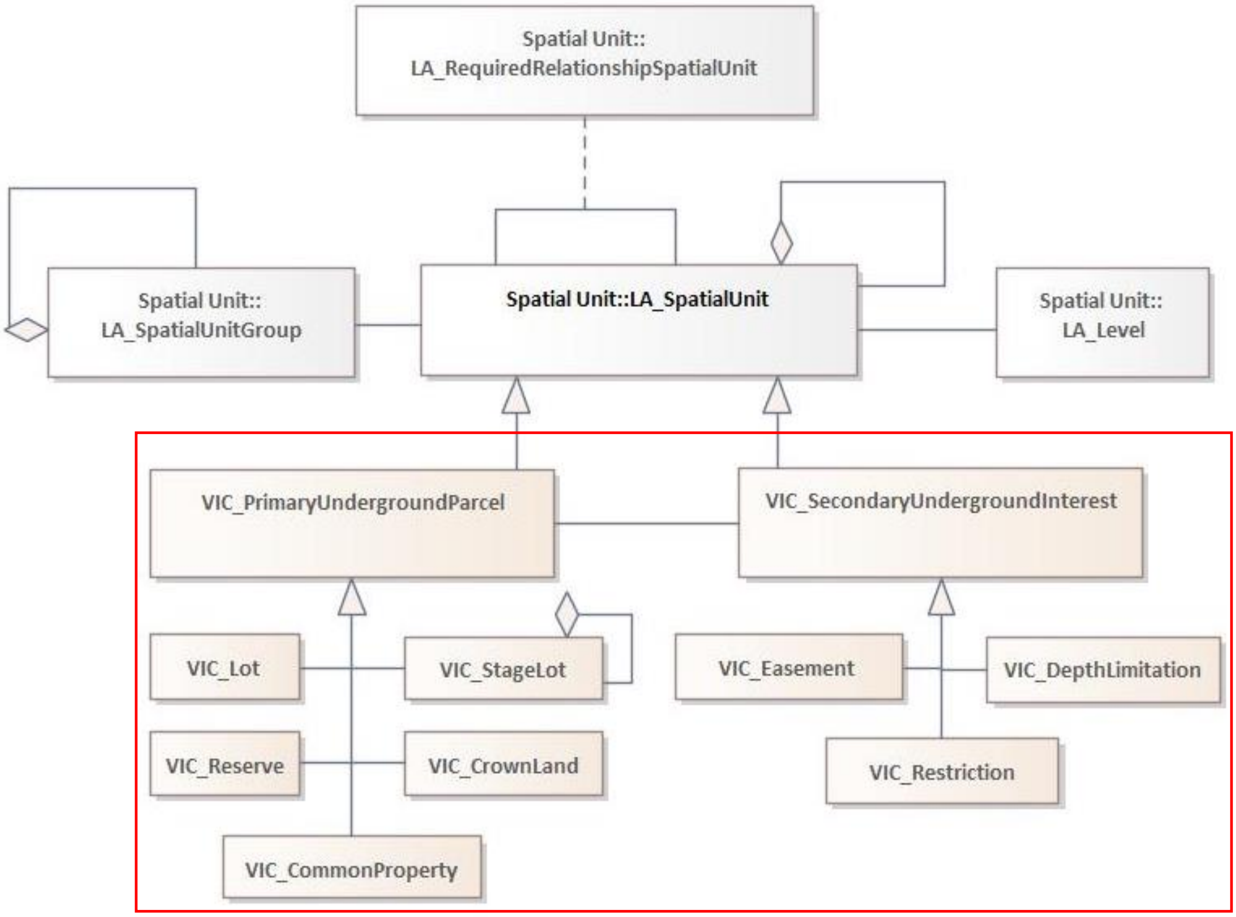


Figure 12. Extending LADM to support ULA legal objects in Victoria; "VIC_" is the prefix for the Victoria country profile

As mentioned in Section 4, spatial data is presented in different forms in subdivision plans. "LA_SpatialUnit" supports a wide range of representations such as text for annotations and lower and upper limits, 2D polygon, 2D topology, 3D topology and so on. Therefore, in this part, LADM can support all the requirements mentioned in Section 4. In LADM, information about measurements and observations is provided by "LA_SpatialSource". It should provide a range of underground measurements such as depth measurements by GPR, Gyro-based techniques, etc.

LADM uses external classes defined as <<blueprint>> to model physical objects. However, there are only two classes for utilities and buildings: ExtPhysicalUtilityNetwork and ExtPhysicalBuildingUnit. They are not adequate to model all underground physical assets. Figure 13 shows the proposed external classes to support all underground assets. Underground asset owners in Victoria are Electricity Generation, Transmission and Distribution, Tram and Rail, VicRoads, Local Authorities, Telecommunications, Private (e.g. lots, privately owned water pipelines, underground storage tanks), Gas Transmission and Distribution, Petrochemical, Oil, Water, Drainage and Sewerage (Victoria 2004). The building elements are also required to define legal boundaries.

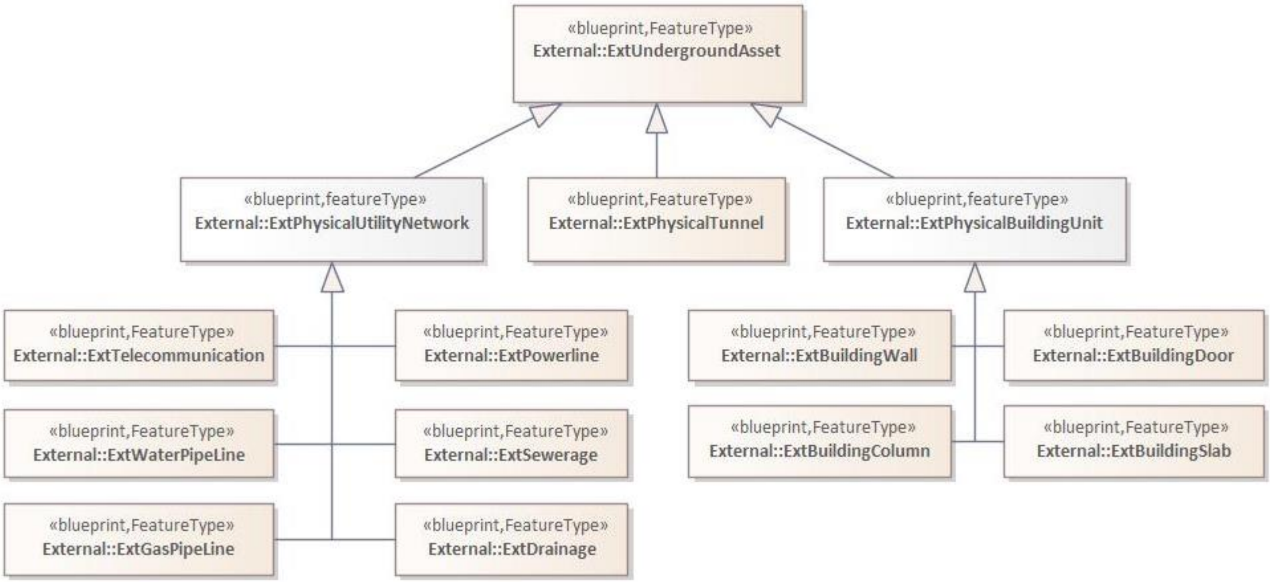


Figure 13. The proposed external classes to support ULA physical objects

The next step is the relationship between the physical objects and legal objects. In the current edition of LADM, legal spaces of utilities and buildings can link to their physical counterparts. In the Victoria country profile, legal spaces also need to be linked to their physical counterparts (Figure 14). As noted in Section 4.1.3 (underground legal boundaries), physical structures are necessary to define some underground legal boundaries. On the other hand, physical information and the link between legal and physical objects are the demands required from an integrated 3D underground data model for different use cases. To link legal spaces to their physical counterparts, the unique identities (IDs) of the physical counterparts must be specified as attributes of the legal spaces. All legal spaces are parcel-based; however, a long tunnel or pipeline can pass through several parcels. This physical tunnel or pipeline need to be defined as a single object, and it is not applicable to divide it by parcels. Assigning unique identities (IDs) to physical objects and specifying them as attributes of legal spaces can help link a single physical asset to all its legal spaces.

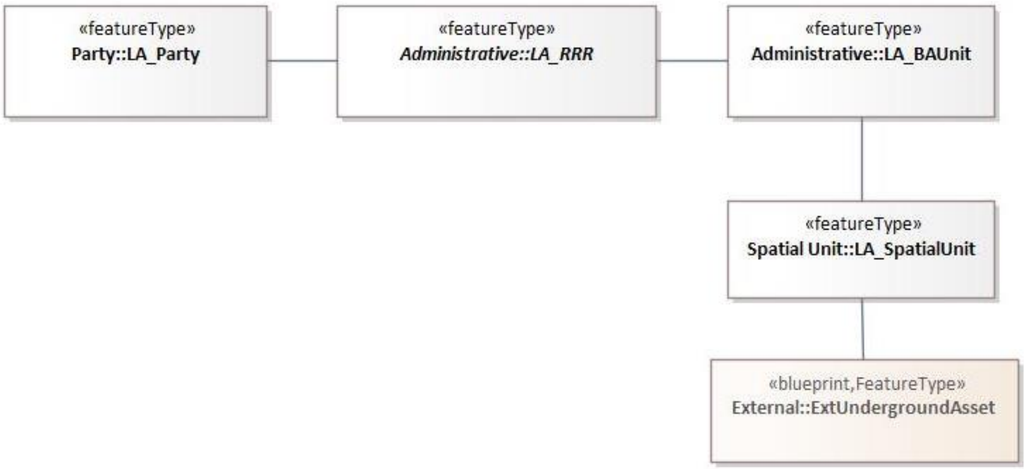


Figure 14. Relationship between legal and physical objects

6. CONCLUSIONS AND RECOMMENDATIONS

LADM is a prominent conceptual data model for 3D land administration. Several countries and studies have used it for 3D cadastral purposes. However, it does not fully support underground land administration in its current form. In addition, as an international model, this data model needs to be investigated and customised based on the requirements of jurisdictions. More importantly, this data model is a legal data model and does not support physical elements. Physical data is required to define some legal spaces and support other use cases of ULA. A few studies have suggested linking LADM with other well-known physical data models such as CityGML (Góźdź, Pachelski et al. 2014, Rönsdorff, Wilson et al. 2014, Li, Wu et al. 2016) and BIM (Oldfield, Van Oosterom et al. 2017, Atazadeh, Olfat et al. 2021). Linking LAMD with a physical data model through external connections has some challenges such as geometric conversion and semantic harmonisation (Atazadeh, Kalantari et al. 2017, Saeidian, Rajabifard et al. 2021).

This study focused on extending LADM to support underground physical data. LADM was investigated and expanded to cover the requirements of ULA in Victoria. Classes in the proposed data model are derived directly from LADM and be extended with new attributes and classes when needed. This study shows that it is necessary to consider physical elements in LADM. The data model proposed in this study can be used for expanding future version of LADM to cover physical data. It enables adopting LADM in implementing the 3D underground land administration systems in the jurisdictions where both surveyed and physical boundaries are utilised. This expansion also supports more use cases of ULA, unlocks the value of legal information beyond land tenure and covers other functions of ULA, including land use, land development and land value.

The data model proposed in this study is at the conceptual level. Future works will focus on real-world case studies and prototyping of the proposed data model. The prototype will provide an appropriate demonstration of the proposed 3D data model. Examples will include visualisation of a specific underground ownership space, determining the physical location of an underground asset, and identifying underground ownership boundaries. It is also necessary to test and evaluate the proposed 3D data model by key stakeholders in underground land and assets management and 3D data modelling experts. Finally, this paper did not investigate survey, administrative and party elements. They can be considered in the data model.

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