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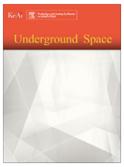

Review Article

# Building information modelling for 3D underground land administration: Research challenges and future pathways

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## Abstract

Underground land and property information is currently recorded, registered, and managed using two-dimensional (2D) datasets provided in survey plans. There are significant communication challenges associated with fragmented 2D land and property data in complex underground projects. On the other hand, building information modelling (BIM) has been adopted for three-dimensional (3D) digital management of the lifecycle of built assets, including those of underground infrastructure. BIM can potentially provide a fully integrated 3D representation of rights, restrictions, and responsibilities for underground assets. Therefore, this study investigates the potential of BIM to support the development of 3D underground land administration (ULA) through an integrated data modelling approach. By reviewing the current body of knowledge, research challenges, and future pathways for adopting BIM-based approaches for 3D ULA data management are identified, specifically across legal, institutional, and technical dimensions. One key finding is the critical transition from current 2D approaches to BIM environments. This will lead to integrated and smooth information flow, which is critically important for more efficient ULA practices, enhancing communication among various stakeholders, improving decision-making in ULA, and contributing to sustainable underground space planning and development.

*Keywords:* Underground land administration; Underground infrastructure; 3D ULA; 3D data model; Underground data model; Building information modelling

## 1 Introduction

In recent decades, cities are increasingly expanding underground due to urbanization. This is driving an escalating need for precise and holistic information regarding subterranean land and property assets, especially since a significant number of utilities and service networks are located underground. For instance, in Melbourne, Australia, underground infrastructure spanning approximately 740 000 km is valued at over $340 billion, including the Melbourne Central railway station shown in Fig. 1 (Department of Infrastructure, 2022). As another example, over 99.9% of buildings in Tokyo, Japan, including the Tokyo Skytree (Fig. 2), have basements up to four stories (Peng et al., 2021).

Underground land administration (ULA) refers to the subdivision, registration, and continual management of rights, restrictions, and responsibilities (RRRs) associated with stratified private, public, and communal properties in underground environments (Saeidian et al., 2021, 2023a). A significant issue associated with two-dimensional (2D) datasets used for ULA is their inability to provide fully integrated representations of the complex geometry of RRRs in underground structures, such as tunnels, utility networks, and train stations (Aien et al., 2011). This issue challenges the comprehensibility of 2D underground land and property information. This is especially true when it comes to connecting underground assets to the surface parcels. These parcels are typically the spatial representation of the cadastre within information systems,

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Fig. 1. Westbound view of Melbourne central railway station, Australia.

Fig. 2. Basement of Tokyo Skytree, Japan.

highlighting the need for more sophisticated approaches. To address the limitations of 2D representations, three-dimensional (3D) environments present a significant advancement in managing underground space for sustainable urban development (Rajabifard et al., 2019; Kalogianni et al., 2020a). Therefore, the transition from 2D to 3D ULA is crucial for the sustainability of ULA practices, driven by the escalating importance of underground space in urban development and the increasing demand for precise, holistic underground land and property information. This transition is predicated on the fundamental role of data modelling for ULA purposes such that physical and legal data related to underground assets should be integrated (Saeidian et al., 2021).

Building information modelling (BIM) stands out for its comprehensive representation of built assets by providing rich geometric and semantic information (Kalogianni et al., 2020a; van Oosterom, 2018). Additionally, BIM's capability for high-quality visualizations facilitates an integrated understanding of legal and physical aspects of underground assets (Atazadeh, 2017). Importantly, the interoperability of BIM with other 3D data models such as land administration domain model (LADM), CityGML, and LandInfra is critical for 3D data integration in ULA (Ramlakhan et al., 2021).

BIM not only improves the visualization and integration of physical and legal data but also contributes to the sustainability of subterranean spaces by facilitating more efficient maintenance, resource allocation, and risk mitigation, ensuring long-term resilience of underground infrastructure (Zhou, 2024). Moreover, BIM could enhance information flow in the lifecycle of underground assets, thereby supporting more efficient communication and collaboration over the course of underground projects (Zhu & Wu, 2022). Thus, BIM's lifecycle support and detailed visualization indicate its suitability for 3D ULA (Kalogianni et al., 2020b).

There are several studies related to legal and physical aspects of underground assets (Atazadeh, 2017;

Kalogianni et al., 2020a; Peng et al., 2021). Nevertheless, most of these studies focus on 2D datasets derived from underground survey plans (Atazadeh et al., 2019a; Saeidian et al., 2021). In addition, there are limited investigations on the BIM-based approaches for 3D digital representation of the legal ownership of underground assets. Therefore, there is a knowledge gap in adopting BIM for modelling legal spaces and boundaries of underground assets to support 3D land and property data management in ULA. BIM plays an important role not only in the Architecture, Engineering, and Construction (AEC) industry, but its potential benefits extend to other domains, including land administration and asset maintenance (Atazadeh, 2017; Barzegar et al., 2021). Therefore, this research aims to identify the current challenges in three main aspects, namely legal, institutional, and technical, for employing BIM-based approaches to 3D data management in ULA by reviewing existing literature. In addition, the potential solutions for adopting BIM for 3D ULA will be outlined to highlight future research pathways. A BIM-driven approach for 3D ULA is essential for managing the legal and physical complexity of subterranean assets.

The paper is structured as follows. First, the methodology is described in the next section, applying the preferred reporting items for systematic reviews and meta-analyses (PRISMA) method for reviewing and analysing the related literature. Section 3 provides a definition of ULA as part of the general land administration. In addition, two main categories of legal and physical data are explained to highlight the necessity for a transition from 2D to 3D digital data management. Furthermore, Section 4 provides an overview and analysis of current 3D data models that can be adopted for ULA. Section 5 specifically describes BIM for 3D ULA and identifies current challenges in legal, institutional, and technical aspects. Based on these challenges, Section 6 gives a discussion of potential solutions to guide future research pathways in adopting a BIM-based approach for 3D ULA. Finally, Section 7 provides the main findings and conclusions.

## 2 Review methodology

PRISMA aims to standardize the reporting of systematic literature reviews and ensure research transparency (Page et al., 2021a). In this study, various studies on BIM in ULA are reviewed and synthesized to explore research challenges and future directions. At the same time, the PRISMA method could be used to systematically collect, screen, and synthesize relevant literature, thereby improving the credibility and applicability of the research (Page et al., 2021a, 2021b). The effectiveness of PRISMA lies in its rigorous methodology, including comprehensive search strategies and transparent selection criteria (Page et al., 2021b). Therefore, PRISMA is an appropriate methodology for this paper to review existing literature and identify challenges to highlight future pathways of BIM for 3D ULA. Using PRISMA, the methodology of this research is structured into 3 main steps as follows.

Step 1: Eligibility criteria

All original studies investigating 3D approaches, including BIM, for both above-ground and underground land administration, were eligible for this study. Further criteria adopted in this study are:

(i) Publication date between 2018 and 2025. This is to ensure that the research is timely, accurate, and sensitive to emerging trends in ULA. Such selection criteria aim to build a solid theoretical and methodological foundation to support the achievement of research objectives.
(ii) Written in English. The selection of English literature as the research base is due to its wide international acceptance, the richness of academic resources, and the consideration of improving the transparency and inclusiveness of the research. Such criteria could ensure effective communication and impact of this study in the international academic community.
(iii) Published in a scholarly peer-reviewed journal and international conference. This is based on the consideration that the selected literature can provide quality-assured, credible, up-to-date, and influential research results.
(iv) Conducted a review of case studies and evaluations for ULA. This criterion provides in-depth insights into the complexities of ULA by investigating the case studies in different jurisdictions.

Therefore, these criteria form a comprehensive and balanced research method strategy to ensure that this study is academically rigorous, practical, and has an international perspective.

Step 2: Information sources and search

Four types of information were reviewed, namely scientific publications, government publications, organizational reports, and online resources. Specifically, for the various types of scientific publications, which have been highlighted in this study and were retrieved from Google Scholar, Scopus, ResearchGate, International Federation of Surveyors (FIG) archives, and 3D cadastre literature webpage (https://www.gdmc.nl/3dcadastres/literature), as well as related international journals and conferences. The initial screening of documents involved an assessment of titles and abstracts to verify their relevance to this research. Key terms used for this preliminary evaluation included ‘Underground Land Administration’, ‘Underground Boundaries’, ‘3D Legal Spaces’, ‘Subsurface’, ‘3D cadastre’, ‘3D land administration’, ‘3D Data Model’, ‘Building Information Modelling’, ‘BIM’, ‘Industry Foundation Classes’, and ‘BIM/ Industry Foundation Classes (IFC)’.

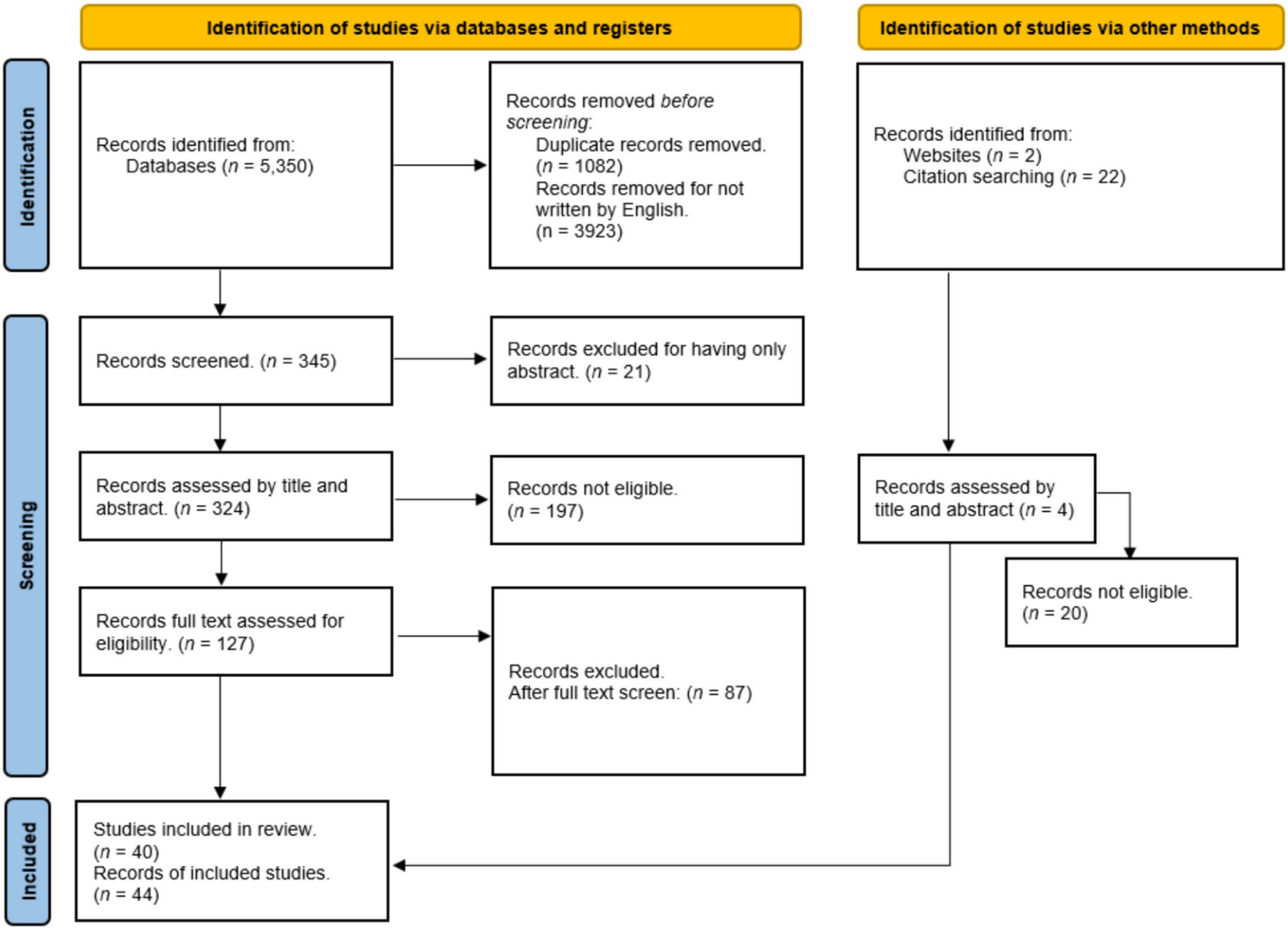


Fig. 3. PRISMA flow diagram for literature review.

Step 3: Study selection processes

The PRISMA flow diagram (Fig. 3) provides more detailed information regarding the selection process of studies. After performing the initial literature searches, each study title and abstract was screened for eligibility. Full text of all potentially relevant studies was subsequently retrieved and further examined for eligibility. Then, after reviewing the full-text versions of the selected articles, those with the highest relevance were selected for in-depth analysis. The references within these articles underwent further scrutiny. Articles identified as pertinent through this secondary review process were also incorporated into the study. Finally, 44 papers were selected as eligible and included in this study and can be accessed via the GitHub repository at https://github.com/Lanxuan-Shen/3D-ULA-Literature-Review. Table 1 presents a summary of research studies on BIM-based approaches adopted in ULA to model and manage legal and physical aspects of different underground assets in various jurisdictions around the world.

## 3 Underground land administration

Recent research suggests that ULA is primarily concerned with the management of underground infrastructure (Peng et al., 2021; Saeidian et al., 2023b; Yan et al., 2021). This refers to the man-made space beneath cities, utilized for various essential infrastructures like transportation networks, subways, shopping areas, walkways, and utility systems including electricity, gas, water supply, sewage, drainage, and communication cables, as well as parking facilities (Rajabifard et al., 2019; Saeidian et al., 2021; Yan et al., 2019a). ULA includes three aspects: legal, institutional (administrative), and technical (Saeidian et al., 2021). The technical aspect is the key component supporting modern ULA practices (Yan et al., 2021). Through the continuous development and application of new technologies and methods, the efficiency and accuracy of ULA could be improved, and the sustainable utilization and management of underground assets can be promoted (Saeidian et al., 2021).

Table 1
BIM-based approaches for 3D ULA in different jurisdictions.

| Study | Jurisdiction | Data model | Asset type | Description |
|---|---|---|---|---|
| Liu & Issa, 2012 | General | BIM-GIS | Subsurface pipeline network | BIM-GIS conceptual framework. |
| Kim et al., 2015 | Republic of Korea | As-built BIM | Subway station | BIM adoption in design phase of underground utilities construction. |
| Atazadeh et al., 2017a | Victoria, Australia | IFC | Parking lots<br>3D ownership interests | Underground ownership representation in IFC. |
| Zerhouny et al., 2018 | Helsinki, Finland | BIM-GIS | 3D cadastre | Visualizing 3D Cadastral Data |
| Arroyo Ohori et al., 2018 | Netherland | GeoBIM | High-level and semantic aspects of GIS-BIM integration | GIS-BIM adoption under national standards. |
| H. Wang et al., 2019 | Hong Kong, China | BIM-GIS | Pipeline network | An integrated framework is proposed based on the integration of BIM and GIS through mapping data schema of IFC and CityGML. |
| Kaş, 2019 | Turkey | BIM-based collaboration system | Metro projects | Propose a Design-Bid-Build delivery method in the Turkish AEC industry. |
| Ying et al., 2021 | China | IFC-LADM | General underground easements | Linking LADM to IFC to represent legal and physical underground data |
| Chapman et al., 2020 | General | BIM-SketchUp | Pipeline network | Trenchless construction visualization |
| Kalogianni et al., 2020a | General | BIM-IFC | Urban and construction projects. | Improve the management and registration of real properties across their lifecycle |
| Maree et al., 2021 | New Zealand | BIM | planning for excavation operations in New Zealand. | Beneficial for communication between all stakeholders. |
| Li et al., 2021 | Xiamen, China | BIM 3D, 4D, 5D – cloud platform | Submarine Tunnel | BIM (nD) current adoptions and future work. |
| Huang et al., 2021 | Melbourne, Australia | Multi-LOD BIM | Metro station | A multiple level-of-detail (LOD) metro station BIM model is introduced to represent information at distinct levels of geometric and semantic richness required for varying application scenarios. |
| Liu et al., 2021 | Singapore | BIM | Construction phase | Conceptual and regulations framework. |
| Baraibar et al., 2022 | Bilbao, Spain | BIM | Underground tunnel | BIM adoption in the entire project lifecycle. |
| Sun et al., 2023 | Sweden | BIM-information delivery manual (IDM) | Design a lifecycle 3D property formation process | 3D property formation process framework. |

### 3.1 3D data in ULA

Integration of 3D legal and physical datasets plays an important role in supporting modern ULA (Saeidian et al., 2021). These datasets are critically important in recording, registering, and managing legal boundaries and RRRs associated with underground assets (Kim et al., 2015; Rajabifard et al., 2018; Yan et al., 2021).

#### 3.1.1 Underground legal data

Underground legal data encompass both spatial and semantic information related to legal spaces and boundaries associated with subsurface assets (Saeidian et al., 2023a). Table 2 classifies underground legal data into three common categories: legal boundaries, RRRs, parcel data, and planning data. These datasets are recorded in survey plans created by the land surveyors (Saeidian et al., 2023b).

Legal boundaries and RRRs are used for defining the legal extent of different assets in underground spaces. In addition, the parcel data include spatial and semantic information about the underground parcels. In addition, planning data include zoning laws and land use regulations that govern underground development. The legal data are crucial because it ensures that underground assets are legally managed, and comply with planning standards, facilitating better governance and sustainable use of subterranean spaces.

#### 3.1.2 ULA physical data

Underground physical data encompass spatial and semantic information pertaining to the tangible aspects of underground assets (Likhari et al., 2017). This encompasses a geometric representation of the underground structure, inclusive of its precise location, dimensions, and associated attributes, delineating its physical characteristics (Atazadeh et al., 2019b). In this study, the common physical data within the ULA environment are categorized into five primary aspects: Underground utility types, building structures, infrastructure, building components, and

Table 2
Common underground legal datasets.

| Underground legal data | | Description | Example |
|---|---|---|---|
| Legal boundaries | Surveyed boundaries | Defined based on surveying measurements. | Horizontal boundaries defined by distance and bearing, curves defined by radius and chord, and vertical boundaries defined through textual notations indicating upper and lower limits. |
| | Building boundaries | Specified by physical objects, which are tangible spatial objects and can be observed in the real world. | Interior faces of walls, doors, floors and ceilings, median faces within the middle of underground building structures, and exterior faces along external parts of building basements. |
| | Projected boundaries | Delineated through projecting an underground boundary element | Legal boundaries of a tunnel defined by the highway centreline (surveyed projection) and the projection of tunnel walls (building projection). |
| RRRs | Rights | Information about the type and extent of ownership rights associated with specific underground legal spaces | Legal boundaries defining the extent of ownership spaces and rights associated with them. |
| | Restrictions | Relates to legal restrictions on the use of underground space, such as environmental protection regulations, public safety regulations or urban planning requirements. | Such as buffer zones around underground constructions to maintain force and displacement equilibrium, protective areas of utilities based on regulations. |
| | Responsibilities | Specify responsibilities for maintenance, safety and environmental protection of underground spaces. | (See underground planning data in this table.) |
| Parcel data | Underground legal parcel | Parcels created to define properties (attributes and relationships) required by all legal parcels, including spatial dimension, name, state, title type, parcel type, use, area, volume, and description. | Lot and stage, such as storage, basements, shopping malls, private parking, and wine cellars. |
| | Primary underground parcel | Base-level parcels forming the cadastral fabric cannot overlap, and no gaps between them. | Such as a crown lot in Australia, owned by the government, examples include tunnels, public parking, walkways, and train stations. |
| | Secondary underground interests | Rights allow an individual or public authority to utilize a specific portion of land owned by another for designated purposes, with potential overlap across primary or secondary parcels. | Underground easements, such as utility networks, entrances to subterranean infrastructures, and lights. |
| Planning data | Contracts and agreements | Include government plans and policies affecting the development and use of underground space. | Such as underground space development documents, construction standards, and environmental impact assessment requirements. |

Table 3
Common physical data for ULA.

| ULA physical data | Description | Example |
|---|---|---|
| Underground utility types | Categorization of underground utilities based on their physical characteristics. | Such as power lines, water pipelines, gas pipelines, telecommunication cables, electrical cables, and sewerage systems. |
| Underground building structures | Geometric representation of buildings and their physical attributes. | Such as underground elements' shapes, height, footprint, and volume. |
| Underground infrastructure | Representation of underground facilities. Encompasses larger-scale installations and networks designed for transportation, utility distribution, or other communal services. | Such as underground tunnels, subways and train stations, basements, stormwater management systems, and underground access shafts. |
| Building components | Specific elements that constitute parts of underground building structures, detailing the construction and design aspects. | Such as underground building floors and ceilings, walls, doors, columns, rooms, and structural elements. |
| Spatial topology | Describes the arrangement and relationship of different physical elements in space, emphasizing connectivity and hierarchical structure. | Such as underground network connectivity, spatial hierarchy and relationships between buildings, utilities and infrastructure. |

spatial topology, as illustrated in Table 3. Furthermore, corresponding examples are provided for enhanced clarity (Kalogianni et al., 2020b; Peng et al., 2021). The significance of physical data lies in its pivotal role in facilitating efficient planning, construction, and management of underground space (Yan et al., 2021).

Underground physical data enable the accurate management and documentation of the physical reality of subterranean environments. The data are important since they help to link and reference legal data to the real-world, which is helpful for better communication of legal boundaries of underground assets. This would enhance integrated underground infrastructure planning and promote efficient use of underground spaces.

### *3.2 Necessity for transition to 3D ULA*

The transition from 2D to 3D ULA is particularly necessary, because currently underground 2D datasets could not accommodate the increasing need for managing legal and physical complexities of underground assets (Saeidian et al., 2021). Several Eastern European countries, including Bulgaria, Slovenia, and Poland, have maintained extensive Utility Cadastres as official registers of underground utility data since the analogue era (Karabin et al., 2020). For example, Turkey has developed the TUCBS data model, integrating its cadastral system with international standards such as CityGML and LADM (Sürmeneli et al., 2024). The case of underground utility networks in Istanbul showcases how physical and legal data of underground infrastructure have been managed systematically. The development of this data model illustrates the adaptability of established cadastres to modern standards (Sürmeneli et al., 2024). Furthermore, in Bulgaria, the city of Sofia has recorded detailed information about underground metro systems and utility lines, which is available through public geoportals, although predominantly in 2D formats (Karabin et al., 2020). Similarly, Slovenia and Poland have legal and institutional frameworks that facilitate the registration of underground objects like tunnels and pipelines (Drobež et al., 2017). While these systems remain largely 2D, they provide a strong foundation for transitioning to 3D ULA models by offering extensive historical data on underground assets (Madsen & Paasch, 2023). These established Utility Cadastres, though not fully integrated with modern 3D models, offer critical insights into how 2D analogue data can be digitized and integrated into comprehensive 3D ULA systems.

Integrated 3D digital models significantly enhance the efficiency and accuracy of ULA (Saran et al., 2018). Integration of physical and legal data enables a unified representation of physical structures and legal boundaries (Atazadeh et al., 2022). This unified data environment facilitates the clear recording and management of subsurface RRRs, reducing ambiguities and spatial conflicts (Atazadeh et al., 2022). 3D digital representation of underground environments can reduce conflicts and accidents caused by insufficient or misunderstood data in 2D approaches.

## 4 Overview of existing 3D ULA data models

In the field of 3D land administration, 3D data models are generally categorized into three types: legal, physical, and integrated. Among the 3D legal data models, the LADM Edition II has been introduced internationally (Kara et al., 2024). On the other hand, CityGML and IFC are designed to handle 3D physical data effectively. Additionally, recent efforts have focused on integrating physical and legal data models, enabling the integration representation within frameworks such as LandInfra, CityGML-LADM, LandInfra-LADM, and IFC-LADM (Guler, 2024).

In the context of 3D ULA, this section reviews existing 3D data models with a particular emphasis on their capabilities and inherent limitations. While most of these 3D data models have been extensively explored for both above-ground and underground environments, this review explores the specific challenges they encounter when applied to the underground environment. By critically assessing their suitability for managing subterranean 3D data, this section highlights key areas where further improvements are necessary to fully support 3D ULA.

### *4.1 Model for underground data definition and integration*

Model for underground data definition and integration (MUDDI) was developed by Open Geospatial Consortium (OGC) to address the challenge of representing underground infrastructure in urban systems. MUDDI provides a solution for addressing the challenges of integrating and managing underground data (OGC MUDDI Conceptual Model, 2024). As underground spaces are increasingly critical in urban development, MUDDI provides a standardized framework that ensures interoperability between different data sources, such as BIM and GIS, which is essential for accurate land administration in an underground environment (Lieberman & Roensdorf, 2020).

- Data modelling approach

The MUDDI conceptual model has been used in some prototyping efforts, such as London's Underground Asset Register (LUAR) and National Underground Asset Register (NUAR) pilot projects by the UK Geospatial Commission (Saeidian et al., 2022). This data model is designed to ensure compatibility with existing standards like ISO 19107, and provides a flexible architecture that can be adapted to various use cases, including underground utilities and natural phenomena such as geologic features (Pavlidou, 2022). The latest MUDDI conceptual report pointed out that the use of conformance classes allows it to be implemented progressively, with a "core" class providing a basic, standardized model for underground assets, and an "extended" class offering additional features tailored to specific contexts (OGC MUDDI Conceptual Model, 2024). This flexibility enables organizations to implement MUDDI incrementally while maintaining interoperability (Ramlakhan et al., 2021). By developing comprehensive data models, MUDDI aims to improve the quality and availability of subsurface data, promoting the efficiency and safety of future 3D ULA.

- Limitations

While MUDDI offers a comprehensive framework for integrating underground infrastructure data, several limitations remain in its application to ULA. One key issue is that MUDDI's regional focus often reflects localized priorities, which may not fully capture the diverse complexities of underground environments across different jurisdictions. This lack of a global perspective hinders its ability to provide a unified understanding of underground spaces (Baraibar et al., 2022). Furthermore, MUDDI's modular approach, although flexible, introduces complexities in maintaining consistency across different use cases, particularly in ULA, where precision and reliability are crucial (Lieberman & Roensdorf, 2020). Recent updates from the OGC aim to mitigate these challenges by enhancing MUDDI's integration with standards such as CityGML, BIM/IFC, and GeoSciML, improving data interoperability across built and natural environments. These advancements mark significant progress in making MUDDI more adaptable and effective in real-world applications (OGC MUDDI Conceptual Model, 2024).

### 4.2 Land administration domain model

The LADM is one of the most widely used 3D legal data models at the international level (Lemmen et al., 2015). LADM provides a conceptual and formal language for describing both semantic and spatial information associated with RRRs that affect pieces of land or water, buildings, and airspaces (Kara et al., 2023). van Oosterom and Lemmen (2015) proposed that the primary goal for LADM is to provide an extendable approach for developing and refining land administration systems.

- Data modelling approach

Currently, LADM is widely used for modelling 3D legal spaces. While Edition I (ISO 19152:2012) primarily focused on managing RRRs in land administration, it did not fully address infrastructure and underground facilities modelling (Buuveibaatar et al., 2022).

The newly released LADM Edition II significantly enhances the capabilities of LADM by introducing new spatial profiles specifically aimed at modelling infrastructure and subsurface facilities, such as underground utilities, tunnels, and pipelines (Kara et al., 2024). This latest edition offers extended 3D spatial profiles and new subclasses of spatial units to enhance the flexibility and adaptability of land administration systems (Kawasaki et al., 2024). The extended functionalities of Edition II not only maintain the core focus on managing physical and legal data but also introduce additional components that better support complex physical and legal data relationships, particularly for 3D digital representations (Kara et al., 2024). Figure 4 presents the class diagram for Parts 1, 2, 4, and 5 of LADM Edition II, clearly illustrating the interrelationships among these components.

- Limitations

Despite the significant advancements introduced in LADM Edition II, particularly with the new spatial profiles for infrastructure and subsurface facilities, several limitations remain in fully addressing the complexities of underground data modelling. While the latest edition improves the ability to model infrastructure and subterranean assets, such as pipelines, tunnels, and utilities, it still lacks comprehensive support for the intricate management of underground water resources, mineral deposits, and the complex interactions between different layers of subterranean infrastructure (Kalogianni et al., 2024). Further developments should continue to refine these areas, ensuring that LADM can support the growing complexity of underground environments. Integrating BIM/IFC with LADM could further enhance its application in ULA, ensuring greater interoperability and more integrated management of 3D physical and legal datasets in subterranean contexts (Kara et al., 2024).

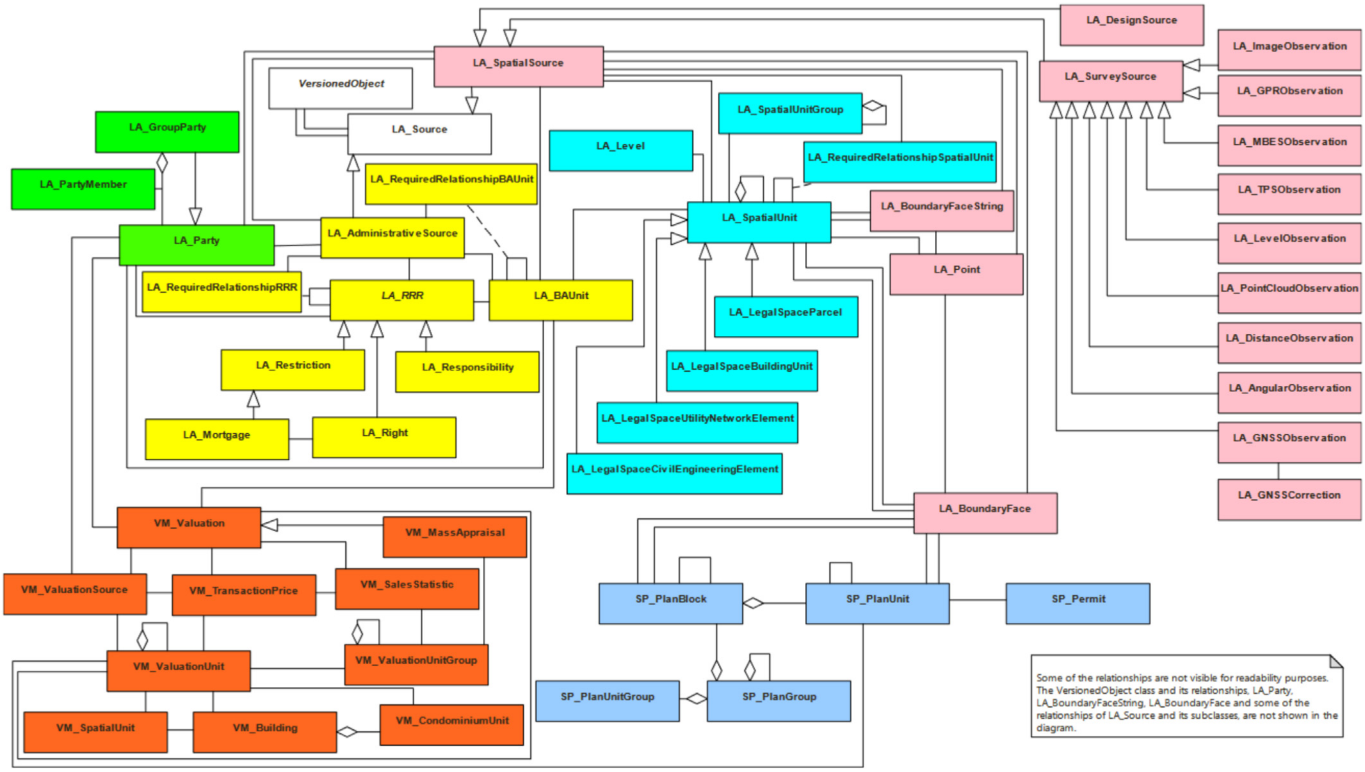
### 4.3 CityGML

CityGML is a widely recognized 3D data model in geospatial science that provides a standardized framework for representing urban environments (Saran et al., 2018). It captures detailed information about terrain, buildings, land use, and other urban features using rich semantic definitions and a modular structure (Saeidian et al., 2022). Although originally designed for above-ground urban modeling, CityGML's extensible nature, through its Application Domain Extensions (ADE), enables the incorporation of subsurface legal and physical data, making it increasingly relevant for 3D ULA (Saeidian et al., 2022; Yu & Ahn, 2022).

- Data modelling approach

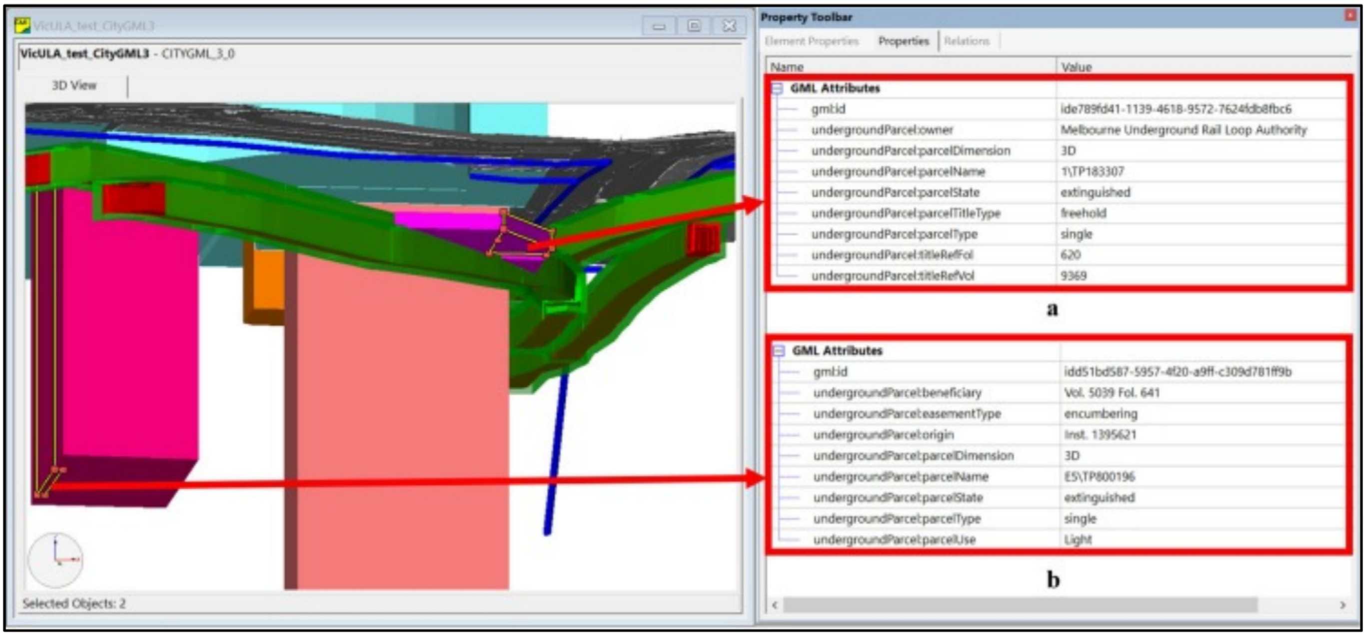
In the context of 3D ULA, CityGML's key advantage lies in its ability to extend its modelling capabilities to the subsurface domain. Through ADE, CityGML supports the simulation and management of underground legal boundaries and physical structures. For instance, the CityGML 3.0 framework includes an underground conceptual data structure that integrates both above-ground and subsurface features, thereby enabling an integrated approach for ULA at an urban scale. This capability is essential for addressing complex spatial relationships and legal constraints inherent in 3D ULA. An example of underground conceptual data structure in CityGML 3.0 environment is shown in Fig. 5 (Saeidian et al., 2022).

In CityGML, various entity classes are available to model underground physical data. For instance, within CityGML 3.0, the Building and Construction modules serve as suitable options for representing underground constructions, including basements, train stations, and corridors. Moreover, the Tunnel module offers an alternative for depicting underground structures such as tunnels. Extending these modules and classes can further encompass a broader range of subsurface assets, facilitating the simulation and management of subsurface physical entity data.



Some of the relationships are not visible for readability purposes. The VersionedObject class and its relationships, LA_Party, LA_BoundaryFaceString, LA_BoundaryFace and some of the relationships of LA_Source and its subclasses, are not shown in the diagram.

Fig. 4. Overview of LADM Edition II parts 1, 2, 4, and 5 and their relationships, adopted from Kara et al. (2024).



| Name | Value |
|---|---|
| **GML Attributes** | |
| gml:id | ide789fd41-1139-4618-9572-7624fdb8fbc6 |
| undergroundParcel:owner | Melbourne Underground Rail Loop Authority |
| undergroundParcel:parcelDimension | 3D |
| undergroundParcel:parcelName | 1\TP183307 |
| undergroundParcel:parcelState | extinguished |
| undergroundParcel:parcelTitleType | freehold |
| undergroundParcel:parcelType | single |
| undergroundParcel:titleRefFol | 620 |
| undergroundParcel:titleRefVol | 9369 |

a

| | |
|---|---|
| **GML Attributes** | |
| gml:id | idd51bd587-5957-4f20-a9ff-c309d781ff9b |
| undergroundParcel:beneficiary | Vol. 5039 Fol. 641 |
| undergroundParcel:easementType | encumbering |
| undergroundParcel:origin | Inst. 1395621 |
| undergroundParcel:parcelDimension | 3D |
| undergroundParcel:parcelName | E5\TP800196 |
| undergroundParcel:parcelState | extinguished |
| undergroundParcel:parcelType | single |
| undergroundParcel:parcelUse | Light |

b

Fig. 5. Example view of underground data modelling in CityGML 3.0 environment, adopted from Saeidian et al. (2022).

- Limitations

CityGML remains primarily focused on above-ground assets, providing limited support for the comprehensive representation of underground utilities and infrastructure, where the integration of physical and legal data is critical (Saeidian et al., 2021). Moreover, CityGML struggles with complex underground geometries and interactions between multiple layers of infrastructure, limiting its effectiveness in modelling the full scope of subterranean assets. This shortcoming hinders the ability of stakeholders to gain a complete view of underground environments, which is essential for effective planning and management (Jeong & Shin, 2021). In the context of 3D ULA, CityGML faces specific limitations that restrict its effectiveness for subterranean applications. While CityGML is well-suited for modelling above-ground urban features, its standard schema is not designed to capture the multi-layered complexity and vertical connectivity of underground infrastructures (Saeidian et al., 2021). The existing feature classes and semantics primarily target surface structures, leaving significant gaps in representing underground utilities, tunnels, and other subsurface assets. Additionally, CityGML's framework offers limited support for managing critical legal data in the underground context. This deficiency, combined with challenges in accurately modelling the complex, non-linear geometries often found in subsurface infrastructure, hinders urban planners from obtaining a comprehensive and reliable view of underground environments, ultimately impacting effective planning and regulatory compliance (Saeidian et al., 2021; Jeong & Shin, 2021).

### 4.4 Land and infrastructure conceptual model standard

The land and infrastructure conceptual model standard (LandInfra) is an integrated Unified Modelling Language (UML) conceptual model developed by the OGC (Scarponcini et al., 2016). It facilitates the representation and management of underground infrastructure, including utilities, transportation networks, and tunnels (Peng et al., 2021).

- Data modelling approach

LandInfra plays a crucial role in managing underground infrastructure, encompassing pipelines, tunnels, and underground chambers (Saeidian et al., 2021). By modelling the geometric shapes, positions, and attributes of these physical structures, LandInfra facilitates the planning, construction, and maintenance of underground infrastructure systems (Yan et al., 2021). LandInfra provides a 3D physical presentation of infrastructure assets and facilities (Rajabifard et al., 2019; Kalogianni et al., 2020b; Rajabifard et al., 2018). 3D data in the form of LandInfra standard can be used for making well-informed decisions during the design and construction phases of infrastructure projects (Lieberman & Roensdorf, 2020).

- Limitations

Although LandInfra includes physical aspects of underground assets, it also considers ownership elements related to land parcels and buildings. The motivation of Kumar et al. (2019) to apply LandInfra to model underground data is to solve the problems of complex legal and physical relationships existing in current land administration practices (Buuveibaatar et al., 2022; Kumar et al., 2019).

However, it lacks the capability to differentiate the semantics of legal boundaries, a limitation highlighted by Atazadeh (2017). Similar to the LADM model, a problem with LandInfra is that it only models the geometry of the legitimate interest boundary and does not distinguish the semantics of the boundary surfaces (Saeidian et al., 2021). This is because LandInfra is still in the early stages of development and currently does not have sufficient capabilities to model the spatial complexity inherent in 3D RRR spaces (Yan et al., 2019b). The studies by Buuveibaatar et al. (2022) are to apply LandInfra to ULA to build a comprehensive 3D spatial information model by integrating legal and physical information to better manage underground land.

### 4.5 Summary

All 3D data models offer valuable frameworks for handling underground land administration data, particularly in managing both physical and legal data. These data fall short in addressing challenges in 3D digital data management for underground environment, particularly in fully integrating physical and legal information and multilayered spatial relationships between underground assets. These challenges, which are crucial for the accurate management of subterranean spaces, remain unresolved by existing 3D data models. This gap sets the stage for exploring how BIM can overcome these limitations, providing a more integrated solution for 3D ULA in the following sections.

## 5 Designing and developing a BIM-based approach for 3D ULA

BIM offers a distinct advantage by providing a comprehensive framework for integrating physical and legal data in complex underground environments. In particular, the IFC standard provides an open standard format for BIM data exchange and sharing (Atazadeh et al., 2022). IFC standard is object-oriented and contains a comprehensive set of entities for managing spatial and semantic information about building elements and modelling spatial relationships between these elements (Daum & Borrmann, 2014). Atazadeh et al. (2017c) and Rajabifard et al. (2018) showed that BIM/IFC models can be used for an integrated representation of built assets including underground ones. Furthermore, Atazadeh et al. (2019b) demonstrated that the enrichment of IFC with 3D legal information could facilitate the volumetric representation of RRRs for built assets, which is particularly significant when integrating physical models and their legal counterparts in underground assets.

### 5.1 BIM for 3D ULA

#### 5.1.1 Physical data modelling

Physical data in ULA encompasses the geometric and semantic aspects of physical components in the underground environment. Numerous studies have employed these models to address different issues in the underground environment (olde Scholtenhuis et al., 2018; M. Wang et al., 2019). BIM mainly models physical data through components (such as walls, columns, pipes) and related physical properties (such as materials, sizes, locations) (Atazadeh et al., 2019b). These components can be defined in detail, including their geometry, physical properties, and relationships to other components (Baraibar et al., 2022).

Atazadeh et al. (2017c) conducted a case study in Victoria, Australia, on modelling building ownership boundaries, which may provide practical insights for the application of BIM in physical data modelling of ULA. Atazadeh et al. (2016b) explored extending a BIM-based data model to support the management of complex ownership spaces, offering potentially enlightening perspectives for BIM applications in physical data modelling of ULA.

Several studies have employed BIM models to address different issues associated with the physical reality of the underground environment (olde Scholtenhuis et al., 2018; H. Wang et al., 2019). The Arnotegi tunnel project in Bilbao, Spain (Fig. 6 shows the initial BIM model) is an example of application of BIM for underground facility modelling (Baraibar et al., 2022). Having an initial digital model of the projected work serves as a support for initial decision-making and as a reference for work control and monitoring. Baraibar et al. (2022) stated that the application of BIM in the Arnotegi tunnel project has made great contributions to improving project efficiency and mitigating risks related to geotechnical uncertainty.

### *5.1.2 Legal data modelling*

While BIM has traditionally focused more on the physical aspects of a building, it can also be extended to support 3D legal data, such as using IFC's spatial structures (e.g., site, spatial zone, space) to represent different legal spaces or ownership boundaries (Kalogianni et al., 2020a). IFC4 adds support for legal space entities, which can be used to represent legal information such as property rights and leased space (Saeidian et al., 2021).

Meulmeester (2019) proposed the use of IFC data models to define legal spaces for apartment rights in Dutch national surveying, offering valuable references for modelling underground legal spaces. Similarly, Matuk (2019) provides insights into the registration of underground space structures in modern 3D cadastral systems, contributing beneficial perspectives to the legal registration of underground spaces. These studies underscore the pivotal role of BIM in enhancing communication and management of 3D legal data within ULA (Atazadeh et al., 2018a; Kalogianni et al., 2020b). Figure 7 shows some examples of building boundaries in the basement level and their spatial relationship in 3D underground environments (Saeidian et al., 2024). Saeidian and his research team (2024) proposed that most legal boundaries are defined by physical structures, such as wall, column, and floor surfaces. This example provided a clear 3D representation of boundaries compared to traditional 2D plans. Therefore, this advancement not only supports the legal data modelling in 3D ULA, as the example is building boundaries, but also can be extended to other types of legal data in complex real-world underground infrastructure projects, such as projected boundaries and ambulatory boundaries.

### *5.1.3 Integrated data modelling*

The IFC framework excels in modelling the physical aspects of underground assets, providing a detailed and standardized approach for capturing the geometric and material properties of structures (Atazadeh et al., 2022). This precision in documentation and visualization is crucial for the effective planning, construction, and maintenance of infrastructure (Atazadeh et al., 2017b; Borrmann et al., 2024). Central to the IFC's utility is its focus on the physical dimension of building information, yet its design is versatile enough to include legal attributes (Rajabifard et al., 2019). By integrating legal information, stakeholders can better understand the complexities of ULA, such as overlapping rights or restrictions that impact development and use (Saeidian et al., 2021). Some recent studies explored the potential of the IFC standard for supporting data flow from different complex project lifecycle stages, such as designing, construction, and operation (Antunes et al., 2024). Each of these stages involves distinct data requirements and a range of stakeholders: urban planners

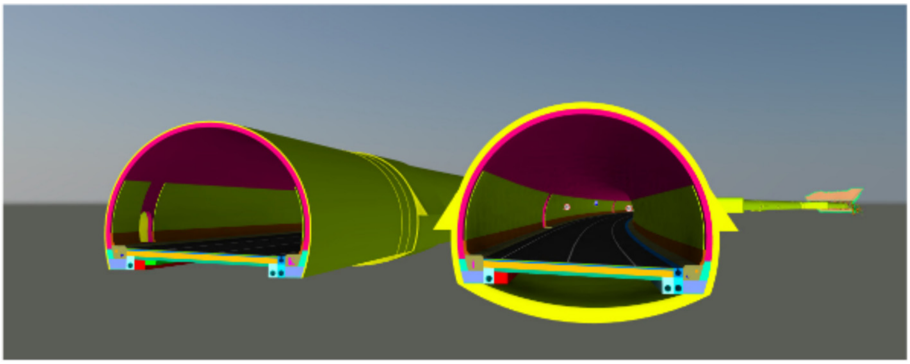


Fig. 6. Initial BIM model of an underground tunnel project in Bilbao, Spain, adopted from Baraibar et al. (2022).

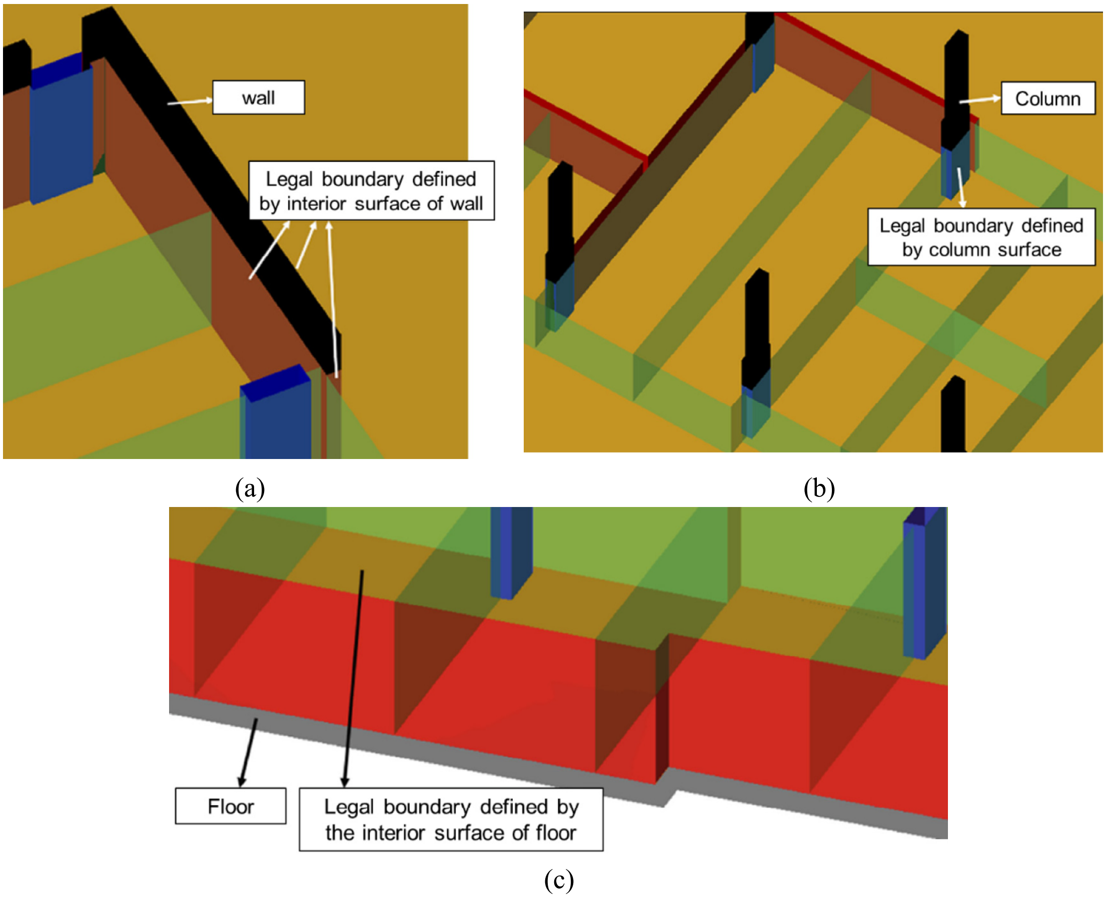


Fig. 7. Some legal boundaries (building boundaries) 3D representation in basement level defined by (a) walls, (b) columns, and (c) floors, adopted from Saeidian et al. (2024).

and local councils provide regulatory and zoning information; civil and geotechnical engineers contribute physical and structural data; land surveyors supply precise legal boundaries and cadastral data; while engineering consultants, utility providers, and construction teams construct, operate, and maintain underground infrastructure. This fragmentation leads to disconnected workflows and siloed data environments, which makes the coordination of legal, survey, planning, and physical information challenging (Raitviir & Lill, 2024).

In response to this challenge, BIM environment, in particular the IFC standard, provides a common data environment for integrating legal data (e.g., ownership, easements), survey data (e.g., measurements, survey control points), planning data (e.g., zones, overlays), and physical data (e.g., material, physical dimensions, condition) (Erharter et al., 2023). As illustrated in Fig. 8, adopted from (Raitviir & Lill, 2024), traditional paper-based workflows exhibit fragmented, stepwise data delivery that introduces significant delays and information loss over the asset lifecycle, including underground assets. 2D digital workflows (e.g., PDF files), while incorporating some digital elements, still suffer from inefficiencies due to manual data exchange and system incompatibility. In contrast, BIM-enabled workflows demonstrate a significantly smoother and continuous data flow. Legal, survey, planning and physical data are seamlessly exchanged across various stakeholders, minimizing redundancy, reducing delays, and supporting better-informed decision-making throughout the lifecycle of underground development projects.

### 5.1.4 Information flow in BIM-driven 3D ULA

Information flow within BIM environment refers to the seamless, systematic transfer and integration of diverse legal and physical data (Rathnasinghe et al., 2022; Zhu & Wu, 2022). This concept is crucial in ensuring that every phase of underground infrastructure projects, from initial design to construction and maintenance, is supported by accurate, up-to-date and fully-integrated data (Floros et al., 2020). Such a robust foundation not only enhances overall project efficiency but also prepares the groundwork for integrating underground legal and physical data in 3D ULA. Building on this foundation, it is essential to explore what constitutes a smooth information flow in the context of 3D ULA. Within 3D ULA, smooth information flow transcends basic data exchange, and it embodies the continuous, real-time synchronization of information among BIM, GIS, and legal data models such as LADM (Floros et al., 2020; Svalestuen et al., 2017; Zhu & Wu, 2022). A smooth information flow is also critical for real-time

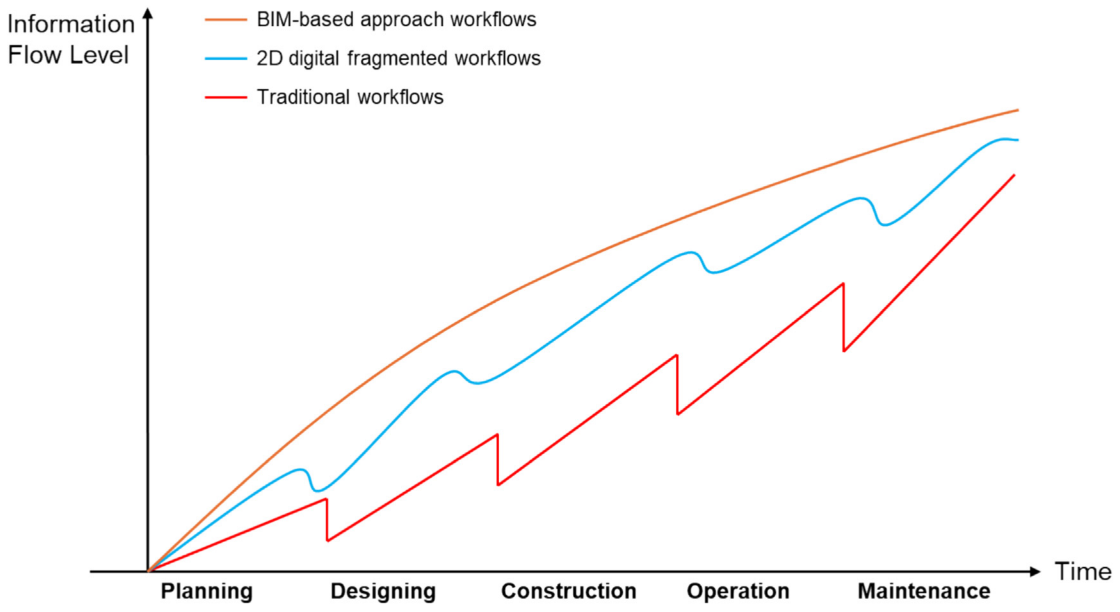


Fig. 8. Suggested information flow diagram compared with different methods through infrastructure lifecycle, adopted from Raitviir and Lill (2024).

decision-making, as it facilitates immediate data updates and fosters collaborative problem-solving among multiple stakeholders, including government agencies, developers, and engineers (Zhu & Wu, 2022). Zhu and Wu (2022) highlight that the efficiency of information flow directly impacts model reliability, data conversion effectiveness, and cross-domain data interoperability. In 3D ULA, achieving smooth flow ensures that physical data (e.g., underground infrastructure models) is integrated seamlessly with legal data, thereby enhancing urban planning accuracy and transparency (Sürmeneli et al., 2024).

### *5.2 Current challenges in adopting BIM for 3D ULA*

#### *5.2.1 Legal challenges*

The modern development of underground space introduces a set of key legal challenges, particularly in employing BIM related to data management. In the domain of ULA, the legal aspect includes the definition of underground legal objects, RRRs, and legal statements, revealing overlapping areas of the assets' legal space (Barzegar et al., 2020; Kim & Heo, 2019; Zaini et al., 2017). However, there are challenges with the adequacy of current legislation for BIM in addressing the complexities of the underground environment.

Firstly, when adopting a BIM-based approach to optimize the registration process of subsurface data, the first legal challenge is ensuring that the process is consistent with existing legislation in different countries (Saeidian et al., 2021). This challenge is not only related to the optimization of the data registration process, but also involves how to evaluate the priority of underground data for 3D digital registration using BIM models (Atazadeh et al., 2018b). For example, globally, different countries have responded to legal challenges in ULA by implementing various strategies and models, especially in the adoption of BIM to optimize subsurface data registration and management. For example, Singapore has adopted a highly centralized approach to managing subsurface data. This approach ensures a high degree of consistency and accuracy of subsurface data, but also presents specific challenges in integrating with existing BIM-based approaches (Yan et al., 2021).

Additionally, ensuring that the security of ULA data in the BIM environment complies with relevant data security laws and regulations in different countries is another important legal challenge (Baraibar et al., 2022). This includes security measures such as protecting data from unauthorized access, preventing data leaks, and ensuring data is encrypted during transmission and storage (Atazadeh et al., 2016a). For example, Australia has taken forward-looking legislative initiatives in underground data security management, especially through the implementation of the "Cadastre 2034: Powering Land and Real Property" strategy (Atazadeh et al., 2023). Through these measures, Australia has provided a more comprehensive and systematic legal framework for the security and integrity of subsurface data, demonstrating its special attention and efforts in protecting subsurface data.

Finally, establishing a comprehensive legal framework to ensure that BIM technology can realize its full potential in current and future 3D ULA, especially in the technical aspects of data modelling, poses the third legal challenge (Meulmeester, 2019). This legal framework needs to cover all aspects at the institutional and technical levels to promote the development and application of BIM (Ramlakhan et al., 2021).

#### *5.2.2 Institutional challenges*

Institutional considerations for 3D ULA play a crucial role (Saeidian et al., 2021). The institutional framework not only provides necessary policy and regulatory support for the planning, development, and management of underground space, but also promotes coordination and cooperation among various stakeholders (Atazadeh et al., 2016b; Karabin et al., 2020). However, although BIM offers the potential to improve project delivery, increase collaboration efficiency, and enhance data management capabilities, its application in ULA is challenging (Baraibar et al., 2022).

Initially, in the current ULA projects, stakeholders may have different understandings and expectations regarding ownership of 3D digital data, which is particularly complex in a BIM environment (Yan et al., 2019a). For example, the project Flanders' cable and pipe information portal in Belgium (KLIP), its process of collaboration between government agencies, private companies, and public interest groups on an underground space development project reveals the complexities of data ownership (Helmi et al., 2024). BIM models rely on experts in different fields to provide data, and this process involves multiple stakeholders. In the KLIP project, since the roles of each party in data input and update were not clearly defined, if the data submitted by one party was inconsistent, other stakeholders may not be able to easily distinguish the source of the data problem, resulting in reduced efficiency of collaborative work (Helmi et al., 2024; Hooimeijer & Tummers, 2017). In addition, inconsistencies in collaborative work will lead to a decline in the quality of the final output BIM model and increase the risk of errors.

Secondly, from the workflow perspective, the integration and optimization of workflows between different departments within organizations are not sufficient in meeting the demands of BIM-based approaches (Ramlakhan et al., 2021). Despite its potential, BIM-based workflows in ULA still face significant challenges. In Victoria's system, for example, the SPEAR platform, introduced in 2004 to support online approvals, continues to rely heavily on PDF documentation, which forces manual data conversion and repeated data entry (Olfat et al., 2019). This inconsistency in data standards among departments leads to inefficient communication and delays (Abdallah et al., 2024). At present, the application of BIM models in actual projects, such as underground drainage department design and pipeline design, will have potential workflow conflicts, leading to major coordination issues during construction.

Finally, cultural resistance is also a major challenge BIM faces in the current ULA. This resistance often stems from insufficient communication and collaboration, leading to the formation of information silos, which in turn hinders the development of cross-departmental cooperation (Saeidian et al., 2021). In addition, cultural restrictions may also lead to a lack of common vision and goals, making it difficult for team members to maintain consistent direction and efforts during the BIM implementation process, affecting the overall effectiveness of the project (Baraibar et al., 2022). For example, cultural leadership is highlighted as a more effective way to deal with institutional challenges. Therefore, successful implementation of BIM in 3D ULA requires a new way of thinking and a cultural shift (Ho & Rajabifard, 2016).

#### *5.2.3 Technical challenges*

The geometry and topology of underground assets may differ from that of the land parcel of above-ground level (Kalogianni et al., 2020a). For example, underground utilities are often long and cross multiple parcels or other underground utilities, such as pipelines, which may have complex geometries and attribute information (Saeidian et al., 2023b). BIM enables designers, engineers, and managers to understand and interact with underground spaces in new ways by providing detailed 3D digital models that not only include the physical and geometric properties of the structure, but also integrate time, cost, and maintenance information (Saeidian et al., 2023a). However, a significant technical challenge is whether BIM can fully realize its potential in the lifecycle of underground data in future 3D ULA development (Rajabifard et al., 2018). Achieving smooth information flow is a critical component of this challenge as it ensures that accurate underground legal and physical data is consistently exchanged during the lifecycle of underground assets, thereby maintaining data integrity and supporting real-time decision-making in underground infrastructure projects (Kalogianni et al., 2020a). This section discusses technical challenges in various stages of underground ULA data lifecycle in BIM, from data acquisition to data query and analysis.

- *Data capturing/acquisition*

Conventional 3D data capturing approaches could not provide effective solutions for capturing 3D location and depth information of underground assets in a BIM environment due to the lack of direct visibility and the complexity of these assets (Saeidian et al., 2023b). The core of this challenge lies in how to use technical means to overcome the opacity of the underground environment and accurately locate and map underground structures and facilities (Ramlakhan et al., 2021). Yan et al. (2019a) proposed a study that compared conventional surveying and ground penetrating radar (GPR) for underground utility mapping in Singapore. The application of traditional surveying methods and GPR technology for mapping underground facilities was compared (Atazadeh et al., 2021b). The comparison results show that traditional measurement methods are mainly limited in obtaining underground data, especially in complex underground environments. It is unable to obtain more accurate and detailed underground data, including pipeline location, depth, material, and other information.

- *Data processing*

Data processing in the BIM models and the accuracy and consistency of these models for 3D ULA are another technical challenge faced in underground land development (Atazadeh et al., 2022). Accuracy requires that BIM models must accurately reflect spatial and semantic aspects of the underground assets, which involves the comprehensive integration and verification of multi-source data. Consistency emphasizes that legal and physical data needs to be federated coherently in BIM models to ensure the data integrity of the overall project (Peng et al., 2021). Additionally, ensuring interoperability among disparate standards (e.g., IFC, GIS, and LADM) is critical to maintaining accurate, up-to-date information flow for effective decision-making in 3D ULA (Sun et al., 2019). Another challenge of data processing is that employing BIM to meet unique requirements of different 3D ULA projects (Yan et al., 2021). This adaptation is crucial for ensuring the precise and unambiguous visualization of subsurface assets, alongside the detailed information on RRRs associated with them (Ramlakhan et al., 2021). In BIM models, comprehensive integration and verification of data from multiple sources is required to ensure the accuracy and consistency of underground legal and physical data (Saeidian et al., 2021). As shown in Fig. 9, underground assets such as tunnels and utilities have complex geometries such as curved shapes, which makes their verification even more complex (Saeidian et al., 2023b).

- *Data modelling*

Regarding the data modelling stage, there are many studies that focus on the single physical or legal data models in ULA, which identify critical challenges in the consistency and management of underground data. Furthermore, many underground assets such as tunnels and utilities need to be modelled (Saran et al., 2018). The primary challenge is that BIM-based approaches in 3D ULA data modelling are that BIM lacks the functionality to cover and describe legal information for underground assets in the context of cadastral requirements (Ramlakhan et al., 2021). Taking Victoria, Australia, for instance, the management of legal and physical data for subsurface assets is exemplified by a case in Fig. 10, in which intersecting easements in a registered subdivision plan are depicted (Saeidian et al., 2021; Ploeger & Stoter, 2004). This representation lacks specifications on the complex underground objects, which poses challenges in clearly understanding the legal ownership associated with these easements (Peng et al., 2021; Ramlakhan et al., 2023; Ploeger & Stoter, 2004).

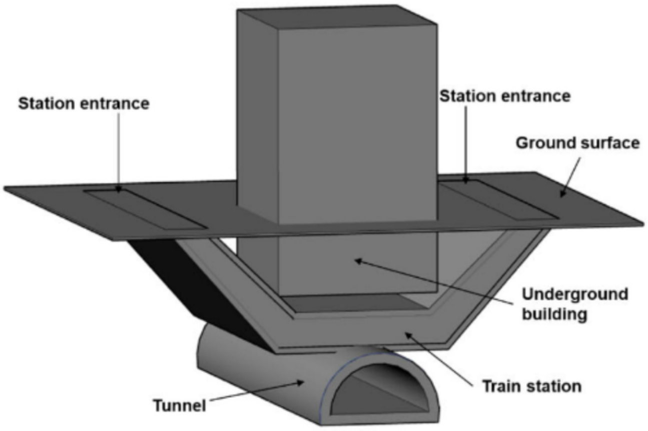
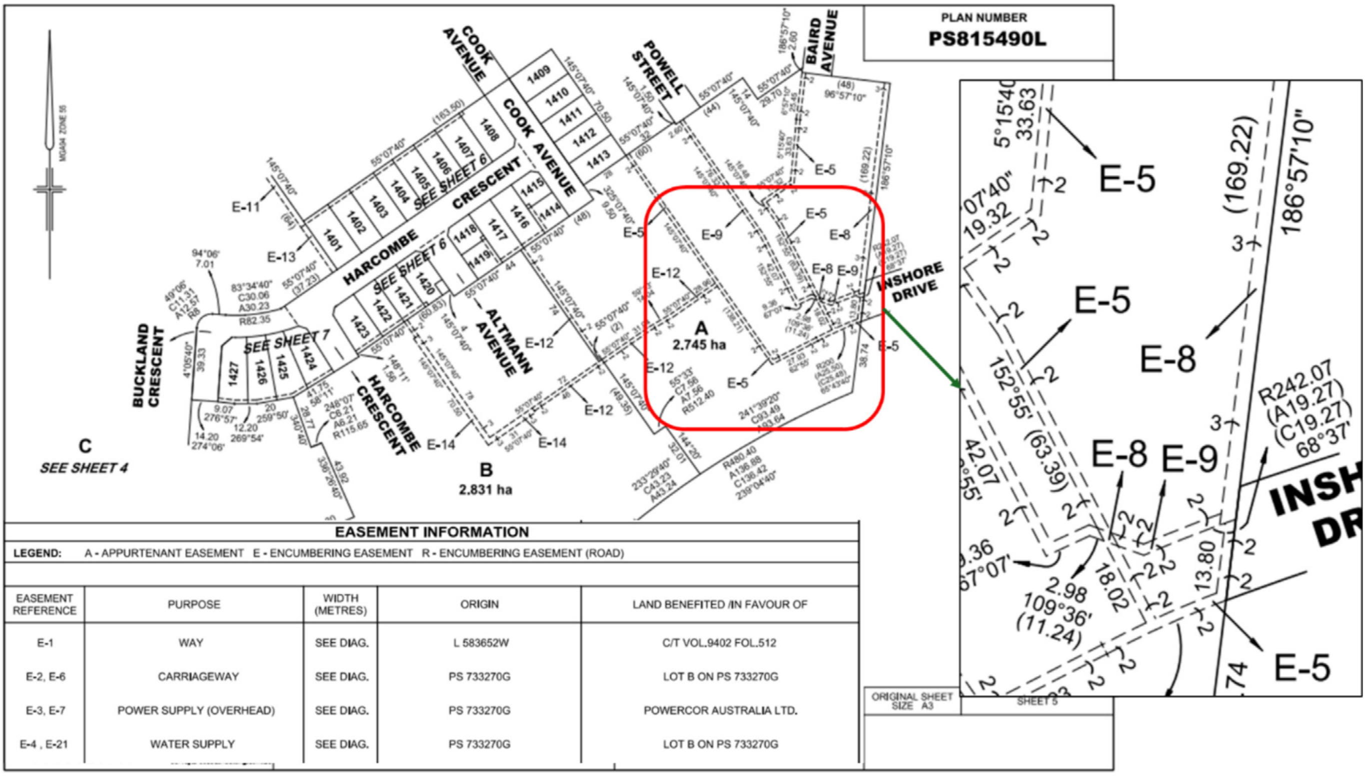


Fig. 9. Examples of underground assets with various spatial complexities, adopted from Saeidian et al. (2023b).

In addition, not only are all underground assets developed in building scale, but the need for modern urban ULA is in city scale (Saeidian et al., 2021). Therefore, BIM has been widely used at the building scale, but its application at the city scale is relatively rare (Ramlakhan et al., 2021). For example, as the demand for modern underground infrastructure increases, BIM is extended to the urban scale to meet the requirements of 3D integrated models (Saeidian et al., 2022). Then, due to the increasing need for modern underground infrastructure, there is a challenge that extending BIM-based approaches to meet the 3D integrated model requirements for different practices of integrated 3D ULA data models (Atazadeh et al., 2017a). Additionally, other steps of the ULA data lifecycle rely on the data structures defined by the data model. Extending important physical data models to support legal information may be a feasible solution to meet the 3D integrated model requirements for different use cases of ULA (Dursun et al., 2022; Gürsoy Sürmeneli et al., 2022).

- *Data visualization*

The data visualization of underground assets and associated RRRs is different from above-ground level because of the special concerns and requirements. BIM-based approaches could facilitate visualisation of legal and physical elements in underground space (Saeidian et al., 2021). However, there are a few studies on this field and some challenges still exist. During the data visualization phase, there may be many underground physical and legal objects, resulting in high data density, which can create visual clutter in 3D BIM models. Based on this, the initial challenge is how BIM-based approaches could effectively process and present these large amounts of underground data to ensure the readability and understandability of the model (Kara et al., 2023). Secondly, each type of ULA data visualization task differs in its specific needs for accurate representation of subsurface physical and legal data, which require that the BIM-based approaches be customized to the specific needs of the project. For example, in the Czech Republic, a BIM model is used to provide 3D visualization of the subway station (see Fig. 11) (Karabin et al., 2020). Although 3D BIM representations are much clearer than 2D survey plans, high data density and lack of customized visualization models are still challenges (Andrée et al., 2018). In addition, from a 3D ULA perspective, optimizing underground 3D data visualization is not only about enhancing representation through advanced graphics and



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-1 | WAY | SEE DIAG. | L 583652W | C/T VOL.9402 FOL.512 |
| E-2, E-6 | CARRIAGEWAY | SEE DIAG. | PS 733270G | LOT B ON PS 733270G |
| E-3, E-7 | POWER SUPPLY (OVERHEAD) | SEE DIAG. | PS 733270G | POWERCOR AUSTRALIA LTD. |
| E-4 , E-21 | WATER SUPPLY | SEE DIAG. | PS 733270G | LOT B ON PS 733270G |

Fig. 10. Easements as the ownership extent of underground utility networks in a subdivision plan, adopted from Saeidian et al. (2021).

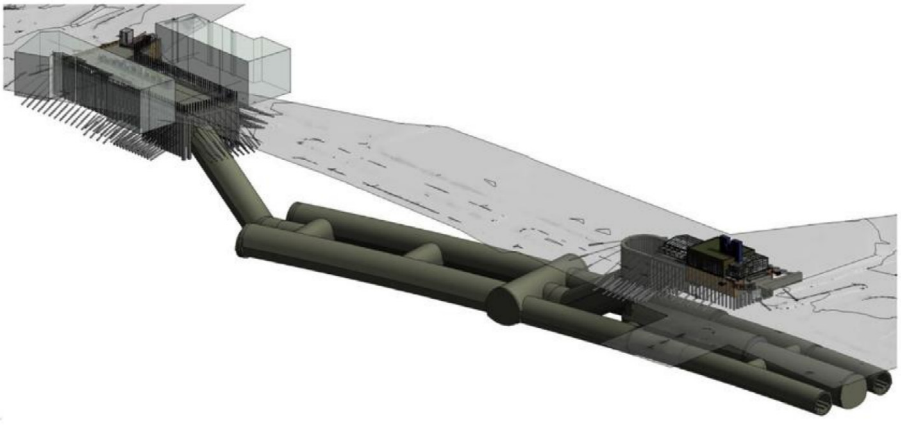


Fig. 11. 3D geospatial model of the metro in BIM data model visualization (adopted from Karabin et al. (2020); reproduced with permission, courtesy of Elsevier).

improved user interfaces but also about ensuring smooth 3D information flow (Peng et al., 2021; Sun et al., 2019).

- *Data query and analysis*

In current 3D ULA data management, BIM-based 3D data query and analysis could be complex and is beyond 3D visualization (Kara et al., 2023). These challenges stem primarily from the complexity of 3D data querying and analysis, which goes beyond 3D visualization and requires clearly identifying the types of analysis and querying required and developing methods for them (Atazadeh et al., 2019b). Furthermore, given the importance of the time dimension for underground assets, especially utilities, it becomes critical to incorporate time factors into analysis and queries (Barzegar et al., 2020). This means not only processing 3D spatial information but also managing and analysing dynamic data (such as temporal changes in RRRs) from underground assets over time. For example, the management of underground pipelines requires not only knowing their current location and status but also tracking their legal ownership and determining RRRS during construction and maintenance.

## 6 Discussion on potential solutions and future pathways

This section discusses potential solutions and future research opportunities in terms of addressing current technical, institutional, and legal challenges in order to drive innovation and development in the field of BIM-based 3D ULA. The unique focus on the integration of physical and legal aspects in subterranean contexts through BIM provides new insights into overcoming current barriers. Moreover, addressing these challenges not only advances the state of the art in sustainable urban development but also establishes a solid foundation for future interdisciplinary research. This critical discussion sets itself apart from existing literature by directly addressing the complexity of underground assets and offering a targeted exploration of how BIM can serve as a transformative tool in the development of more accurate and sustainable 3D ULA.

### *6.1 Legal aspects*

In terms of legal aspects of recording, managing, and dissenting 3D RRRs, it is important to develop a legislative framework suitable for BIM to realize the potential benefits of adopting BIM for governments, local councils, and landowners in different countries and jurisdictions. This process not only highlights the need to review existing laws and regulations to identify and legalize the application of 3D digital BIM environments in underground space, but also emphasizes that regulations should fully support the application of 3D BIM models in the legal subdivision and registration of subsurface assets (Zaini et al., 2017; Kim & Heo, 2019; Kalogianni et al., 2020a).

With the development of technology and changes in application requirements, it is particularly necessary to gradually update existing laws and regulations (Ho & Rajabifard, 2016). This process requires careful consideration of the specific needs of 3D digital BIM environment and ensuring that the legal framework keeps pace with technological advancements (Li et al., 2016; Rajabifard et al., 2018). In addition, the promotion of legal education and training activities is crucial to increasing awareness among governments, local councils, and landowners of the potential of BIM in ULA (Saeidian et al., 2021). In most jurisdictions, while surface boundaries are well-defined, the legal demarcation of subsurface assets remains vague, leading to unstable public and private interests (Paasch & Paulsson, 2021). These issues become even more critical for adopting the BIM environment for 3D ULA. BIM systems, which integrate detailed spatial and legal data, require precise, standardized legal definitions to effectively manage and register underground RRRs (Olfat et al., 2019). Addressing this legal ambiguity, by clarifying underground property boundaries and the extent of ownership, will not only enhance the interoperability and reliability of BIM-based approaches but also stabilize the legal framework necessary for sustainable underground asset management (Peng et al., 2021).

### *6.2 Institutional aspects*

In terms of institutional aspects, BIM-based 3D ULA requires the involvement of numerous stakeholders involved in all stages of the underground asset lifecycle (Ho & Rajabifard, 2016). The key to effective implementation of a BIM-based 3D ULA is to clearly define the roles, responsibilities, tasks, needs, and interests of all stakeholders involved (Peng et al., 2021; Saeidian et al., 2021; Yan et al., 2021).

Future pathways for institutional aspects should concentrate on strengthening underground data sharing and security policies to enhance data accessibility and transparency, while protecting privacy and security (Baraibar et al., 2022; Kalogianni et al., 2020b). Additionally, the use of cloud-based platforms can facilitate efficient data sharing among stakeholders while adhering to stringent security protocols (Paasch & Paulsson, 2021).

Improving stakeholder understanding of BIM applications through educational programs may help promote acceptance of the technology and reduce resistance (Liao & Teo, 2018). A detailed needs analysis of various stakeholder groups, including engineers, urban planners, and policymakers, reveals that their primary concerns often revolve around the perceived complexity of BIM tools and the costs associated with transitioning from traditional systems (Travaglini et al., 2014). Customized training sessions that demonstrate the tangible benefits of BIM for specific tasks, such as asset tracking and maintenance, can help bridge this knowledge gap and increase support of stakeholders (Murphy, 2014). In addition, as BIM and related technologies develop, it is especially important for institutional policies and processes to be flexible to quickly adapt to technological advancements and market changes (Atazadeh et al., 2016a, 2021a).

Moreover, stakeholder perspectives must be considered in the context of institutional aspects for BIM adoption (Zhang et al., 2023). Integrating BIM with legacy systems such as GIS and 2D CAD requires not only technical solutions but also organizational adjustments, including updates to regulatory frameworks and workflows (Paasch & Paulsson, 2021; Andrianesi & Dimopoulou, 2020). For instance, many agencies may need to revise their land administration policies to accommodate 3D data management, while ensuring compatibility with existing LAS. Implementing pilot projects and cross-disciplinary working groups can help identify potential integration challenges early on and provide actionable insights for smoother transitions (Murphy, 2014; Chinyio, 2018).

### 6.3 Technical aspects

In terms of technological advancements, several data stages need to be considered, including capture, verification, modelling, visualization, and query and analysis of subsurface data. These steps are central to overcoming technical challenges and improving management efficiency and decision-making quality (Saeidian et al., 2021).

In the phase of underground data capturing, the cases of Singapore's underground utility mapping project clearly illustrate the technical challenges faced. This case exemplifies how BIM, combined with advanced sensing technologies, can enhance data acquisition for complex subsurface environments (Yan et al., 2021). A similar case is the London Underground Infrastructure Mapping Project, in which BIM was crucial in addressing delays caused by unforeseen underground conditions (Likhari et al., 2017). A cloud-based geological BIM system enabled efficient data storage and sharing, reducing project risks (Mansoori et al., 2022).

Additionally, incorporating historical data through the British Geological Survey minimized future ground investigation costs, illustrating BIM's value in streamlining underground land and asset management (Kupriyanovsky et al., 2020; Travaglini et al., 2014). Despite these technological advances, effective data capturing in 3D ULA is only part of the solution; ensuring that BIM data flows seamlessly among government agencies, developers, and contractors remains a critical challenge (Raitviir & Lill, 2024; Zhu & Wu, 2022). To address these issues, cloud-based collaboration platforms provide a shared digital environment, enabling stakeholders to access, update, and synchronize the latest underground land data in real time. Additionally, digital twins, combined with IoT sensors, continuously monitor underground infrastructure conditions and integrate with BIM-GIS platforms to deliver real-time updates, improving decision-making and project adaptability (Sun et al., 2019).

By integrating land ownership, infrastructure, and legal data, the system enables multiple agencies to instantly synchronize updates, enhancing regulatory coordination and minimizing conflicts in underground development (Chia et al., 2021). This case underscores the importance of cloud-based and digital twin solutions in ensuring real-time information flow, reducing project risks, and optimizing underground space management in 3D ULA (Akob et al., 2019).

In the underground data processing phase, BIM-based approaches integrated with artificial intelligence (AI) and machine learning (ML) algorithms can provide automatic detection and correction of inconsistencies in ULA data (Pan & Zhang, 2023; Zabin et al., 2022). For instance, AI-driven models, such as convolutional neural networks (CNN), can analyze large datasets from multiple sources, flagging discrepancies in underground geometries or attributes in real-time (Pan & Zhang, 2023). This approach ensures not only accuracy but also the timeliness of processing, crucial for large-scale projects where real-time data integration is needed (Andrianesi & Dimopoulou, 2020). Furthermore, the integration of BIM and GIS has proven successful in improving the accuracy and consistency of underground data (Yan et al., 2021). For example, in the Chalandri area of Athens, researchers used a BIM-GIS integrated platform to create a detailed 3D model of an urban block (Block 464), incorporating both aboveground structures and underground infrastructure (Andrianesi & Dimopoulou, 2020). This example not only enabled effective management and processing of underground spaces by visualizing spatial relationships between diverse assets but also streamlined the processing through the application of the IFC standard for data exchange. By ensuring that legal information and ownership data are accurately maintained, these techniques contribute significantly to a smooth information flow. This integrated approach ensures that validated data is transmitted across digital platforms, enabling real-time collaboration among stakeholders (Zhu & Wu, 2022).

In the data modelling phase, one of the key challenges is ensuring that both physical and legal information is adequately captured in 3D ULA models. Firstly, the use of extended BIM models, incorporating both physical and legal data, offers a potential solution. For example, in the Melbourne Metro Tunnel Project, researchers successfully developed a BIM model that included not only physical attributes of underground infrastructure, but also legal information related to easements and ownership boundaries (Huang et al., 2022). This model provided a unified framework for managing both physical and legal dimensions, improving data consistency and reducing ambiguities in asset ownership. In addition, employing the IFC standard in these models enables interoperability between different platforms and systems, ensuring that both legal and physical data can be easily exchanged and verified. Another successful application is the four-story building on Kithaironos 21 Street, where the integration of IFC and GIS data was used to clearly visualize underground pipelines, ensuring both data accuracy and consistency (Andrianesi & Dimopoulou, 2020). The incorporation of the IFC standard allowed for the efficient integration of legal information, such as ownership data, into a detailed 3D BIM model. By bridging disparate systems and facilitating real-time data exchange, these models exemplify how effective information flow is fundamental to 3D ULA data modelling, ultimately supporting timely decision-making and improved underground space management.

To optimize BIM visualization of underground data, the first step is to expand its functions to ensure that key facilities such as underground structures and pipelines can be fully displayed (Saeidian et al., 2021). By integrating advanced graphics technology and improving the user interface, interactivity and user experience are enhanced, making underground space analysis intuitive and efficient (Ho &

Rajabifard, 2016). In 3D ULA, ensuring real-time updates of underground infrastructure and property data is crucial. However, as information flows across multiple platforms, issues such as data redundancy, propagation of errors, and version conflicts often arise, leading to inefficiencies in 3D visualization within BIM environments for real-world projects (Raitviir & Lill, 2024; Yan et al., 2021; Zhu & Wu, 2022). To address these challenges, AI-driven automated data validation and transformation tools are crucial for maintaining seamless interoperability among standards such as IFC, LADM, and GIS. For instance, the London Crossrail project employed AI-based consistency checks to harmonize planned and as-built data, while Sydney's underground pipeline management integrated BIM with augmented reality to provide real-time on-site visualization and guidance. These approaches underscore that ensuring a smooth information flow is key to reducing errors and optimizing the management of underground spaces in 3D ULA (May et al., 2017; Smith, 2014). Similarly, in Sydney's underground pipeline management, BIM was combined with augmented reality (AR) technology to enhance the maintenance and management of underground networks (Chen et al., 2019; Shivasami et al., 2023). Maintenance personnel used AR glasses on-site to visualize the 3D models of the pipelines along with relevant data, receiving real-time guidance for repairs. This integration not only improved operational efficiency but also enhanced safety standards. These examples demonstrate how BIM, in conjunction with VR and AR, can optimize the visualization and management of underground assets, reduce project risks, and improve maintenance workflows.

These integrated approaches underscore that robust information flow among different data stages is vital for reducing errors and ensuring data consistency in 3D ULA. By enabling real-time collaboration among government agencies, developers, and contractors, such systems support dynamic decision-making and enhance overall project efficiency. Moving forward, further research should explore advanced cloud-based platforms, digital twin technology, and enhanced AI algorithms to sustain seamless information exchange throughout the entire ULA information lifecycle, thereby optimizing underground space management for practical application (Cho et al., 2023; Cheng et al., 2024; Mahant, 2025).

## 7 Conclusions

This study investigated the critical role of BIM in advancing 3D ULA with a particular focus on legal, institutional, and technical dimensions. Through a systematic literature review, this research identified key challenges in adopting BIM for 3D ULA, including fragmented legal frameworks, institutional coordination barriers, and technical limitations across the data lifecycle from acquisition to visualization and analysis. More specifically, existing 3D data models, such as MUDDI, LADM, CityGML, and LandInfra, were examined for their capabilities and limitations in representing legal and physical dimensions of underground assets. While these data models offer fundamental entities for managing underground legal, survey, and physical data, they have limitations in fully integrating the complex spatial and legal relationships required for effective 3D ULA. In response, this study proposed BIM, particularly the IFC standard, as a promising solution for 3D ULA by enabling 3D integrated representation of legal, survey, and physical underground data.

The findings highlight the need for jurisdiction-specific BIM-driven solutions for 3D ULA that address context-dependent legal and institutional arrangements. One of the key findings is the importance of smooth information flow across the planning, construction, and maintenance phases. Ensuring full integration and real-time exchange of 3D legal, survey, and physical data among stakeholders is essential for improving decision-making, minimizing legal conflicts, and enhancing transparency in ULA processes. The study highlights that smooth information flow is not just a technical requirement but a fundamental enabler of collaboration among various stakeholders, including surveyors, land registries, councils, engineers, and planners. Achieving this flow demands interoperable data standards (i.e., IFC), cloud-based platforms, and integration with emerging technologies such as AI and digital twins.

Despite its potential, BIM adoption in 3D ULA remains limited by a lack of real-world case studies demonstrating end-to-end lifecycle implementation. Therefore, future research should focus on empirical validations, prototype developments, and comparative analyses across jurisdictions to establish best practices for BIM-driven 3D ULA. This will be important for realizing the full potential of BIM in 3D ULA, which will support more resilient and sustainable underground space development worldwide.

## Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## CRediT authorship contribution statement

**Lanxuan Shen:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Behnam Atazadeh:** Writing – review & editing, Supervision. **Serene Ho:** Writing – review & editing, Supervision. **Abbas Rajabifard:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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