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From underground utility survey to land administration: An underground utility 3D data model

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ABSTRACT

Subsurface utility infrastructure is omnipresent in the often highly contested shallow layers of the subsurface of densely urbanised areas. Reliable information on the location of such utilities is pivotal for the planning and management of such space. Land administration tasks such as ownership management, land acquisition, planning and (re)development depend on and benefit strongly from the availability of reliable information of sufficient quality on the underground including utilities. The objective of the Digital Underground project in Singapore is to establish an authoritative dataset of underground utilities that aims to serve the needs of land administration practices. The work described in this paper aims to develop an underground utility 3D data model to manage and integrate various data from underground utility survey to underground utility data using in land administration. The Land Administration Domain Model (LADM) provides a formal language to manage the rights, responsibilities and restrictions information of land (or water), and the geospatial components. The Underground Utility Data Model (UUDM) inherits some definition from LADM to manage the information related to underground utility survey and land administration. This work provides a preliminary to explore the modelling and using underground utility information in land administration. It can help to develop the data model as a standard for underground utility data management and quality control in the next step.

1. Introduction

Reliable and accurate information on underground assets is of vital importance for the planning and management of land and the space below its surface. Underground utilities typically reside in the shallow part of such space. They are just one of its many competing uses, which include building basements and interlinking pedestrian corridors, piles, transportation infrastructure, and more (Chandran, 2019). The presence, layout, and organisation of underground utilities directly affect the value that the land can continuously deliver. It may limit the potential for future development and use or the capacity to host new infrastructure and may present significant obstacles, risks, and nuisances for owners, developers, engineers, and users of the land. It is reasonable to expect that the need for reliable information on underground utilities will become increasingly relevant as cities over the world continue to grow, densify, and change. Vertical and in particular underground development is a way to deal with the limited availability of land above ground. Furthermore, ongoing developments such as the introduction of new services such as 5G (Mims, 2019) and district cooling or heating systems (Bradley, 2020; Wee, 2017), the transition to non-fossil energy sources, and the need to replace existing ageing utility infrastructure will only increase the pressure on an often already congested underground space.

Some cities have responded to these challenges. The City of Helsinki released its first Underground Master Plan in 2011 (City of Helsinki, 2020) and aims to release a new plan at the end of 2020. The Municipality of Rotterdam has adopted an asset management strategy for the management of underground space and infrastructure. It has a specialised unit coordinating utility developments and the collection of survey data (Rotterdam, 2019). In Japan, the Road Administration Information Centre coordinates all utility works that occur on roads in metropolitan areas and, to support that, maintains a centralised dataset of all road and utility information (Zeiss, 2019). For the city-state of Singapore, "going underground" is one of its strategies to deal with limited land availability. The Master Plan 2019 (Urban Redevelopment Authority of Singapore, 2019a) highlighted underground space use as a means to create space for growing needs. The Urban Redevelopment Authority of Singapore (URA) furthermore mentions that planning the

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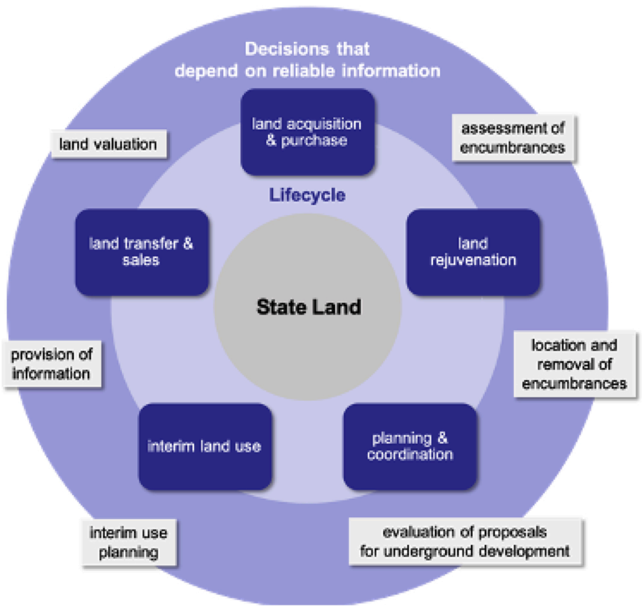


Fig. 1. The using of underground utility data in land administration (Schrotter and van Son, 2019).

underground space upfront in 3D based on BIM and GIS data and the mapping and dissemination of data on shallow utility lines are required to safeguard underground space for future uses and to eliminate uncertainty and risk during the planning process (Urban Redevelopment Authority of Singapore, 2019b). Besides master planning, reliable information on underground utilities is expected to continuously provide value throughout the life cycle of land assets.

As can be inferred from Fig. 1, from the acquisition to its eventual disposal or transfer of land, the availability and quality of information on underground utilities will affect the effectiveness and efficiency of various decision-making processes. For example, in land valuation for acquisition and purchase, assessment of encumbrances present underground that affect land value and may require land rejuvenation efforts. During the interim land use, it is necessary to assess the feasibility of underground utilities. The correct and complete information on land must be provided in land transfer and sale, including the location information and ownership of existing underground utilities (Yan et al., 2019a). Currently the management and maintenance of underground utilities are responsible by service company. In Singapore, the utilities themselves are not registered as legal objects under an authority as compared to cadastral lots. Even there is a changed law of underground space ownership in Singapore (Ministry of Law, 2015), it does not affect underground utilities directly. In a land-scarce city-state where close to 90% of all land is owned by the state, the value of reliable data is expected to be very high.

The primary underlying motivation for the recommendations is the issue that much of currently available data on underground utilities is of insufficient quality – in particular of insufficient locational accuracy. To ensure, improve, and reconcile locational accuracy, a variety of strategies and techniques are required. Furthermore, the quality or lack thereof is often unknown or undocumented and may lead to inappropriate use of the data in planning and land administration decision making processes. These issues are particularly challenging for underground assets: Since they are buried and therefore unseen and often inaccessible, there are limited to no opportunities to reliably and accurately re-survey the structures or verify and assess the quality of available data (Van Son et al., 2019). Another issue is that there is a significant latency between the actual construction of a utility and the structure being reflected in various datasets, which makes trouble to evaluate land value or redevelop urban. To help address these issues, Yan et al. (2019b) introduced a conceptual data model for the management, representation, and integration of underground utility data that incorporates three main components: utility assets, survey information, and land administration information.

This paper describes an extension of the model to incorporate detailed information to support the management and quality control of as-built survey projects. Additionally, the model introduces a temporal aspect to utilities that describe its status (planned, in development, and built). In this paper, Section 2 explains the requirements for an underground utility data model and reviews the related works and introduces the connection of the existing work and the underground utility data model, which includes the LADM and the Singapore cadastral data model. Section 3 introduces the details of the Underground Utility Data Model that focuses on the description of the physical characteristics of underground utility and survey information. And a demonstration aims to present the connection of underground utility and cadastral land parcel, and discuss the affection on the underground utility survey. At last, we conclude with a summary and an outlook on future work.

2. Related works

Some of the existing 3D city models have been extended to include the information of underground utility, such as the CityGML utility network Application Domain Extension (ADE) (Becker et al., 2011) and the Industry Foundation Classes (IFC) utility model (Liebich, 2009). Based on a comparison of the existing data models in the previous work (Yan et al., 2019b), it can be concluded that most existing work only focuses on 3D representation of underground assets but not quality or reliability. A new conceptual underground data model, which is called Model for Underground Data Definition and Interchange (MUDDI), has been developed by OGC (Lieberman, 2019). The goal of MUDDI is not to replace existing models but to serve as the basis for the integration of datasets from different models. Hence, MUDDI will connect to a series of candidate models, includes the CityGML Utility Network ADE and INSPIRE Utility Networks. The development of MUDDI is based on five essential requirements: functionality, compatibility, modularity, traceability and flexibility. From the geometric aspect, there are many similar characteristics of above- and under-ground utilities, especially for 3D visualisation. Hence, some of the existing data models can cover the utility networks above and under the ground. However, from the data acquisition aspect, it is much more difficult to get accurate data as the underground is unseen. To provide reliable information about the underground utility, a data model is necessary to integrate underground utility survey data and related survey information. Before describing the data model, the background and context of the data model are introduced. Starting with requirements, the following section proceeds to describe why and how the UUDM uses the LADM. It concludes with a review of Singapore's cadastral data model as it is expected that the UUDM links to the existing land survey and cadastral management in Singapore.

2.1. Requirements for an underground utility data model

For Singapore, to plan and manage land and its underground space and optimise its value, reliable and accurate information on underground utilities is essential. To achieve that goal, a data management system is required that supports data quality control, the verification and reconciliation of data quality, and management of the data as an authoritative source for use in planning and land administration applications. A data model is required to function as the core of that data management system. Currently, a standard data model is expected to support and incorporate a range of other data sources such as cadastral information, utility development plans and field observations. It needs to align closely with Singapore's existing utility survey standards. Taking inspiration from the LADM and echoing or extending upon some of its requirements, the following illustrates seven critical requirements for

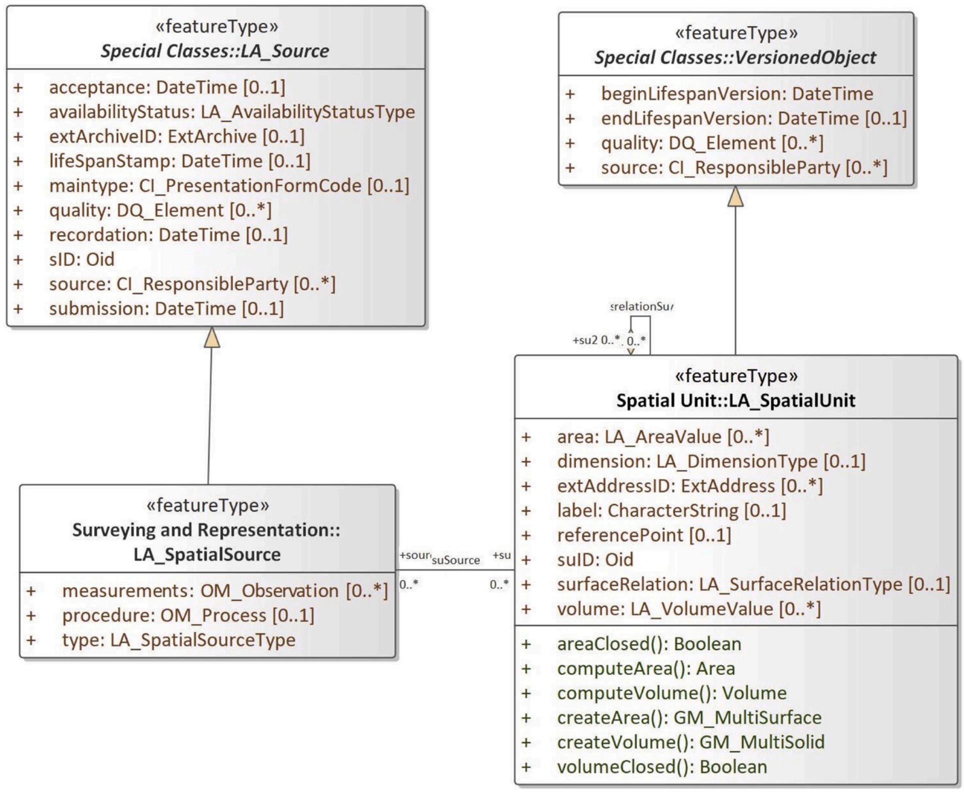


Fig. 2. The part of LADM is inherited in the UUDM.

the data model based on our previous studies of roadmap (Schrotter and van Son, 2019).

- **Location.** Accurate locations and other spatial attributes that describe the physical structure of an asset, where it is and what extent of space it occupies (e.g. the diameter of a pipe) are the most important aspects to capture about utilities in the data model. Specific other attributes are irrelevant and need not be supported initially. For example, attributes that describe the topology of a utility network.
- **A range of data acquisition methods.** The data model should incorporate the range of data acquisition methods that are supported by Singapore's utility survey standards and specifications (Singapore Land Authority, 2017). It includes those that are currently used and supported, i.e. total station and GNSS RTK. However, it should also be extendable to include other methods if and when they become supported. Examples of these methods are gyroscopic mapping for utilities built using horizontal directional drilling and non-destructive geophysical surveying techniques for detection and mapping existing utilities.
- **Supporting data for data acquisition methods.** To enable quality control of incoming data, supporting data is required that describes that the work was done according to standardised operating procedures or that the accuracy of surveyed locations is sufficient.
- **A range of data sources.** The data model should support a potentially ever-extending range of data sources. These should primarily include the as-built survey for newly built utilities. However, other sources that describe the location of underground utilities also need to be considered to provide a complete picture of what lies beneath. These include existing records from utility owners and planned or designed alignments for future utilities. There are also sources that, rather than describing the location of underground utilities, describe something about the said location. Trial trenches, for example, are required to be excavated before any earthworks to verify the location of existing utilities and may contain valuable observations.
- **Temporal aspect.** The data model should manage the temporal aspects of data. Data may be collected and integrated at various points during the lifecycle of a utility asset (e.g. at the planning phase, directly after installation, or many years into an asset's operation). A second temporal aspect to consider for the data model is that many underground utilities are installed and surveyed progressively as part of a larger project, which may take several months or years to complete. In current practices, survey results typically are not collected until after the completion of the project. The data model should therefore support the progressive collection of data in order to avoid the latency caused by the time difference between utility installation and project completion. Lastly, end users in the planning and land administration domain typically make decisions for the future. Therefore, the data should not only be able to represent the current state of the underground, but rather the most likely expected state for the moment that the decision is made for.
- **Lineage.** Closely tied to the temporal aspect is that of lineage. Data may undergo various changes as it is updated based on surveys and other data sources. Capturing and understanding the various changes and processing steps that the data has undergone is necessary to accurately assess the quality of the data that is delivered to users of the data.
- **Quality.** Ensuring data quality is a key objective of the data management system and the data model. The most important factors of quality are locational accuracy, currency, and completeness. The quality of the data therefore needs to be described through a quality classification system. Furthermore, the classification system needs to distinguish between classification for data quality management purposes and classification for end users, where data quality needs to be related to directly to its suitability to support certain processes.

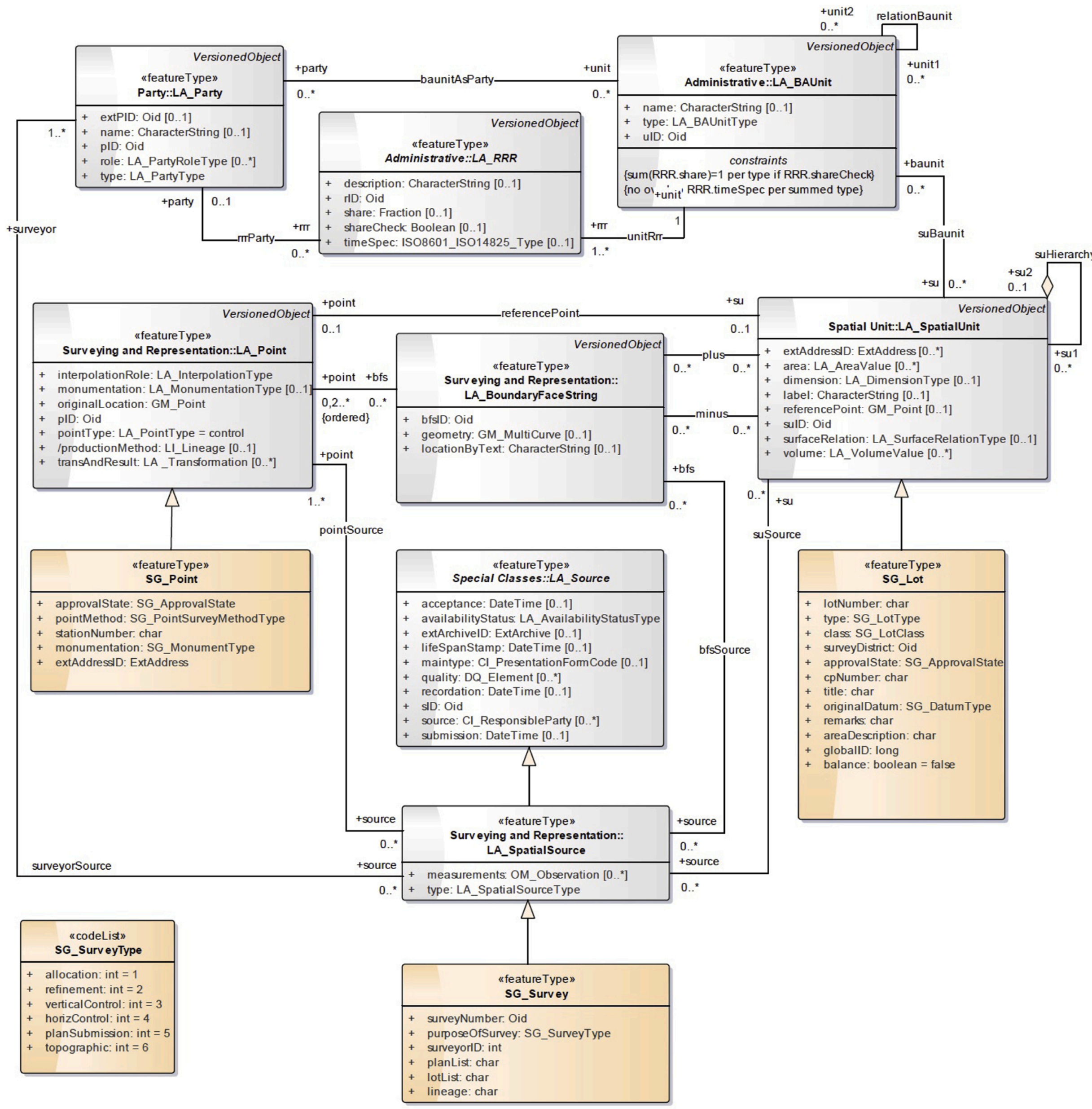


Fig. 3. The survey and spatial definition in the Singapore cadastral data model (source: Singapore Land Authority).

2.2. *Review of the Land Administration Domain Model (LADM)*

The LADM (ISO 19152) (Van Oosterom et al., 2012) is a flexible conceptual model to provide a formal language for describing information in the land administration domain. This International Standard focuses on rights, responsibilities and restrictions affecting land (or water), and the geometrical (geospatial) components with four packages:

- parties (people and organisations);
- basic administrative units, rights, responsibilities, and restrictions (ownership rights);
- spatial units (parcels, and the legal space of buildings and utility networks);
- spatial sources (surveying), and spatial representations (geometry and topology).

Generally, the LADM provides a well-developed set of classes to model both spatial and non-spatial information in the land administration domain. The research activities surrounding LADM have covered some topics from legislative aspects about terminology and rights to data management and visualisation (Paulsson and Paasch, 2015). Meanwhile, through integration of 2D and 3D information, the LADM provides the solutions for a 3D cadaster. Additionally, the LADM uses the *VersionedObject* class to manage and maintain historical data in the database. History requires, that inserted and superseded data, are given a time-stamp. In this way, the contents of the database can be reconstructed, as they were at any historical moment. Fig. 2 shows the main LADM classes are inherited by UUDM.

Currently, several land survey or 3D cadastral works uses the LADM. Some countries already developed a country profile for land administration based on the LADM. The Netherlands has developed a Valuation Information Model based on the LADM, which aims to specify the semantics of registries used in immovable property valuation activities and relations between these registries (Kara et al., 2019). Malaysia developed a 3D national digital cadastral database based on LADM to

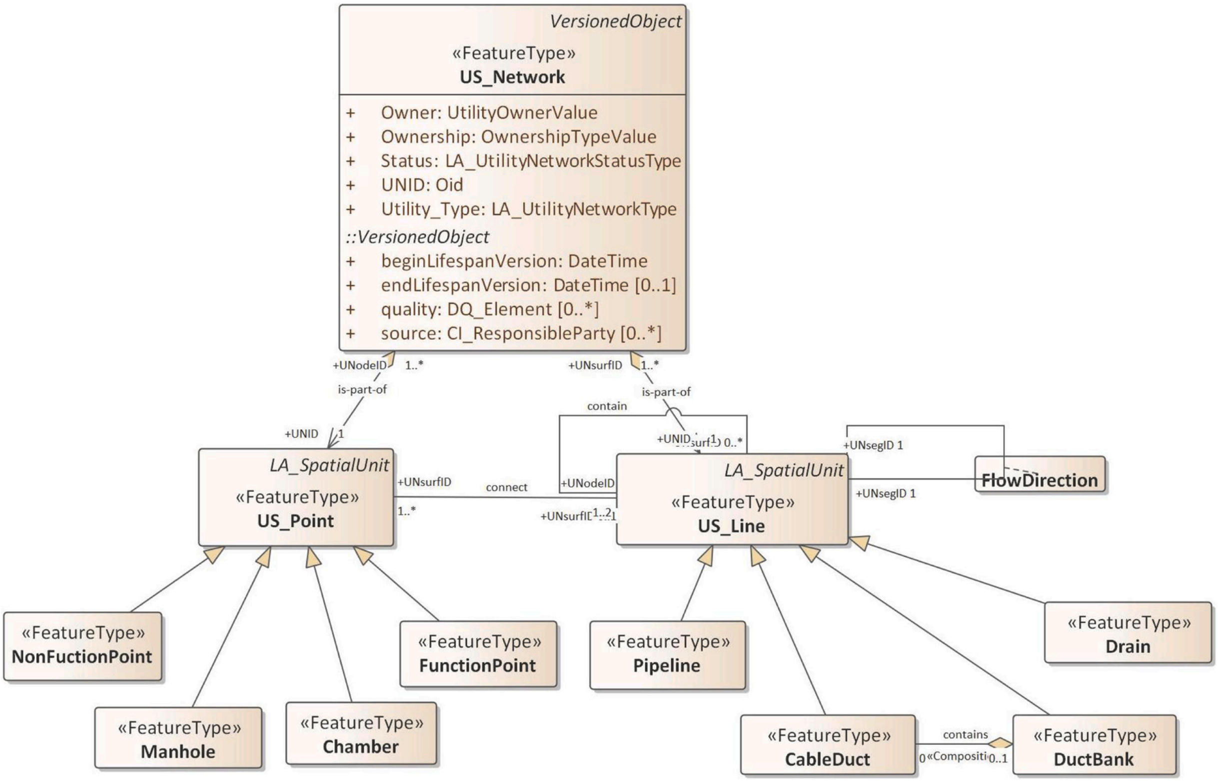
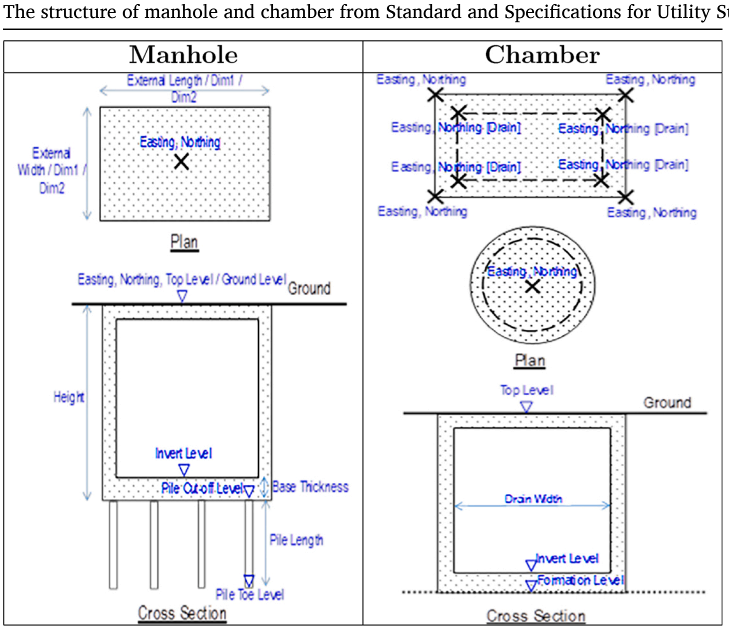


Fig. 4. The Utility Core package.

upgrade 2D to 3D environment (Rajabifard et al., 2019). The Polish cadastral model was developed to reduce data redundancy and may facilitate cadastral data transfer and exchange between different countries (Bydlosz, 2015). The Israel developed a new 3D data model and 3D land administration system for the representation and management of 3D cadastral data (Jaljolie et al., 2018). Based on LADM, Kim and Heo (2017) proposed a new concept of 3D underground parcel and developed a 3D underground cadastral data model to register and manage underground space. This is a good beginning of land administration of under-ground property. All of these existing work provide the useful practice to expand cadastre from 2D to 3D. But none of them consider underground utility in the land administration. The LADM uses the *LA_LegalSpaceUtilityNetwork* and *ExPhysicalUtilityNetwok* classes to describe utility networks. Some general attributes have been defined to describe utility networks and support for land administration, such as type, status and direction of utility networks. In the LADM country profile of Serbia, utility information has been included for a utility network cadastre (Radulovic et al., 2019)), supporting the development of a system for registration and maintenance of ownership of underground utility networks.

Table 1
The structure of manhole and chamber from Standard and Specifications for Utility Survey in Singapore (Singapore Land Authority, 2017).



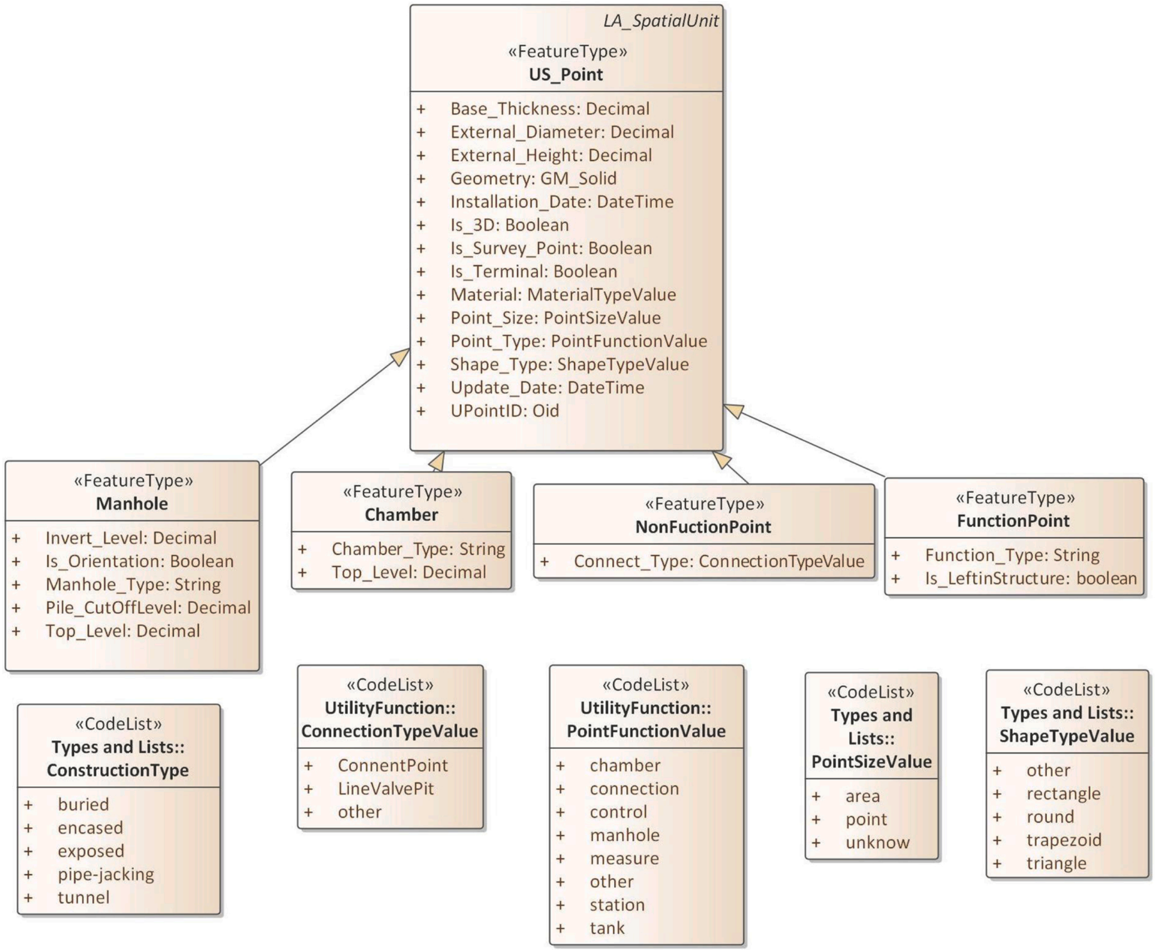


Fig. 5. The *US_Point* class and its subclasses.

The LADM plays a vital role to support land survey and land administration in 3D. The UUDM inherits the geometry description of spatial units from LADM. Additionally, the UUDM inherits the *VersionedObject* class to manage historical data. Nevertheless, the general definition cannot describe the structure and geometric information of utility networks. The LADM lacks the information about underground utility survey information in the data model, especially the new technology of underground utility survey. The integration of the existing and newly collected underground utility data and data quality management are still the challenges in the development of underground utility data model.

2.3. Singapore cadastral data model

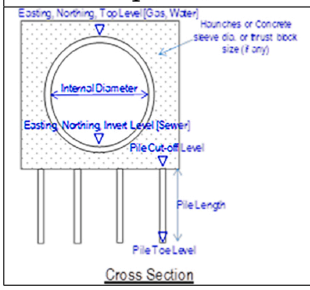
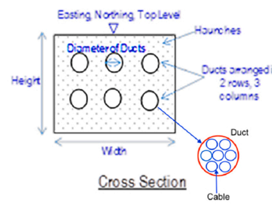
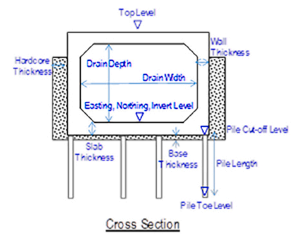
The Singapore cadastral data model is developed as a country profile using LADM objects, attributes and relationships where possible, and implementing new items where necessary. It uses administrative, party, and spatial packages to manage cadastral data in Singapore. Fig. 3 provides an overview of the Singapore Cadastral Data Model about the survey, surveyor and spatial information. As an important class, the *SG_Lot* has been defined to describe the spatial unit. It is an extension of the *LA_SpatialUnit* class that inherits all attributes and methods while adding attributes specific to Singapore. The *SG_Survey* class aims to describe the land survey project in Singapore. The surveyor is defined as a party to connect registry objects and information of Registered Surveyors. The Singapore cadastral data model inherits the *VersionedObject* class to manage historical data.

Currently, the Singapore cadastral data model does not include information about underground utilities. Same as most of the other countries in the world, Singapore lacks reliable information about underground utilities, which can support efficient decision-making, cost saving, and additional revenues for land administration professionals. Our previous work gave an introduction of the urgent needs of reliable underground utility information to support land administration in Singapore (Yan et al., 2019a). Hence, the UUDM is necessary to connect SG cadastral data model to manage the underground utility information for land administration in two main aspects. One is to connect the underground utility surveying and cadastral land surveying. The other is to find the spatial relationship between land parcels and underground utilities. The connection details of UUDM and SG cadastral data model are described in the following sections.

3. The Underground Utility Data Model (UUDM)

A conceptual design of underground utility 3D data model has been proposed in the previous work (Yan et al., 2019b). The detailed design of the underground utility data model (UUDM) focuses on two main aspects: 3D geometric and functional information of utilities, and survey information. Currently, the UUDM describes two types of temporal information. The first is the timestamp of data to manage the historical data. The other is the timing of utilities construction and surveying project progress. The Utility Core package describes the necessary information of utility survey networks in three levels: geometric, spatial and physical information. The Utility Survey package organises utility survey information in the utility survey project. In addition, the utility survey can be connected to land survey in order to explore the

Table 2
Vertical structure of underground utility lines (Singapore Land Authority, 2017).

Pipeline	Duct Bank	Drain
		

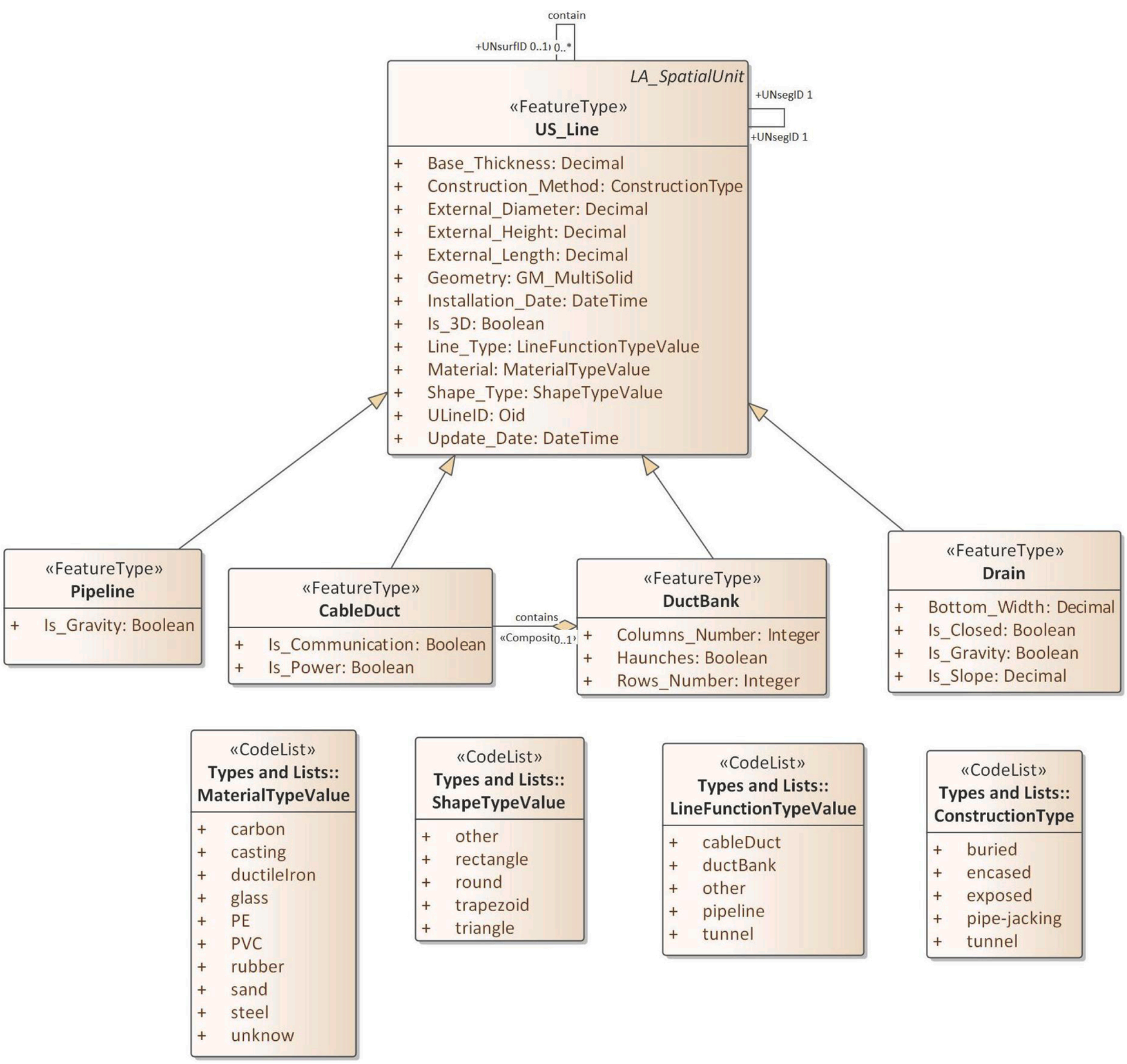


Fig. 6. The *US_Line* class and its subclasses.

interdependence of underground utilities and land parcels. The details and definitions of each package will be presented in the following sections.

Generally, there are two main types of definitions that are inherited from the LADM. One is the geometric and spatial definition from LADM. The other is the timing attributes of data from LADM to manage and maintain historical data. The other generic attribute values use the definition from ISO/TC 211 Geographic information/Geomatics standard,[1] such as units of measure and date.

[1] www.iso.org/committee/54904.html.

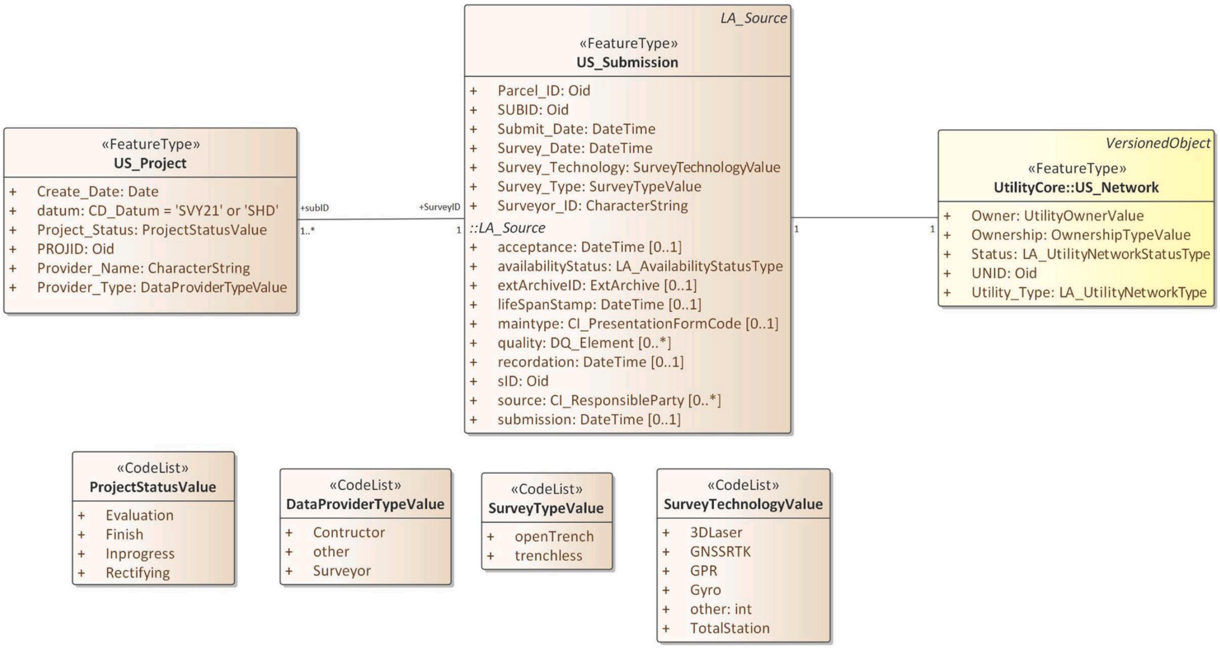


Fig. 7. The Utility Survey package.

3.1. *The Utility Core package*

Based on the partonomy (part-whole) relationships, this work defines the hierarchy of utility networks in three levels. Fig. 4 is the class diagram of the Utility Core package with code lists, and presents the relationships of different classes. The macro-level is the group of the utility objects in each surveying, which is called *US_Network* class. The *US_Network* class describes the general information of the utility survey network, includes owner, ownership, type and status of underground utilities. The utility survey network means the whole dataset in a utility survey project is an independent utility network. It could be one utility line with two utility points, or several utility lines with several utility points. Therefore, the *US_Network* class is composed of two sub-classes at the meso-level: *US_Point* class and *US_Line* class. Each class has a primary attribute to store the identification ID of each object. Each class of the meso-level has sub-classes at the micro-level to describe specific underground utility objects. The *US_Network* class inherits the *VersionedObject* class of LADM to manage the historical data.

The Standard and Specifications for Utility Survey in Singapore (Singapore Land Authority, 2017) require surveyor to submit the essential attributes of underground utility point feature and specific attributes related to the different types of utility objects. Table 1 displays the structure of manhole and chamber. Even both of them are point feature, there are some difference between them and the connection point feature without any functions in the utility network. For example, the top level and invert level are specific attributes of the manhole. Therefore, the *US_Point* class describes the general characteristics of point feature. And four subclasses describe the specific characteristics of utility survey point feature based on their functions.

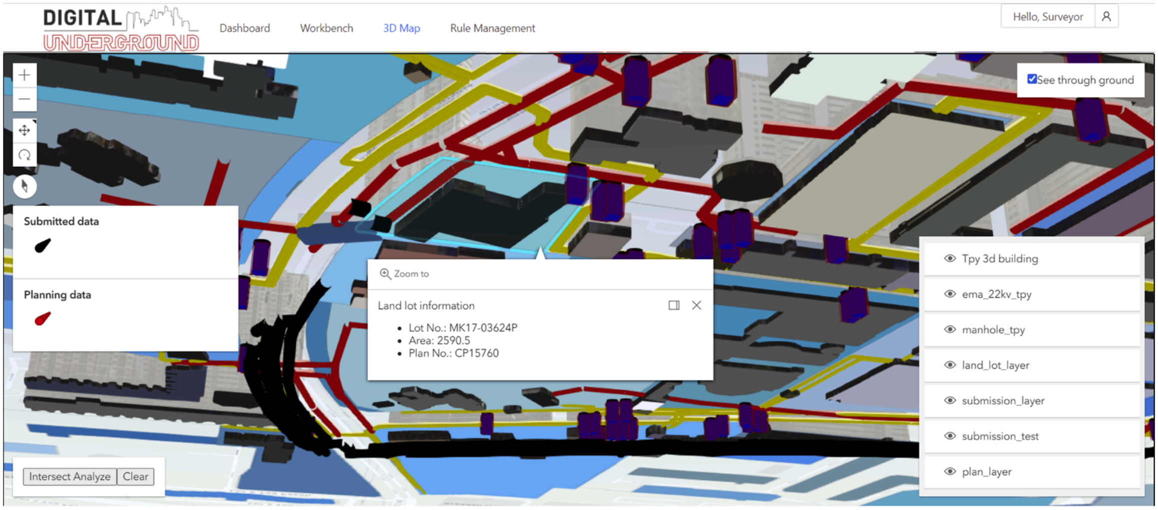
Fig. 5 shows the structure and attributes of he *US_Point* class with four subclasses. It includes height, inner diameter, thickness, shape, material and so on. Also, there are two timestamp attributes to describe the timing of utility construction, install time and maintain time. The *is3D* attribute is defined as a label to distinguish the 2D and 3D data. Each utility survey point connects to 1 or more utility survey lines. The *NonFunctionPoint* class describes connection point without any functions in the utility network, such as pipeline joint. The manhole and chamber are widespread underground utility point objects. Hence, the separate class is defined to describe the specific attributes of different types of utility, such as the *Manhole* and *Chamber* classes. The *FunctionPoint* class is described as the other general utility point objects which have the functions in the underground utility network, such as air valve. The *functionType* attribute can use string to describe the function type of point feature. The geometric attributes are inherited from *LA_SpatialUnit* class of LADM.

The utility survey line is the line feature in the utility network. According to the Standard and Specifications for Utility Survey in Singapore (Singapore Land Authority, 2017), line feature not only has general characteristics, but also has specific characteristics related to their functions. Table 2 shows the structures of pipeline, duct bank and drain (Singapore Land Authority, 2017). Hence, the *US_Line* class defines the general attributes of line feature at the meso-level, and four subclasses describe the specific attributes of line features at the micro-level (Fig. 6).

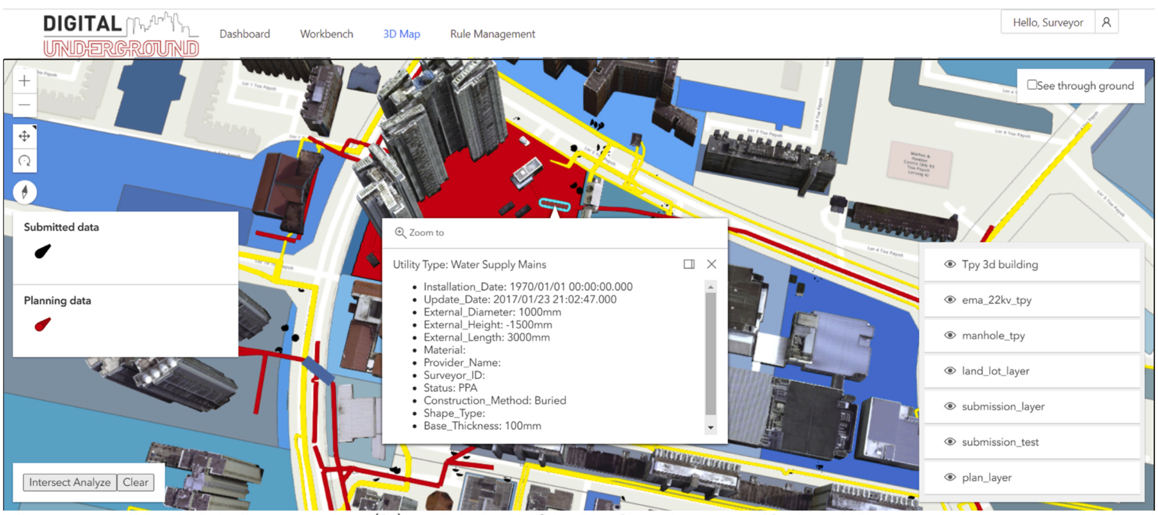
The general attributes of the *US_Line* class include inner and external diameters, height, material, shape and line type. It also has two timestamp attributes to describe the timing of utility lines construction and maintenance. Each line feature connects to 1 or 2 point features. There are two self-associations of the *US_Line* class. One contains the relationship of line features. A utility line feature might contain 0 to several lines. The other is to describe the flow direction. SourceID is the utility line ID of flow in, and SinkID is the utility line ID of flow out. The subclasses focus on the definition of the underground utilities' function. The *Pipeline* class describes the pipes that are used in the water and sewer domain. The *DuctBand* class describes the space includes a group of cable ducts, which includes the number of columns and rows of ducts inside a duct bank. (Table 2). The *CableDuct* class aims to describe the duct that contains a group of cables. The *Drain* class describes an ample space of drain line.

3.2. *The Utility Survey package*

The Utility Survey package aims to organise underground utility survey information. It could help to manage survey status and progress. Fig. 7 describes the relationship, attributes and codelists in the Utility Survey package. There are two main classes in this package. The *US_Project* class aims to describe survey information in each utility surveying project, which includes project id, data provider information,



(a) 3D view from underground



(b) 3D view from above ground

Fig. 8. 3D visualisation of underground utilities with the land parcel.

and coordinate system that has been used in the surveying. In Singapore, the requirement of geodetic datum is SVY21. The *US_Submission* class aims to describe the details of the survey in each submission. Each submission has a unique id as well. Because of the accuracy of underground utility data is related to surveyor's experience and survey technology, surveyor information should be stored, such as surveyor ID and survey technology. The underground utility survey is different from the land survey. Therefore, the survey type is described as open trench, trenchless technology and others. Meanwhile, the survey project uses survey time to manage progress. Each survey project has one or several submissions. In addition, each survey project might connect to 0 or several land survey projects, which helps to build a relationship between the land survey and underground utility survey. Each submission must connect to a utility survey network as well. In order to use LADM to manage historical data management, the *US_Project* and *US_Submission* class inherit from *LA_Source* class in the LADM.

3.3. A demonstration and discussion

Even though much of the existing information on underground utilities may not be accurate, a baseline is required as a point of initialisation for the consolidated database. Here is a demonstration to visualise the underground utility data and land parcel based on the UUDM. It aims to show how the UUDM works with the land parcel for land administration and discuss how is the UUDM compliant with the Singapore Utility Survey Standard.

Singapore has a geospatial database to share the data between the government agencies, which is called GeoSpace (Singapore NSDI). Most of the existing utility data in GeoSpace database are 2D as-built data includes water supply, sewerage, drainage, telecommunication and power grid networks. Fig. 8 shows an example of 3D visualisation of underground utilities in which red lines are planning utility data, black lines are newly submitted utility data and purple polygons are land parcel with cadastral information. It is easy to query the information of land parcel and the related underground utilities through the spatial relationship of them.

The cadastral information of selected land parcel can be visualised in Fig. 8(a). The attributes of related utilities are shown in Fig. 8(b). The selected utility locates inside the selected land parcel and is a water supply main. As the current cadastral data is 2D in Singapore, the basic spatial relationships (e.g. within and cross) are used to query the relationship of land parcel and the underground utilities. In order to use the information of underground utility in land administration accurately, the 3D cadastre is necessary. Compared to the required data attributes in Standard and Specifications for Utility Survey in Singapore (Appendix A), most of the general attributes are considered in the UUDM, except for the quality information of data. The data quality validation is a significant operation that will be considered in the next step. Meanwhile, the values of some attributes are empty in this demonstration, such as material. Even these values might not come from the survey, they are the critical information of underground utility that should be stored in the database. A data exchange process will be developed to transform submitted survey data to the underground utility database. In addition, the required submission data format should be GML and Esri Shapefile (.shp) format.

4. Conclusions

This work designs an underground utility 3D data model to manage the underground utility survey data and survey information. It aims to fill the gap between the underground utility survey and the using of data. Hence, two main categories of information have been organised in this data model, geometric information in the Utility Core package and survey information in the Utility Survey package. The Utility Core package defines three levels to describe the whole utility survey network. The macro-level is the definition of the utility networks. The meso-level focuses on the general geometric information of utility objects. Moreover, the micro-level describes the specific function information of utility objects. This data model could be used as a standard when the surveyor submits the data. Meanwhile, it can help to manage the historical data.

The current design of UUDM has not cover the whole process of data management. There are some aspects that need to be considered in future work. The data quality control is a big challenge in the 3D mapping of underground utility. The UUDM should play an important role to support data validation and assessment. For future work, we describe how new types of spatial sources that become available at different moments in time, such as plan drawings and field observations, can be integrated into the model to develop a complete picture and support quality control and reconciliation efforts. Apart from this, the metadata is sorely needed by the data using and management. For example, the data administrator and users need to know the information about data lineage and the meaning of data quality classification. Therefore, the UUDM will be extended to include data quality control and metadata management in the next step. The analysis of interdependence between above-ground infrastructure and underground utilities is a potential application in future work.

Authors' contribution

Jingya Yan: conceptualisation, methodology, writing – and editing original draft preparation. Rob Van Son: writing – original draft preparation of Sections 1 and 2, reviewing and editing. Kean Huat Soon: conceptualisation, writing – reviewing and editing.

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Appendix A. An example of the required attributes in Standard and Specifications for Utility Survey in Singapore

Water supply mains/lateral lines (line)	
Geometry	Requirements
X	Easting, Northing To be captured at: - For straight lines: not exceeding 20 m intervals
Y	- For curved lines: as determined by the Registered Surveyor - Salient points, such as bends, tees, control valves, air valves, washouts, meters
Z	Top level of pipe with respect to Singapore Height Datum(SHD) Unit: m To be captured at: - For straight lines: not exceeding 20 m intervals - For curved lines: as determined by the Registered Surveyor - Salient points, such as bends, tees, control valves, air valves, washouts, meters Data type: double (to 2 decimal places)

Attribute name	Attribute domain (exhaustive)	Requirements
Nominal diameter		Unit: mm Data type: Integer
Quality	1, 2, 3, 4, 5	1: ±100 mm 2: ±300 mm 3: ±500 mm 4: unknown accuracy 5: trenchless method All new lines/points must be surveyed to ±100 mm accuracy, unless otherwise permitted by the Utility Agencies for special circumstances. Data type: integer
Date of Last Survey		Data type: DATE (in DD/MM/YYYY)
Surveyed by		RS company name Data type: String
Status	Ins, PPA, APP, ABD	Data type: string
Type	Buried, exposed, pipe-jacking, tunnel, encased	Refers to construction method

(continued on next page)

(*continued*)

Attribute name	Attribute domain (exhaustive)	Requirements
Water type	0, 1, 2, 3	Data type: string 0: Industrial 1: NEWater 2: Raw 3: Potable Data type: integer
Lateral type (for lateral lines only)	Hydrant, meter, air valve, washout	Refers to connection pipes to meters, hydrants, air valves, washouts Data type: string
Date of installation		Data type: date (in DD/MM/YYYY)

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.landusepol.2020.105267.

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