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3D Modelling of Subsurface Legal Spaces and Boundaries For 3D Land Administration

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Conflict of Interest statement

None of the authors have a conflict of interest to disclose.

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Abstract

The increasing trend of urbanization results in various problems regarding enabling the livable cities such as traffic congestion, environmental pollution, and inadequate disaster preparedness. These problems are considerably related to deficiencies in the aboveground usable areas that can be exploited for the development of urban areas. Underground development is one of the strong solutions to cope with the aforementioned problems. The holistic planning of underground space is an important factor in ensuring the efficient use of underground space. Land administration that deals with the cadastral rights, restrictions, and responsibilities (RRRs) on the surface and subsurface is highly significant in the context of planning the underground space. By nature, there is a need for three-dimensional (3D) ownership information below the surface in order to carry out the analyses within planning studies regarding different aspects such as the existing subsurface structure and environmental impacts. This paper therefore enriches the core data model of the CityJSON standard such that it allows for 3D modelling of legal spaces and boundaries in the subsurface. It presents the usability of the proposed extension by visualizing the underground cadastral RRRs in 3D through the created and validated CityJSON file based on this extension. The practical opportunity arising from the use of CityJSON files derived from the developed extension is demonstrated. Different case studies are presented including the compliance checking regarding the designed underground tunnel within building permitting. The results of this study show that integrated 3D land administration including subsurface can contribute to the facilitation of the overarching planning of underground space.

Keywords: Underground space, 3D geoinformation, Sustainable development, Resilient cities, 3D cadastre, 3D city model.

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1. Introduction

Since urbanization is increasing globally, the usable areas on the surface of the cities are decreasing day by day (OECD/European Commission, 2020). The management of urban areas is getting difficult because of various problems from different aspects such as the environment, economy, and social welfare (Broere, 2016; Durmisevic, 1999). To overcome these problems, administrations seek efficient solutions that can provide the sustainability of the urban areas (Bobylev, 2010; Qiao et al., 2024). The use of underground space is a powerful one among the possible solutions because it holds robust opportunities such as urban renewal that might be exploited in the context of sustainable urban management (Cui et al., 2021; Hunt et al., 2016; Parker, 1996). These opportunities come from different types of structures (e.g., storage, transportation, and utility) with various functions (e.g., shopping centers, private garages, and railways) that can be utilized within the subsurface space (Edelenbos et al., 1998). Underground space is a resource asset more than a natural asset because it contributes to a great number of goods or services with its natural and artificial properties (Qiao et al., 2022). There is a growing trend in various metropoles including Hong Kong, Helsinki, and Singapore for creating strategies for sustainable development and efficient management of urban underground space (Reynolds, 2019).

Many issues related to different disciplines should be considered for making decisions with respect to developments within underground space, for example, geology, engineering, psychology and physiology, ventilation, property ownership, safety, and economy (Goel et al., 2012). Practicing inclusive and integrated planning approaches is of great significance to get the most out of underground space (Clarke, 2000; Zhao et al., 2016). It is essential to carry out thorough analyses regarding different contexts such as the need for subsurface development, existing structure within underground space, performance evaluation with respect to critical situations (e.g., natural disasters), and environmental and social impacts (Bobylev, 2009; Lai et al., 2023).

Coordinating the underground space is a significantly challenging task because the subsurface covers different kinds of structures, facilities, and amenities. A wide range of stakeholders from different sectors such as public administrators, local agencies, city planners, and engineers should be able to access the current information on underground space to achieve this task. Digitalization is one of the efficient ways to share up-to-date information and improve the processes regarding the planning and management of the subsurface (Beatty et al., 2020; L. Peng et al., 2023). Economic profits, transparency, and interoperability between different applications with respect to sustainable urban development are prominent benefits of digital transformation (Sachs et al., 2019). The existence of spatial information regarding the underground facilities is a critical part of the digital transformation that helps to prevent several problems, for example, delays in the projects, unsafety in construction works, and interruptions in the utility networks such as electricity, natural gas, and water (Lieberman and Ryan, 2017; Saeidian et al., 2023a). Geoinformation on the subsurface is quite practical for informing the stakeholders about the decisions regarding the underground developments, fostering the private sector investments, and augmenting likely benefits for the urban areas (Kuchler et al., 2024).

Urban planning is commonly practiced by using two-dimensional (2D) geoinformation. Similarly, the planning and management of the underground space is predominantly maintained by using the 2D spatial data (ITA Working Group 20, 2023). The presence of three-dimensional (3D) geoinformation is significantly important for coordinating the underground space since it provides precise spatial information with rich semantics on the subsurface. For example, the problems regarding the determination of the suitable location and approach for excavations can be solved by benefiting from 3D spatial data in the planning studies (Bobylev et al., 2022; Volchko et al., 2020). There is an increasing demand for 3D planning in which 3D geoinformation is exploited efficiently for conducting the required analyses regarding aboveground and underground (Guler, 2023; Stepien et al., 2022; swisstopo, 2024; Zhou et al., 2019).

Insufficient data infrastructure on underground cadastral rights, restrictions, and responsibilities (RRRs) is one of the critical issues that may impede the underground space development since the decisions in the planning of underground facilities might change depending on the existing situations regarding property ownership (CEDD, 2009; von der Tann et al., 2020). The land administration systems (LASs) that encompass up-to-date geoinformation on property ownership are significant because of increased interest in sustainable underground development. LASs are widely structured based on 2D geoinformation (Rajabifard et al., 2019). However, there is a need for LASs that provide accurate information on 3D legal spaces and boundaries to be able to exploit the underground space efficaciously in the context of sustainable development of urban areas (van Oosterom et al., 2020). This is because the use of 2D geoinformation is insufficient to unambiguously delineate the legal status of property ownership with their physical counterparts (Guler et al., 2022; Gürsoy Sürmeneli et al., 2022b). Sufficient data exchange on property ownership pertaining to underground is an important factor for the decision-making that enables effective planning and effortless constructing of subsurface space (Lai et al., 2023). 3D data flow that is provided in a standardized way hinders the loss of information between different stakeholders and improves the efficiency of the processes regarding urban underground space legally, economically, and socially (Saeidian et al., 2024). 3D geoinformation representing the underground ownership can facilitate the digitalization of building permitting that covers compliance checking with respect to the current cadastral situation (Noardo et al., 2022).

This paper presents a methodology that enables to create and validate 3D spatial data encompassing the legal spaces and boundaries on the subsurface in an interoperable way and demonstrates how to benefit from these data for possible use cases regarding effective planning and management of underground space. The developed 3D model can play a foundational role in creating the digital twin/geodatabase of the underground space. 3D datasets generated by using this model can be exploited for the management of the subsurface in terms of ensuring collaboration between stakeholders, approval of new developments, dynamic planning and data organization, storing standardized data, and achieving smooth data flow and integration. They can be also useful for implementing the analyses regarding current research agendas such as determining the value of underground space.

The next section provides an overview of standards and existing studies in the sense of 3D modelling of subsurface cadastral RRRs. The research gaps are also highlighted in this section. Section 3 covers the aim and contributions of this study. Section 4 explains the methodology of the present research and Section 5 details how the proposed conceptual model and its corresponding extension is developed. The subsequent section covers the 3D representations of cadastral RRRs and demonstrates the case studies. Section 7 provides discussions and Section 8 concludes the paper.

2. Background

Several international standards provide schemas for data modeling regarding different sectors such as land administration, geoinformation, and Architecture, Engineering, Construction, and Operation (AECO). The section gives information about these standards that can be exploited for creating standardized 3D spatial data for underground property ownership. The related previous research that benefits from these standards is examined and the existing research gaps are introduced.

2.1. Standards

The Land Administration Domain Model (LADM) as an International Organization for Standardization (ISO) standard aims to provide a fundamental, conceptual model that covers the features and relationships for carrying out the land administration practices (ISO, 2012). It includes both spatial (e.g., spatial units) and non-spatial (e.g., parties) features for completely modelling the cadastre and land registration activities. LADM core schema covers the features and relationships for utility networks but the use of geoinformation-based standards can be beneficial for efficiently implementing the conceptual model that encompasses the subsurface property rights. A new part regarding the implementation of the conceptual models is included in the second edition of the standard (Kara et al., 2024).

There are two main domains namely Building Information Modelling (BIM) and 3D geoinformation (i.e., 3D GIS) that deal with 3D modelling of physical objects in the built environment. Industry Foundation Classes (IFC) that provides a comprehensive data schema containing specifications and

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concepts on how to compose Building Information Models (BIMs) is the principal data standard in the BIM domain (ISO, 2018). The IFC core schema does not cover the essential entities and relationships for 3D delineation of underground legal spaces and boundaries since it is not developed by considering this issue. IFC standard is also considerable as more suitable for modelling of small-scale areas such as buildings or construction sites however underground property ownership needs to be modelled at the large-scale such as city or region.

The domain of 3D geoinformation aims to provide 3D semantic models of urban areas by considering the larger spatial extent comparing the BIM domain. CityGML that provides a fundamental data model for creating 3D models of cities is the primary standard in this domain. It is an Open Geospatial Consortium (OGC) standard and the latest version (3.0) of it is published in 2021 (OGC, 2021). With the latest version, some modules of the CityGML data model are updated and new modules such as *Construction* are added to the core schema. Also, the new space concept that identifies the logical (e.g., building unit and storey) and physical spaces (e.g., building room) is introduced with CityGML 3.0. CityGML is based on the Extensible Markup Language (XML) encoding approach that uses the hierarchal system that proceeds until the individual object and attributes. Since CityGML 3.0 aims to provide a basic data model for 3D urban modelling, there is an Application Domain Extension (ADE) mechanism to extend the core data model in a way to cover specific application areas such as energy.

CityJSON was developed with the aim of improving the implementation of the CityGML data model as a means of the JSON-based encoding approach that provides more software-developer-friendly data construction (Ledoux et al., 2019). This is because there are several issues that might prevent the efficient production and exchange of CityGML models. First, the software might struggle to read and write CityGML data because of the large file size. Second, the hierarchy in CityGML data might be highly complex and hard to read owing to the use of XML. Third, there might exist some practical challenges due to the extensive use of XML linking language (XLink). Even though CityJSON v2.0 is 100% compliant with the various modules of CityGML 3.0 such as *Bridge*, *Building*, *CityFurniture*, *Construction*, *Transportation*, and *Tunnel*, it follows a different approach for some modules such as

Versioning (OGC, 2023). CityJSON v2.0 also allows for extending the core schema with the concept called *Extensions* that is developed with the aim of enabling an easy-to-implement extension mechanism. New city objects, properties, attributes, and semantic surfaces can be included in the extensions of CityJSON. Although CityGML can be used to model property rights in 3D through extending the core schema, this study utilizes the CityJSON because it does overcome the above-mentioned issues by using the JSON format that provides efficient data exchange and clear data content.

2.2. Related Research

Many works focused on 3D modelling of aboveground property ownership by benefitting from the LADM, CityGML, and IFC standards (Atazadeh et al., 2021, 2017; Cagdas, 2013; Guler et al., 2022; Gürsoy Sürmeneli et al., 2022b; Halim et al., 2022; Kalogianni et al., 2021; Li et al., 2016; Mi, 2019; Sun et al., 2019). The examination of the CityJSON standard with respect to the 3D registration of cadastral RRRs is highly limited (Mohd Hanafi et al., 2022). In addition, researchers conducted studies that cover the 3D registration of underground property rights. As an early study, Ploeger & Stoter (2004) presented the conceptual model containing the registration object that can be exploited for cadastral registration of infrastructure objects. The need for cadastral registration of utility networks was underlined and user needs in the context of 3D cadastre were examined (Pouliot et al., 2015; Pouliot and Girard, 2016). The conceptual frameworks that include the 3D registration of cadastral RRRs regarding the underground assets were proposed to improve the implementation of 3D cadastre practices (Kim and Heo, 2019; Yan et al., 2018). From the legal perspective, Zhang et al. (2020) examined the current situation in China and proposed a framework for improving the management and registration of the cadastral RRRs within urban underground space. As a result of analyzing the different European Union (EU) countries, Karabin et al. (2020) underlined that the existence of the legal basis that contains the specifications regarding the ownership of underground assets such as tunnels can facilitate the practicing the 3D underground property registration.

From the technical perspective, the cadastral registration of utility networks was investigated in a more detailed manner in the sense of a four-dimensional (4D) cadastre (Döner et al., 2010). In a related study, 3D representations of utility networks were exampled within an Oracle database and the possible case studies were presented using spatial queries (Döner et al., 2011). Researchers developed the conceptual models based on the LADM standard for cadastral registration (Kim and Heo, 2017; Saeidian et al., 2022) and presented the 3D modelling of different underground assets such as underground utility networks (Radulović et al., 2019; Yan et al., 2021, 2019), underground vineyard (Janečka and Bobíková, 2018), underground historical structure (Bieda et al., 2020), and underground metro tunnel (Matuk, 2019). In another study, Perperidou et al. (2021) created 3D cadastral parcels and spaces that represent the property ownership situations in Piraeus Metro Station, Greece. Ramlakhan et al. (2023) mapped the features (e.g., *LA_SpatialUnit*) in the LADM standard into entities (e.g., *IfcSpace*) in the IFC schema and showed the 3D representation of legal spaces pertaining to underground utilities such as sewage network. Recently, Saeidian et al. (2023b) developed an extension for CityGML 3.0 schema that focuses on the 3D modelling of underground cadastral RRRs and they presented visualizations using a CityGML file.

Even though the majority of the studies zoomed in on the 3D modelling of legal spaces depicting the cadastral RRRs, there exist works that investigated the 3D representations of legal boundaries. Some of these works approached this issue by including the existing features (e.g., *WallSurface*) that can be used to delineate the surfaces in CityGML data model in their conceptual models (Gozdz et al., 2014; Gursoy Surmeneli et al., 2020; Nega and Coors, 2022; Sun et al., 2019), some researchers converted IFC entities to these existing features to model the cadastral boundaries (Hajji et al., 2021; Mi, 2019). Recently, Saeidian et al. (2024) studied the 3D representation of legal boundaries with respect to underground land administration and proposed a CityGML ADE that covers the additional features that represent the different surface types for better delineation.

2.3. Research Gaps

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As underlined in most of the related research, it is evident that there is a need for solid technical implementations that enable the 3D delineation of underground property rights. The previous efforts approached the 3D representations of property ownership for aboveground and underground separately. A great number of studies focused on the 3D depiction of property ownership aboveground and the existing examinations are not sufficient to uncover the benefits of the 3D modelling of subsurface legal spaces. The sustainable development of urban areas can be supported efficiently if 3D land administration practices provide accurate information on both surface and subsurface property rights in an integrated manner. The interoperability between different applications that utilize the information regarding underground property ownership can be realized if creating and validating the related spatial data is possible through the use of geoinformation-based data standards. A few studies zoomed in on this issue but the utilization of the CityJSON standard that provides effortless 3D data modelling and ease of implementation regarding software development is not sufficiently examined in terms of both surface and subsurface property rights. 3D representation of legal boundaries is mostly considered at the conceptual level and their investigation with respect to implementation is highly limited. There is also a need for elaborate research and demonstration regarding how to practically exploit the created 3D models covering the underground property ownership since the majority of previous studies only showed the visualization of these models.

3. Aim and Contributions of This Study

The present paper aims to extend the core schema of the CityJSON standard such that it allows for 3D representation of both legal spaces and boundaries in order to facilitate the efficient planning and management of underground space. This study provides notable contributions to the existing literature. First, the developed conceptual model can be used to delineate the legal spaces and boundaries that might be established on both surface and subsurface in an integrated way. The legal spaces regarding the apartment units and underground cadastral restrictions are examples of surface and subsurface respectively. Second, the CityJSON extension encompassing the essential features,

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attributes, and relationships for underground and aboveground property rights is generated. The connection between independent units, annexes, and shared facilities is also enabled within the created extension. It can be further extended based on the legal considerations of the specific study region. Third, the CityJSON-based prototyping approach that enables to creation of 3D geoinformation covering the legal spaces and boundaries is delivered in order to overcome the challenges regarding easy implementation of the conceptual models. Fourth, the prospective benefits of using the created 3D geoinformation including underground legal spaces are demonstrated in the sense of digital building permitting through a spatial database enabling 3D spatial analyses within possible case studies related to compliance checking.

4. Methodology

Figure 1 shows the overall methodology that is followed in this paper.

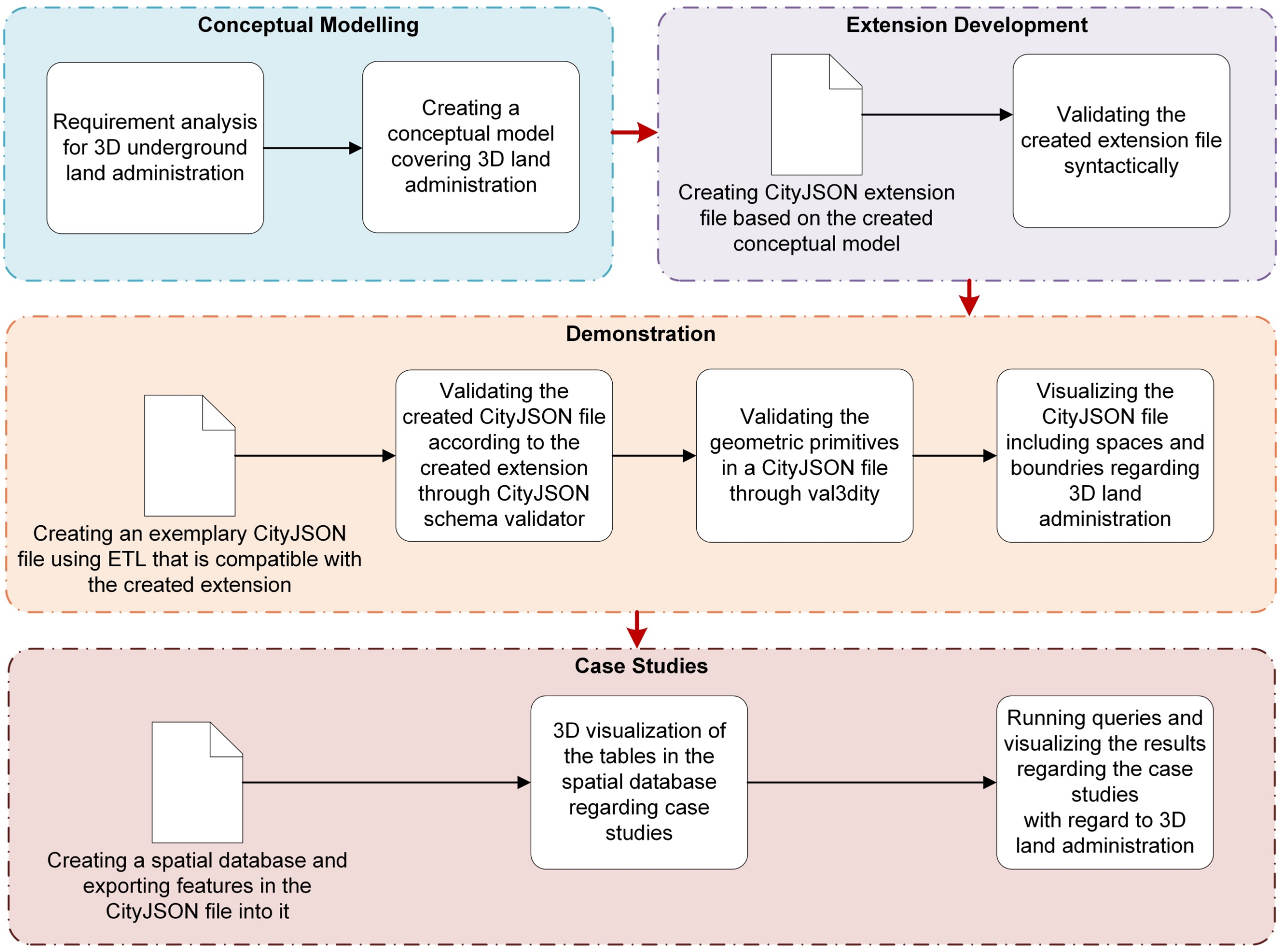

Figure 1. Research methodology.

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As can be seen in Figure 1, the first part of the methodology contains the conceptual modelling that can be used for the 3D delineation of ownership rights and their corresponding physical counterparts. This part covers identifying the various requirements for 3D land administration practices and creating a conceptual model consisting of features and relationships corresponding to these identified requirements. In the next step, the CityJSON core model is enriched based on the content of the developed conceptual model for 3D land administration including subsurface.

To show the usability of the developed CityJSON extension, the CityJSON file that includes many features and attributes that might be utilized when implementing 3D land administration is created, validated, and visualized within the demonstration part of the methodology. In the last part, features in the created CityJSON file imported into the spatial database and the case studies that demonstrate the practicability of the proposed CityJSON extension regarding 3D land administration are presented. It can be noted that each step within the methodology have the innovations in this research. The conceptual modelling part covers both surface and subsurface legal spaces and boundaries as distinct from existing works. The extension development part includes creating a CityJSON extension that is an original approach in the context of 3D land administration. The demonstration part contains novelty in the sense of implementation because of validating the exemplary CityJSON dataset with respect to developed extension and geometrically. The case studies part adds important value to the methodology in this paper by demonstrating how to incorporate the created extension practically.

5. Developing the Conceptual Model and the Corresponding Extension

The requirement analysis regarding the 3D underground land administration practices is carried out to be able to compose both features and relationships between them in the conceptual model efficiently. Since there are detailed studies that provide conceptual models on the 3D cadastral delineation and registration regarding aboveground, it is initially focused on the underground space for the requirement analysis in this paper. Legal and physical data requirements should be considered for implementing 3D land administration including underground space. It is benefited from a

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literature review and case studies from different countries to provide a fundamental and comprehensive integrated model.

Various perspectives should be taken into account for efficient use of underground space (Goel et al., 2012). Cadastral registration is one of these perspectives that deal with different kinds of underground assets such as apartment units and shared facilities (Guler et al., 2022; Gürsoy Sürmeneli et al., 2022a; Kuchler et al., 2024; Lai et al., 2023). The development aspect of the holistic land administration paradigm requires consideration of planning, designing, and constructing activities regarding different underground assets such as road and subway tunnels (Matuk, 2019; Perperidou et al., 2021; Ramlakhan et al., 2023). The management of utilities such as electricity, natural gas, water, and sewerage also covers the important part of 3D underground land administration (Pouliot and Girard, 2016; Yan et al., 2018). From the legal perspective, cadastral rights on the abovementioned objects are required for 3D land administration (Döner et al., 2010). Different cadastral restrictions on underground assets such as tunnels and utilities are needed for different reasons such as protection (Döner et al., 2011; Yan et al., 2021).

To put the legal part of 3D land administration into practice, the physical objects that represent the spatial extent of these legal parts should be provided (Saeidian et al., 2023b). For example, legal spaces regarding the buildings and apartment units and common facilities within the buildings are needed for the 3D underground land administration model (Guler et al., 2022). There is a need for 3D models of different physical objects such as pipelines and tunnels to be able to apply buffer zones related to cadastral restrictions (Radulović et al., 2019). Alongside the legal spaces, it is needed for 3D representation of legal boundaries that define the extent of legal spaces that belong to different underground assets such as columns and floors (Saeidian et al., 2024). Legal surfaces regarding the legal spaces of physical objects such as tunnels and historical sites are also needed to implement 3D land administration completely (Bieda et al., 2020). Figure 2 shows the developed conceptual model that can be used to implement 3D land administration including underground space. This model is mainly structured as generic but the requirements that are proposed in the literature regarding the countries are also considered in order to demonstrate that the developed model can be readily applied to different administrative areas (Guler et al., 2022; Saeidian et al., 2023b, 2024).

Figure 2. The developed conceptual model for the proposed schema extension.

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This model is created based on the requirements that are needed for the 3D modelling of legal spaces and boundaries regarding both surface and subsurface within land administration practices. Extension rules that are defined by the developers of the CityJSON standard are considered when creating the conceptual model. Since the JSON schemas do not allow inheritance, new city objects such as *+LABuilding* are added to the proposed extension. To provide the structural hierarchy/connection, there are two level city objects in the CityJSON schema and the relationship is enabled by the *parents* and *children* properties with respect to the instances of the city objects. For example, a *BuildingPart* instance should have the *parents* property with regard to a *Building* instance.

As can be seen from Figure 2 that all features except *+LABuilding* are modelled as a subclass of the *_AbstractCityObject* feature and *+LABuilding* is modelled as a subclass of the *_AbstractBuilding* feature in the CityJSON core schema. *+Parcel* is the main feature to model the 3D legal spaces on both surface and subsurface. It covers various attributes such as *parcelNumber*, *parcelID*, and *registrationDate* that can be useful for cadastral registration regarding underground assets. As mentioned before, there is a need for a 3D representation of different cadastral restrictions that might occur in the surface and subsurface. For this reason, *+Restriction* is included in the conceptual model with different attributes such as *type*. Cadastral restrictions on historical sites, mining, or wetland can be modelled with this feature.

Another feature type namely *+Easement* can be used for ownership rights regarding the different underground objects such as pipelines belonging to water and telecommunication networks or subway tunnels. It can be defined as a right for a specific reason to an authority that provides the use of the part of the land that is originally pertained by a different authority. Related instances can represent different types such as encumbrance which occurs if someone different from the registered holder has an interest in a piece of land. This feature is also beneficial for modelling the easement rights on different types of aboveground objects such as road bridges. *+DepthLimitation* is also added to the conceptual model to model different subsurface depth limitations. This feature contains *landApplied*

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attribute to store the information regarding affected land and *length* attribute for representing the size of the limitation.

Considering that the implementation of 3D land administration should cover the delineation of condominium rights that might occur in the subsurface within the buildings, the required features and relationships are also included in the conceptual model of the proposed extension. The approach that is proposed by Guler et al. (2022) is implemented in this study. As can be seen in Figure 2, *+CondominiumUnit* is included in the model to be able to represent condominium ownership in which one has the right of use for an independent unit and also a share in the common property within the buildings. A condominium unit can be expressed as the combination of a main unit (i.e., independent apartment unit), annex (e.g., underground private garage, storage), and shared facility (e.g., entrance, corridor). Therefore, *+MainUnit*, *+Annex*, and *+SharedFacility* features are included in the proposed conceptual model to unambiguously delineate the condominium rights. There are aggregation relationships between these features and the *+CondominiumUnit* because they can exist in the buildings even if the condominium rights are not established. *+MainUnit* and *+Annex* instances should have properties indicating a *+CondominiumUnit* instance and they can have only one parent instance. However, *+SharedFacility* instances might have at least one *+CondominiumUnit* instance as a parent since different *+CondominiumUnit* instances can have the right to use on same *+SharedFacility* instance.

The abovementioned features also have various attributes to store essential information regarding the registration of condominium rights. For example, different kinds of annexes and shared facilities can be stored using the *type* attribute. Unique IDs for *+Annex*, *+SharedFacility*, and *+MainUnit* instances can be represented using *annexID*, *sharedFacilityID*, and *mainUnitID* attributes respectively. Figure 2 also contains a number of enumerations that can be used to add values to different attributes such as *ParcelLandUseType*, *SharedFacilityType*, and *RestrictionType*. Since the condominium rights can be established only within existing buildings, there is a composition relationship between the

+CondominiumUnit and *+LABuilding* features. In other words, a *+CondominiumUnit* instance should have a *parents* property indicating a *+LABuilding* instance.

The features that can be utilized to represent the different types of legal boundaries are highly important for 3D land administration practices. In the CityJSON standard, these types of features are modelled as semantic surfaces and different types of city objects can have various types of semantic surfaces. *RoofSurface*, *WallSurface*, and *FloorSurface* are some examples of the semantic surfaces that *Building*, *BuildingPart*, and *BuildingRoom* can have. However, there is a need for semantic surfaces that represent different types of surfaces regarding legal boundaries. For example, *+MedianFloorSurface, +MedianWallSurface, +MedianCeilingSurface,* and *+MedianDoorSurface* that express the median face of the floor, wall, ceiling, and door are included in the developed extension since there is no semantic surface for the median faces in CityJSON core schema that can be subject to cadastral RRRs. A column and its surfaces can be also the subject of condominium rights in the buildings.

Although different types of constructive elements can be modelled using the *BuildingConstructiveElement* feature, there is no specific semantic surface for column surfaces in the core schema of the standard. Therefore, *+ColumnSurface* is included in the developed extension schema. *+CardinalDirectionWallSurface* and *+CardinalDirectionDoorSurface* are the extra semantic surfaces for semantically modelling the legal surfaces regarding the cardinal directions. Since the different surfaces of the door can be subject to cadastral RRRs, *+InteriorDoorSurface* is added to the core schema of the standard. In order to fulfill the need for 3D modelling of both projected and surveyed surfaces within 3D land administration, the extended schema contains *+ProjectedSurface* and *+SurveyedSurface* semantic surfaces. Table 1 lists the new semantic surfaces that are added to the core data model of the CityJSON standard. These semantic surfaces are identified inclusively based on the content of the previous works (Saeidian et al., 2024) and included within the conceptual model in this paper in order to demonstrate the modelling applicability of the developed approach in terms of legal boundaries.

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Table 1. The semantic surfaces that are included in the core schema and their reasonings.

Semantic Surface	**Reasoning**
+MedianFloorSurface	To model the median surface of the floor
+MedianWallSurface	To model the median surface of the wall
+MedianCeilingSurface	To model the median surface of the ceiling
+MedianDoorSurface	To model the median surface of the door
+ColumnSurface	To model the surface of the column
+CardinalDirectionWallSurface	To model the cardinal direction of the surface of the wall
+CardinalDirectionDoorSurface	To model the cardinal direction of the surface of the wall
+InteriorDoorSurface	To model the interior surface of the door
+ProjectedSurface	To model the projected surface
+SurveyedSurface	To model the surveyed surface

After developing the conceptual model, the next step is to create a CityJSON extension file that covers the content of this conceptual model. Different ways that are enabled by developers of CityJSON standard are followed. In this paper, the proposed extension is created based on the latest version of the standard, that is CityJSON v2.0. In the extension file, additional features in the conceptual model such as *+Parcel* and *+LABuilding* are identified as new city objects. The attributes belonging to new city objects and their formats are also included in the extension file. Figure 3a shows the part of the created extension file related to *+LABuilding* feature. Since it is modelled as a subclass of *_AbstractBuilding* feature, the geometry information is not included additionally. As mentioned before, there is a *parents* and *children* relationship between some of the extra features such as *+LABuilding* and *+CondominiumUnit.*

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Figure 3. Some parts of the created extension file.

In other words, every *+CondominiumUnit* instance should have *+LABuilding* instance as a parent. For this reason, *parents* member is modelled as a required member for *+CondominiumUnit.* A similar approach is followed for other extra city objects such as *+Annex* and *+MainUnit*. Since adding extra semantic surfaces within the extension development is enabled with the CityJSON v2.0, the features in Table 1 are included in the created extension file under the extra semantic surfaces part. Figure 3b illustrates part of the created extension file that contains a number of these surfaces such as *+CardinalDirectionDoorSurface* and *+ProjectedSurface*. The extra city objects might be modelled with the geometry types of MultiSurface, CompositeSurface, Solid, CompositeSolid, and MultiSolid. After creating the JSON file representing the proposed extension via the text editor, it is validated syntactically using the validator that is shared by developers of CityJSON[1]. The validation result can be found in the GitHub repository that contains files regarding this research (see Supplementary Files).

[1] https://jsonschemalint.com/#!/version/draft-07/markup/json

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6. Implementation and Demonstration

To show the usability of the proposed CityJSON extension regarding the implementation of 3D land administration, an exemplary dataset is designed and created based on the selected study area. The study area is located in Istanbul, Türkiye and it covers the different cases regarding the cadastral RRRs for surface and subsurface that are selected to present the applicability of the proposed extension schema. As seen in Figure 4, there is a surface building in the study area.

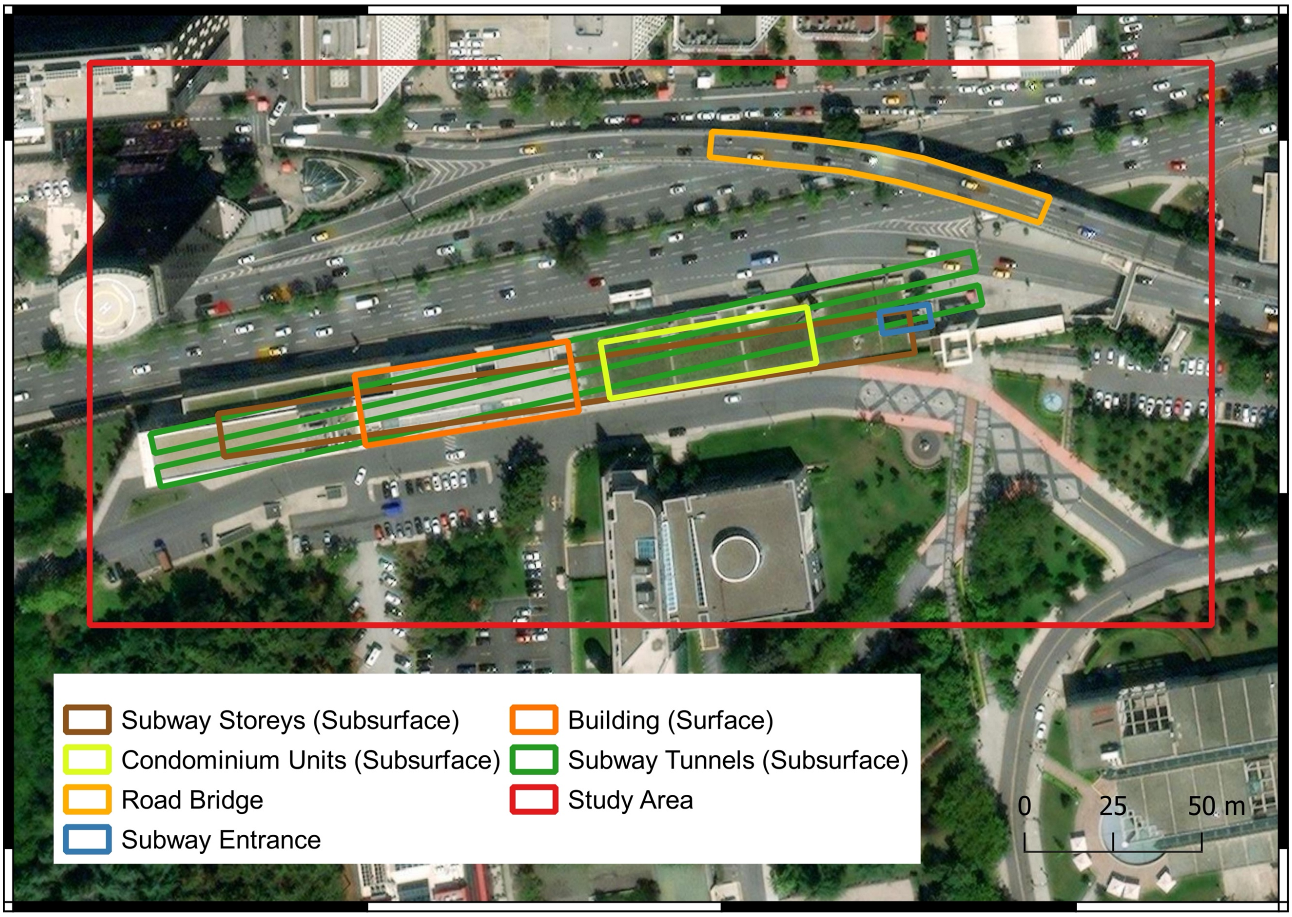

Figure 4. 2D map representing the complex situation regarding aboveground and underground assets.

Below this building, there are subsurface subway storeys and condominium units in these storeys. Condominium units express the combination of an independent unit and also an annex that is located at minus one floor. Below these condominium units, there are also subsurface tunnels. In the study area, there is a road bridge as well. It can be noted that detailed plans of 2D legal spaces regarding the abovementioned underground objects are not available even though there is a highly complex

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situation in terms of underground ownership. Because of this, they are defined and showcased by the authors to present the feasibility of the proposed approach in this paper. To be able to represent the functionality of the proposed extension wholly, extra features such as the powerline network that can be seen in Figure 5 are included in the exemplary data. 2D spatial data of the different features such as buildings, road bridges, powerline networks, cadastral restrictions, and subway tunnels is prepared.

Figure 5. 2D map representing the situation regarding the powerline network and subway tunnels.

This data includes the attributes and their values based on the developed conceptual model. One of these attributes stores the parameter regarding the vertical dimension of the features. FME Workbench 2022.1.3[2] is exploited to transform 2D spatial data in GeoJSON format into 3D spatial data in CityJSON format. A workflow that allows for automating the creation of the CityJSON file based on input spatial data and its attributes is developed within the software. In this workflow, 2D

[2] https://fme.safe.com/

features are transformed into 3D features by using the *Extruder* tool within the software that is executed based on the related attribute of the input feature. The *children* and *parents* relationships are also enabled by matching the attributes that indicate the information regarding *children* and *parents* values in the features with corresponding parameters within the writer. This matching is realized using *AttributeCopier* tool within the workflow. In the software, 3D features belonging to city objects that may have semantic features are decomposed and the semantic information is included to a specific surface instance. The surfaces pertaining to the selected city object are composed to create a resulting city object instance that has various surfaces with different semantics.

The extra city objects alongside the existing city objects can be included in the created CityJSON files so that the prototyping of the proposed conceptual model is achieved. As mentioned before, the proposed extension is developed based on CityJSON v2.0. Since only the CityJSON v1.0 files can be created using this software, the exported CityJSON v1.0 file is converted to CityJSON v2.0 by means of *cjio*[3]. It is a free command line interface (CLI) that is shared by the developers of the CityJSON standard to manipulate the CityJSON files. The compatibility of the resulting CityJSON file that contains the 3D modelling of various features regarding 3D land administration with the developed CityJSON extension is checked by means of the *CityJSON schema validator*[4]. It is a free tool that is shared by the developers of the standard to validate the created CityJSON files in terms of JSON syntax, CityJSON schemas, Extension schemas, parents_children_consistency, wrong_vertex_index, semantics_arrays, textures, materials, extra_root_properties, duplicate_vertices, and unused_vertices. To able to validate the CityJSON file, the JSON file representing the developed CityJSON extension is uploaded to the GitHub repository. The above-mentioned tool provides the result showing that the created CityJSON file is 100% valid. It can be noted that this tool does not validate the geometry or semantics of CityJSON files. The 3D geometric primitives within the created CityJSON file are validated against ISO19107 (ISO, 2019) standard using the *val3dity*[5] tool and the result showing that

[3] https://github.com/cityjson/cjio
[4] https://validator.cityjson.org/
[5] http://geovalidation.bk.tudelft.nl/val3dity/

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all primitives are 100% valid is obtained (Ledoux, 2018). The detailed versions of the validation reports can be seen in the same GitHub repository. Figure 6 presents the parts from the content of the created CityJSON file.

a)


```
"building2":
{
    "attributes":
    {
        "dateOfBuildingPermit": "22.10.2010",
        "numberOfFloor": 8
    },
    "children": ["condo10", "condo20", "condo30", "condo40"],
    "geometry": [
        {
            "boundaries": [[[2803, 2804, 2805, 2806]], [[2803, 2806,
            2807, 2808]], [[2806, 2805, 2809, 2807]], [[2805, 2804,
            2810, 2809]], [[2804, 2803, 2808, 2810]], [[2808, 2807,
            2809, 2810]]],
            "lod": "2.0",
            "type": "MultiSurface"
        }
    ],
    "type": "+LABuilding"
},
```


b)


```
"condo10":
{
    "attributes":
    {
        "dateOfSale": 2023,
        "marketValue": 3100000
    },
    "children": ["c9f99768-6ec8-4590-a541-21238258f3c1",
    "dfb3c447-d295-4ac7-b867-585376078331", "shared10", "shared20"],
    "geometry": [
        {
            "boundaries": [[[[[2819, 2820, 2821, 2822]], [[2819, 2822,
            2823, 2824]], [[2822, 2821, 2825, 2823]], [[2821, 2820,
            2826, 2825]], [[2820, 2819, 2824, 2826]], [[2824, 2823,
            2825, 2826]]]]],
            "lod": "2.0",
            "type": "MultiSolid"
        },
        {
            "boundaries": [[[[[112, 123, 2835, 2836]], [[112, 2836,
            2837, 2838]], [[2836, 2835, 2839, 2837]], [[2835, 123, 2840
            , 2839]], [[123, 112, 2838, 2840]], [[2838, 2837, 2839,
            2840]]]]],
            "lod": "2.0",
            "type": "MultiSolid"
        }
    ],
    "parents": ["building2"],
    "type": "+CondominiumUnit"
},
```


c)


```
"dfb3c447-d295-4ac7-b867-585376078331":
{
    "attributes": {},
    "geometry": [
        {
            "boundaries": [[[[[112, 123, 2835, 2836]], [[112, 2836, 2837,
            2838]], [[2836, 2835, 2839, 2837]], [[2835, 123, 2840, 2839]],
             [[123, 112, 2838, 2840]], [[2838, 2837, 2839, 2840]]]]],
            "lod": "2.0",
            "type": "MultiSolid"
        }
    ],
    "parents": ["condo10"],
    "type": "+MainUnit"
},
```


Figure 6. The parts of CityJSON belonging to different types of object instances: a) a building with the type of +*LABuilding*, b) a condominium unit with the type of +*CondominiumUnit*, c) a main unit with the type of +*MainUnit*.

While Figure 6a contains the details on a +*LABuilding* instance with the id of "building2", Figure 6b shows the content of a +*CondominiumUnit* instance with the id of "condo10". Figure 6c illustrates

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the details of a +*MainUnit* instance with the id of "dfb3c447-d295-4ac7-b867-585376078331". As highlighted in these figures, there is a *children* and *parents* relationship between the above-mentioned instances. This relationship comes from the relationship between the related feature types in the developed conceptual model that is presented in Figure 2. Whereas Figure 6a illustrates that the "building2" instance has four children namely "condo10", "condo20", "condo30", and "condo40", Figure 6b shows that the "condo10" instance has a parent as "building2". Figure 6b also shows that the "condo10" instance has various children instances namely "c9f99768-6ec8-4590-a541-21238258f3c1", "dfb3c447-d295-4ac7-b867-585376078331", "shared10", "shared20". As seen in Figure 6c, "c9f99768-6ec8-4590-a541-21238258f3c1" that represents a +*MainUnit* feature type has a parent as "condo10" instance. In light of this information, it can be underlined that the relationship between the different feature types is enabled properly within the created CityJSON file. While +*LABuilding* instance is modelled as MultiSurface, +*CondominiumUnit,* and +*MainUnit* instances are modelled as MultiSolid. These geometry types are included within the developed CityJSON extension file.

The created CityJSON file is visualized using the *ninja*[6] tool that is a web-based application for visualizing and amending the CityJSON files in order to present the 3D delineations of different features regarding the 3D land administration practices. The CityJSON files that are created based on the extensions can be visualized readily with this tool. Figure 7 illustrates the 3D representations of the subsurface features in which their contents within the created CityJSON file are presented in Figure 6a, Figure 6b, and Figure 6c. These features are related to the registration of condominium rights.

As can be seen in Figure 7, the "condo10" instance has the right to use on +*MainUnit* instance and a +*Annex* instance. These instances have parent value as "condo10" as can be shown with the red plus sign in bold in Figure 7. Similarly, the "shared10" instance has four parents as "condo10", "condo20",

[6] https://ninja.cityjson.org/#

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"condo30", and "condo40" since all condominium units in the building have the right to exploit shared facilities in this building.

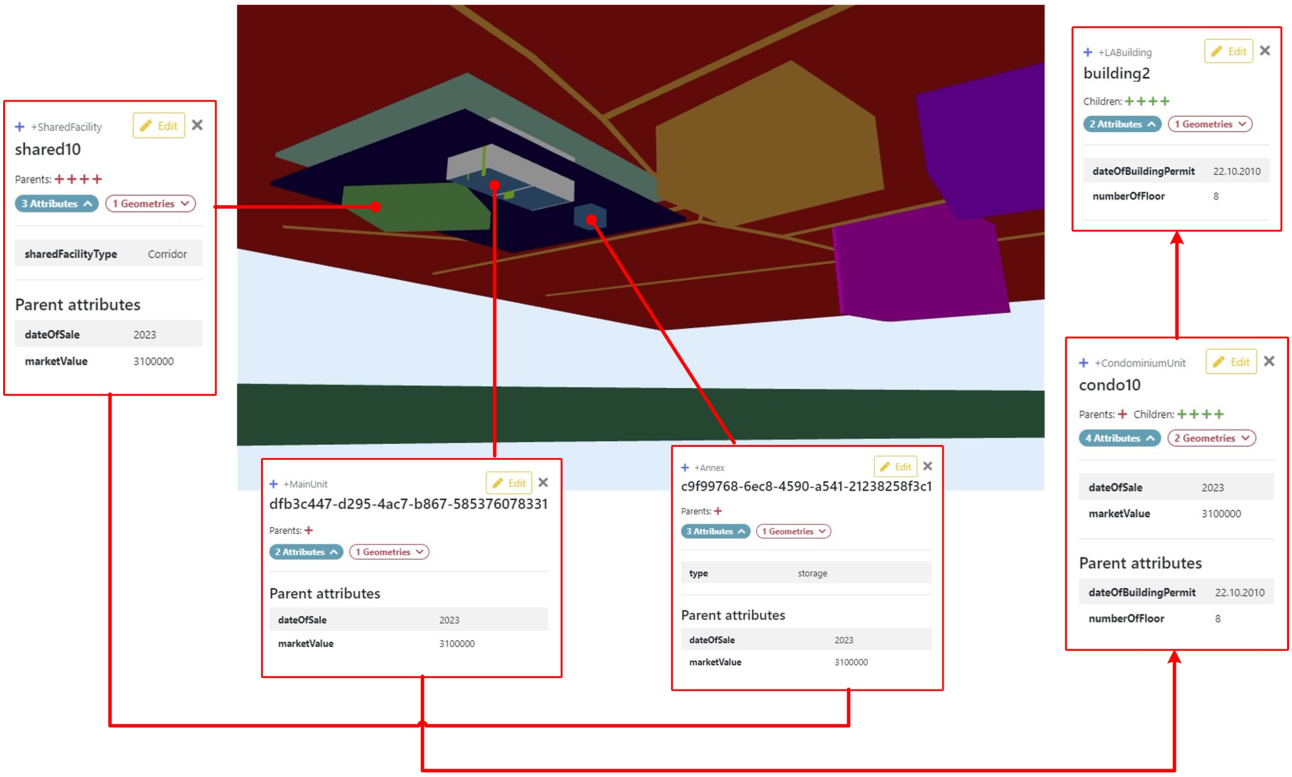

Figure 7. 3D visualization of the features regarding the condominium rights.

Figure 7 presents that the "condo10" instance has two more children in the +*SharedFacility* feature type alongside +*MainUnit* and +*Annex* instances. While the "shared10" instance is modelled as a corridor with the *sharedFacilityType* attribute, the +*Annex* instance has an attribute namely *type* with the value of storage. It can be also seen that the "building2" instance has four children instances as condominium units as mentioned before. As highlighted in Figure 2, the 3D representation of different types of cadastral RRRs regarding both surface and subsurface is enabled in this research. Figure 8 illustrates 3D representations of instances from these types namely +*DepthLimitation*, +*Restriction*, and +*Easement*. The instance with the id of "cb5bc891-db3a-4b85-acd7-a6dcb1ae9f83" expresses the cadastral restriction regarding the underground historical site. Similarly, the restriction on limitation of underground depth is modelled with the id of "11d13955-8acc-465d-ac84-e5fb1726d24d".

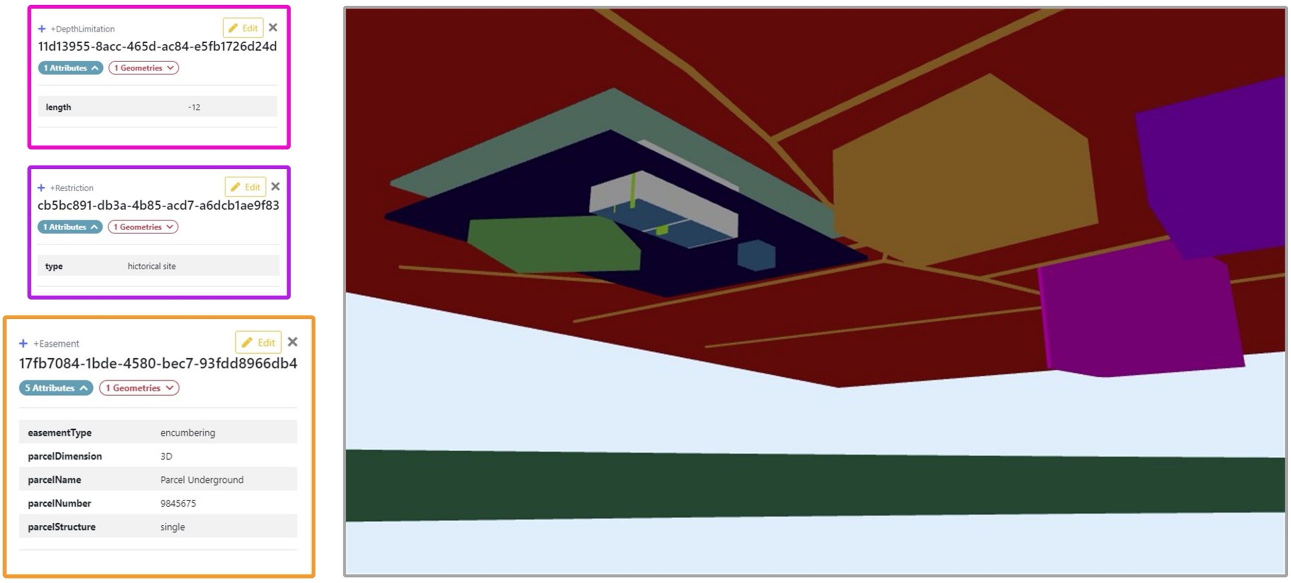

Figure 8. 3D visualization of the features regarding cadastral RRRs (Note: Border colors of the boxes indicate the features).

It also provides the length information as an attribute. An easement that expresses the specified 3D buffer (i.e., 0.5 m) pertaining to the subsurface powerline network is modelled in 3D within the created CityJSON file with the id of "17fb7084-1bde-4580-bec7-93fdd8966db4".

Different types of constructive elements and related cadastral information can be modelled by using the *BuildingConstructiveElement* feature type in the CityJSON v2.0 schema. The legal information regarding the surfaces of these elements can also be delineated within this schema. As mentioned before, extra semantic surfaces that are listed in Table 1 are included in the proposed CityJSON extension to obtain a 3D delineation of legal boundaries comprehensively. In this regard, Figure 9 presents the contents of several instances regarding the different constructive elements within the created CityJSON file. These elements are modelled with the geometry type of MultiSurface. As shown in Figure 9a, the instance with the id of "09e0918f-33d4-4499-9910-e6393816c0d3" expresses a column object within the building and has a parent value for indicating the specific building instance. The surfaces of this column object are also modelled semantically as *+ColumnSurface* which is one of the extra semantic surfaces. Figure 9b illustrates the instance with the id of "1c1555c6-b3ac-4fdf-86cb-fe140af1c411" that represents a wall object within the "building2" instance.

a)


```json
"09e0918f-33d4-4499-9910-e6393816c0d3":
{
    "attributes":
    {
        "function": "column"
    },
    "geometry": [
        {
            "boundaries": [[[8, 9, 10, 11]], [[8, 11, 12, 13]], [[11, 10, 14, 12]],
            [[10, 9, 15, 14]], [[9, 8, 13, 15]], [[13, 12, 14, 15]]],
            "lod": "2.0",
            "semantics":
            {
                "surfaces": [
                    {
                        "type": "+ColumnSurface"
                    }
                ],
                "values": [0, 0, 0, 0, 0, 0]
            },
            "type": "MultiSurface"
        }
    ],
    "parents": ["building2"],
    "type": "BuildingConstructiveElement"
},
```


b)


```json
"1c1555c6-b3ac-4fdf-86cb-fe140af1c411":
{
    "attributes":
    {
        "function": "wall"
    },
    "geometry": [
        {
            "boundaries": [[[44, 45, 46, 47, 48, 49, 50]], [[44, 50, 51, 52]], [[50,
             49, 53, 51]], [[49, 48, 54, 53]], [[48, 47, 55, 54]], [[47, 46, 56, 55
            ]], [[46, 45, 57, 56]], [[45, 44, 52, 57]], [[52, 51, 53, 54, 55, 56, 57
            ]], [[47, 46, 58, 59, 50, 49, 60, 61, 62]], [[47, 62, 63, 55]], [[62, 61
            , 64, 63]], [[61, 60, 65, 64]], [[60, 49, 53, 65]], [[49, 50, 51, 53]],
            [[50, 59, 66, 51]], [[59, 58, 67, 66]], [[58, 46, 56, 67]], [[46, 47, 55
            , 56]], [[55, 63, 64, 65, 53, 51, 66, 67, 56]]],
            "lod": "2.0",
            "semantics":
            {
                "surfaces": [
                    {
                        "type": "WallSurface"
                    },
                    {
                        "type": "OuterCeilingSurface"
                    }
                ],
                "values": [0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
                0]
            },
            "type": "MultiSurface"
        }
    ],
    "parents": ["building2"],
    "type": "BuildingConstructiveElement"
},
```


c)


```json
"3b2716a2-f57a-4434-8934-19f19f993b70":
{
    "attributes":
    {
        "function": "floor"
    },
    "geometry": [
        {
            "boundaries": [[[86, 87, 88, 89]], [[86, 89, 90, 91]], [[89, 88, 92, 90
            ]], [[88, 87, 93, 92]], [[87, 86, 91, 93]], [[91, 90, 92, 93]]],
            "lod": "2.0",
            "semantics":
            {
                "surfaces": [
                    {
                        "type": "FloorSurface"
                    }
                ],
                "values": [0, 0, 0, 0, 0, 0]
            },
            "type": "MultiSurface"
        }
    ],
    "parents": ["building2"],
    "type": "BuildingConstructiveElement"
},
```


Figure 9. The parts of CityJSON for different features: a) a column having a +*ColumnSurface* semantic surface, b) a wall having the *WallSurface* and *OuterCeilingSurface* semantic surfaces, c) a floor having a *FloorSurface* semantic surface.

As seen in Figure 9b this *BuildingConstructiveElement* object representing a wall instance has a number of semantic surfaces and these surfaces can be modelled differently in terms of semantics. For example, one of the surfaces of the mentioned wall object is modelled as *OuterCeilingSurface,*

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and others are modelled as *WallSurface*. In addition, an instance of the *BuildingConstructiveElement* object expressing a floor object can be seen in Figure 9c. Similar to other constructive elements, the surfaces of the floor object can be modelled semantically. The *semantics* member within the *geometry* represents the semantic surfaces regarding the object such as column, wall, and floor. Figure 10 illustrates the 3D representations of the abovementioned *BuildingConstructiveElement* instances. The parent values belonging to these instances and their attributes and surface types can be seen in Figure 10. The legal surfaces such as +*ProjectedSurface* pertaining to an +*Easement* instance that represents the right to use for underground tunnels can be modelled by means of the developed extension.

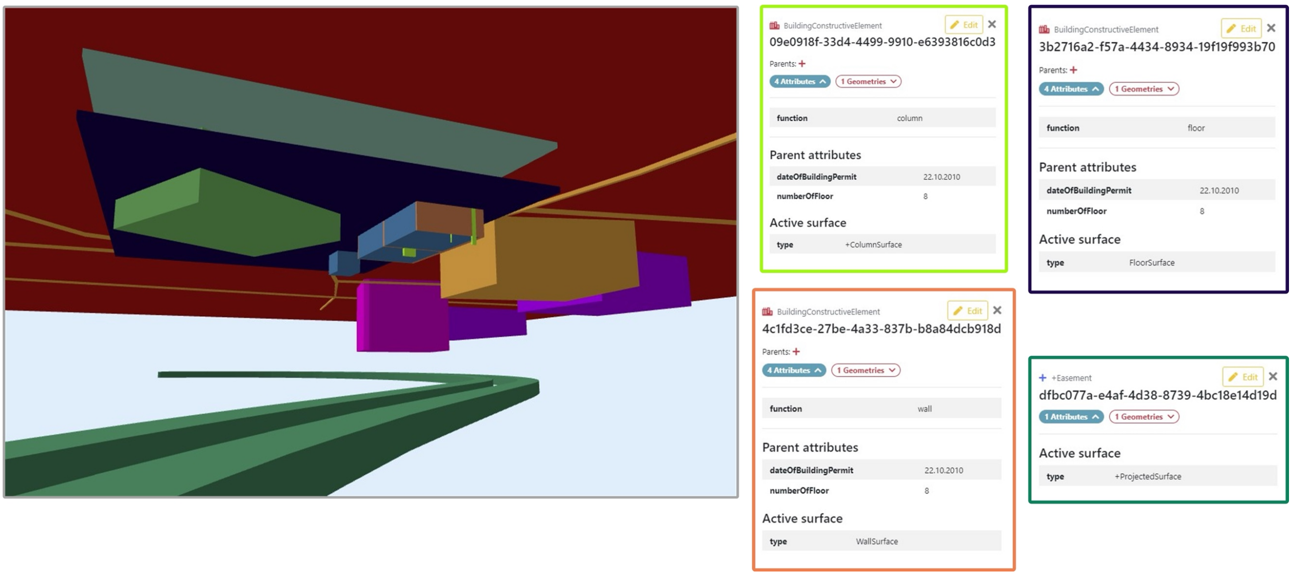

Figure 10. 3D visualizations of the features and their semantic surfaces (Note: Border colors of the boxes indicate the 3D features).

By means of the developed extension, the ownership information about the surfaces of the constructive elements can be modelled. Figure 11 illustrates a *BuildingConstructiveElement* instance as a column in which its legal boundaries have different ownership information. While the selected surface of the column presents the common ownership in Figure 11a, Figure 11b shows that the different surface of the same column expresses the private ownership for "condo20". Figure 11c contains the corresponding part of the CityJSON file for the above-mentioned column instance. As can be seen in Figure 11c, surfaces having different members (e.g., ownership) and values (e.g.,

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common) are declared within *surfaces* property and they are assigned/linked to the surfaces of the column using *values* property.

Figure 11. The semantic surface examples on a column and their details: a) +*ColumnSurface* representing common ownership, b) +*ColumnSurface* representing private ownership, c) corresponding part of the CityJSON file for the column object.

The numbers (e.g., 0 and 1) within *values* property indicate the order of the defined semantic surfaces in *surfaces* property. This is the way how the legal boundaries are defined by physical elements such as columns and walls.

The city objects representing the legal spaces are defined by the authors since there is no detailed plan about them as mentioned and they are created as covering the legal boundaries. Figure 12 demonstrates the +*Easement* instance that represents the buffered legal space and legal boundaries for an underground tunnel. The modelling of two geometry types namely MultiSurface and Solid are represented in Figure 12. The legal boundaries of this instance are modelled as +*ProjectedSurface* that is one of the extra semantic surfaces within the developed extension. For both modelling approaches, the link between legal boundaries (i.e., +*ProjectedSurface*) and legal space (i.e., +*Easement*) instance is realized through *values* and *surfaces* properties within *semantics* member that is covered by *geometry* object. The source of physical data is obtained from the Geography Markup Language (GML) dataset of a zoning plan that covers the geometry of the underground tunnel. It is organized and exported as the GeoJSON file that can be used as the input for the workflow within FME.

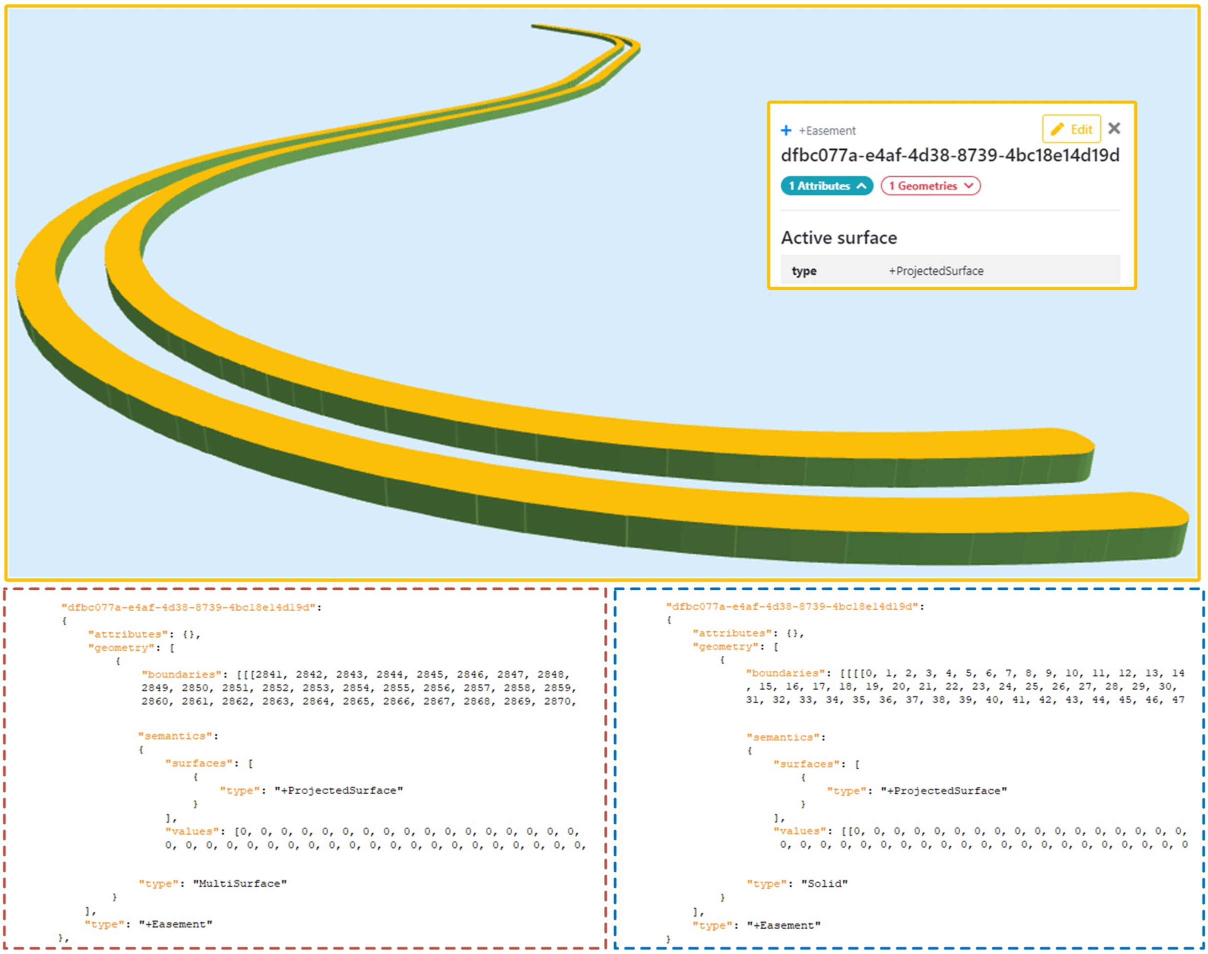

Figure 12. The representations of different geometric modelling approaches for an +*Easement* instance (Note: Some parts of *boundaries* and *values* are removed for clarity because they cover a large number of rows).

To demonstrate the applicability of the proposed extension, various case studies regarding compliance checking based on cadastral RRRs are presented. The descriptions and the reasonings of these case studies are listed in Table 2. The aforementioned case studies contain compliance checking regarding

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an underground tunnel project. The designed tunnel is modelled within the created CityJSON file. To be able to carry out queries regarding the case studies, a spatial database within PostgreSQL[7] is created and PostGIS[8] that allows for applying various spatial analyses is enabled in this database.

Table 2. The case studies and their reasonings.

ID	**Description**	**Reasoning**
C1.1	Results on whether there is an intersection between the tunnel project and cadastral restrictions	It is helpful in decision-making to know that tunnel alignment should not cross any restriction. The designed projects should not intersect with the current cadastral restrictions to get the building permit.
C1.2	Results on whether there is an intersection between the tunnel project and cadastral depth limitations	It is helpful in decision-making to know that tunnel alignment should not cross any restriction. The designed projects should not intersect with the current cadastral depth limitation to get the building permit.
C2	Results of the distance between current buildings and the tunnel project	It is preferred that the tunnel alignment should pass under the minimum number of buildings to reduce the possible effects. The distance that is specified in the zoning regulation should be provided to get the building permit.
C3	Results on whether there is an intersection between the tunnel project and current easements	It is helpful in decision-making to know that tunnel alignment should not cross any restriction. The designed projects should not intersect with the current easements to get the building permit.

[7] https://www.postgresql.org/
[8] https://postgis.net/

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Since the case studies require different 3D spatial analyses, SFCGAL[9] extension that provides 3D spatial functions is also enabled within the PostGIS. The instances within the created CityJSON file are imported to the developed spatial database. Table 3 presents the Structured Query Language (SQL) queries that are used to implement the case studies in Table 2. Different 3D spatial functions are exploited within these queries, for example, *ST_MakeSolid*.

Table 3. The queries that are used for the case studies and their execution times.

ID	Query Content	Execution Time
Q1.1	create table check1_1 as select a.fid, a.geom, ST_3DIntersects(ST_MakeSolid(a.geom), ST_MakeSolid(b.geom)) as intersection from public."depth_limitation1" a, public."tunnel_2" b where ST_3DIntersects(ST_MakeSolid(a.geom), ST_MakeSolid(b.geom))='true';	450 msec.
Q1.2	create table check1_2 as select a.fid, a.type, a.geom, ST_3DIntersects(ST_MakeSolid(a.geom), ST_MakeSolid(b.geom)) as intersection from public."restriction" a, public."tunnel_2" b where ST_3DIntersects(ST_MakeSolid(a.geom), ST_MakeSolid(b.geom))='true';	47 msec.
Q2	create table check2_1 as select a.fid, a.geom as building_geom, ST_3DDWithin(ST_MakeSolid (a.geom), ST_MakeSolid (b.geom), 3) as checking, ST_3DDistance(ST_MakeSolid (a.geom), ST_MakeSolid (b.geom)) as distance from public."buildings" a, public."tunnel_2" b where ST_3DDWithin(ST_MakeSolid (a.geom), ST_MakeSolid (b.geom), 3)='true'; update check2_1 set checking='false' where checking='true';	427 msec.

[9] https://sfcgal.gitlab.io/SFCGAL/index.html

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Q3	create table check3_1_2 as select a.fid, a.type, a.geom, ST_3DDWithin(ST_MakeSolid (a.geom), ST_MakeSolid (b.geom), 15) as checking, ST_3DDistance(ST_MakeSolid (a.geom), ST_MakeSolid (b.geom)) as distance from public."easement1" a, public."tunnel_2" b where ST_3DDWithin(ST_MakeSolid (a.geom), ST_MakeSolid (b.geom), 15)='true'; update check3_1_2 set checking='false' where checking='true';	2 sec. 22 msec.

Within Q1.1 and Q1.2, the *ST_MakeSolid* function creates the 3D solid models of the instances in the input tables namely tunnel and depth limitation. The *ST_3DIntersects* function produces true or false depending on whether these created 3D solids intersect or not. Figure 13a illustrates the 3D representation of the instances in database tables that are utilized within Q1.1. and Q1.2.

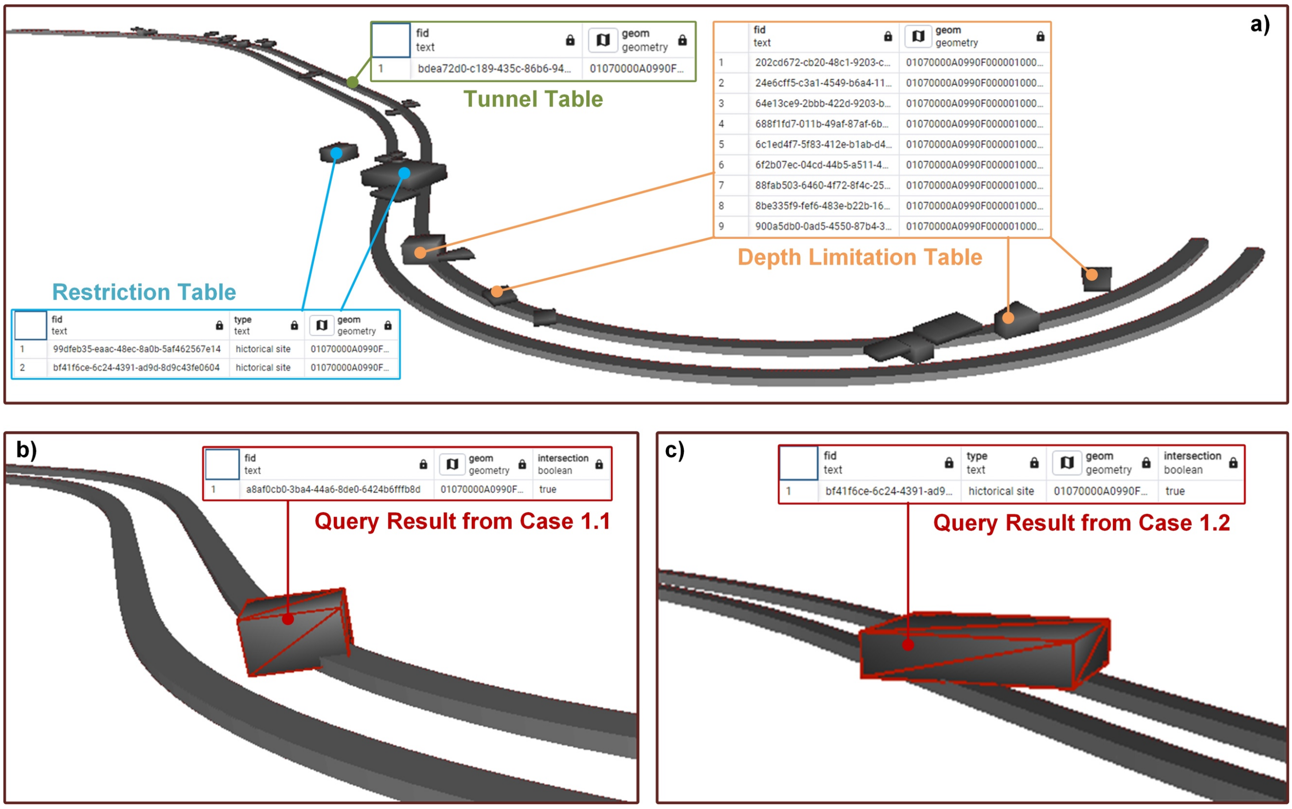

Figure 13. The results regarding Q1.1 and Q1.2.

As can be seen in this figure, there are subsurface cadastral restrictions and depth limitations throughout the underground tunnel. Figure 13b and Figure 13c illustrate the results derived from these queries. As seen in these figures, intersected instances from related tables are identified and their *fid* values and also geometries (*geom*) are shown. The abovementioned queries can be beneficial for decision-making process regarding tunnel design by automating the checking process with respect to cadastral restrictions. The query results are created as new tables in the spatial database and hence they are accessible for further use.

The result of Q2 shows the 3D distance between 3D solid models through the *ST_3DDistance* function. Figure 14a presents the 3D representation of instances in tunnel and buildings tables and a part from the buildings table within the spatial database. It can be noted that some of these buildings have subsurface floors. There are certain legal restrictions on securing the required distance between existing subsurface construction and the designed tunnel. Q2 provides an automated way for finding the buildings in which the designed tunnel is located within this distance. It results in the determined distances between the buildings and the tunnel as well as the attributes of these buildings. As seen in Table 3, "3 m" is selected as the required distance in C2. Figure 14b illustrates the results for Q2 that produces the building instances that are within the specified distance of the tunnel.

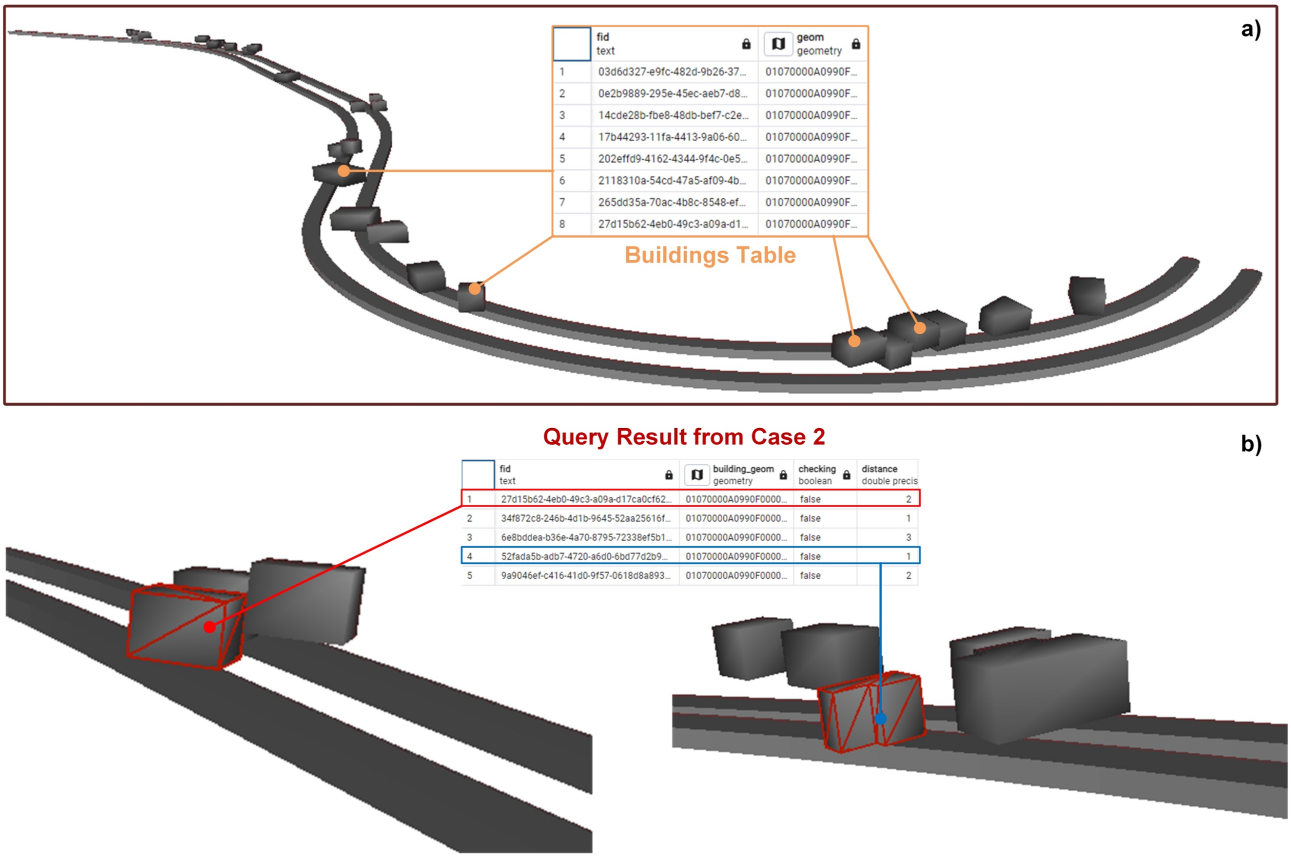

Figure 14. The result regarding Q2.

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The field titled *checking* contains *false* value expressing that the required distance is not maintained. This result is obtained by *ST_3DDWithin* function that provides the true or false result depending on whether the 3D geometries of the inputs are within the specified distance. As demonstrated by Figure 14b, all values within *distance* field are equal or less than the selected distance in this case, that is 3 m. This figure also shows the 3D representation of the determined building instances. Q3 uses a similar approach in Q2 to find whether any easement object is within the specified distance with the designed tunnel. Figure 15a presents the part of the table containing different easement instances regarding various utilities such as powerline network.

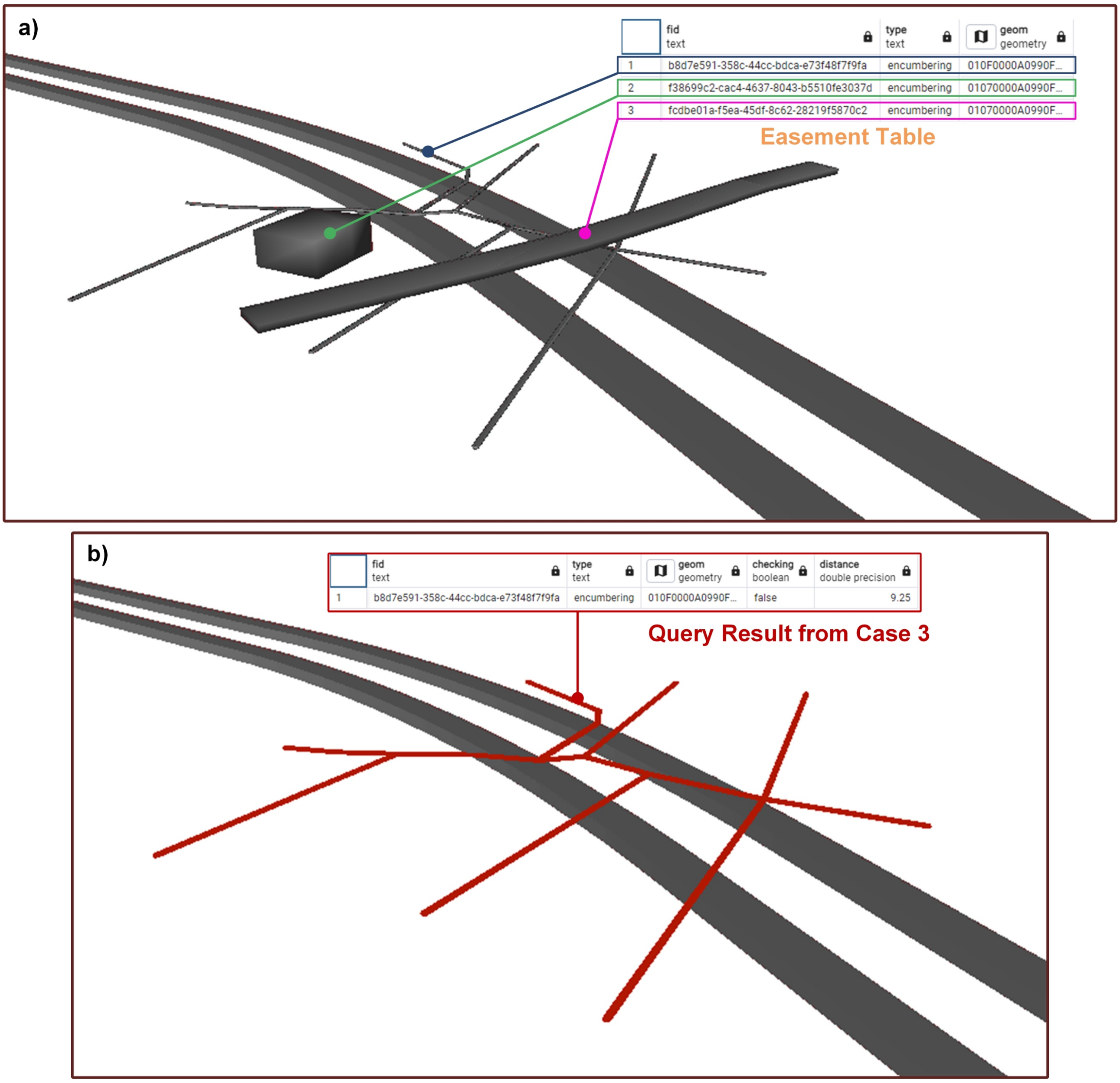

Figure 15. The result regarding Q3.

Figure 15b pinpoints that the quantity of the distance between the easement pertaining to the powerline network and tunnel is smaller than the specified distance in Q3, which is 15 m in this example. The required distance that should be maintained to protect underground ownership and subsurface utilities can be controlled by means of this query.

7. Discussion

This paper develops a CityJSON extension that covers the essential city objects and relationships in order to fulfill the need for standardized 3D geoinformation regarding the 3D land administration including both surface and subsurface. From the legal perspective, the unambiguous legal basis that covers the elaborate information is highly significant to be able to create an overarching conceptual model. This is the first step towards practicing 3D land administration. Updating the related laws and regulations regarding property ownership might be nontrivial. In this sense, the legal descriptions regarding underground cadastral RRRs might not be in-depth (Ramlakhan et al., 2023). This is because the need for development in the subsurface is accelerated due to the increased urbanization in recent years (F.-L. Peng et al., 2023). Since insufficient information with respect to underground cadastral RRRs might impede the advantageous planning of underground space, amendments in the legal documents might be considered. Given that different countries might have distinct legal descriptions regarding property ownership within underground space (Karabin et al., 2020), the conceptual model that can be used as a basis for administrative areas is presented. The cadastral approach regarding the distinct surfaces of the constructive elements within the buildings is one of the different approaches between the countries. For example, the inner surfaces of the columns within the apartment/independent unit are considered shared facilities in some jurisdictions. For this reason, the developed conceptual model can be amended and extended based on the requirements in the legal basis of the countries/jurisdictions.

From the technical perspective, it can be underlined that developing an extension for an existing data model of the standards is limited to presenting the conceptual models. The evidence with regard to the applicability of those models is, therefore, lacking. To overcome this lack, in the present paper, the conceptual model is implemented physically through creating, validating, visualizing, and demonstrating the CityJSON file. Validating the created extension files and datasets is quite important in terms of spatial data modelling. The extension file should be valid to be used for planned application areas and extended for other components regarding sustainable urban development. The datasets should be validated geometrically and with respect to developed extension for integrating them into the geodatabase and achieving up-to-date geoinformation in an interoperable manner. This study provides fundamental evidence regarding the validations of the CityJSON extension and corresponding file in the context of 3D modelling of cadastral RRRs.

The input data is another issue to be mentioned. In the present paper, 2D spatial data (i.e., GeoJSON) representing the different types of cadastral RRRs is utilized to present the prototype of the proposed conceptual model. This data is amended in a way to cover the attributes within the conceptual model and their values. However, the pipeline within the FME workbench can be restructured based on the input spatial data formats, for example, ifc, fbx, glb, and 3ds. This is important because the existing underground assets might be designed by using different software and tools.

The organization of data might be time-consuming when the large application areas are considered. For this reason, it is significant to comprehensively determine data specifications before starting to create 3D models based on the existing 2D cadastral registrations. Considering that there is a growing interest in designing new infrastructure facilities and buildings by using BIM, these BIMs can be beneficial in 3D delineation of property ownership (Guler and Yomralioglu, 2021). For example, the easement on underground tunnels can be modelled through simplifying the detailed BIM model and then converted into a CityJSON file. It can be stored in the spatial database in order to be utilized in urban planning studies regarding the subsurface that require various 3D spatial analyses. It should be underlined that the availability of BIMs of constructed subsurface assets is highly limited today and this augments the importance of the present study that enables to 3D modelling of these assets based on open geoinformation standard.

To inclusively cover the cadastral requirements within the laws and regulations of the countries, extra city objects that are needed can be included in the conceptual model. As demonstrated in this paper, the CityJSON files that will be created according to the developed conceptual model can be validated before registering the cadastral database. It is significant to mention that the versions of the standards provide different specifications in terms of data modelling. For example, CityJSON v1.0 does not allow adding new semantic surfaces within the created extension. The extra semantic surfaces that can be used to comprehensively delineate the cadastral RRRs are able to be included in the extensions through CityJSON v2.0 (see Figure 9). These extra semantic surfaces can be determined based on the requirements of the administrative areas.

Another point from the technical perspective is that there is a need to integrate the condominium rights that might occur in the subsurface within 3D land administration. Since existing studies mainly cover the aboveground condominium rights (Gürsoy Sürmeneli et al., 2022a; Li et al., 2016) and the mentioned issue is not investigated adequately in the previous works, the present study can contribute to facilitating the implementation of 3D land administration including underground cadastral RRRs (see Figure 7). This is because 3D models regarding the aforementioned issue are provided through the developed extension that is based on the proposed model that covers the essential city objects (e.g., *CondominiumUnit*) and their relationships as well.

This study also demonstrates the practicability of developed extension with the potential real-world use cases (see Figure 13, Figure 14, and Figure 15). Given that previous works are commonly limited to presenting 3D visualizations with regard to the conceptual models (Nega and Coors, 2022; Perperidou et al., 2021; Ramlakhan et al., 2023; Saeidian et al., 2023b, 2024), this study provides additional support for practicing the sustainable development and management of urban underground space. This is because it shows the execution of the different 3D spatial analyses that are utilized by using the created dataset based on the proposed extension. These analyses can be useful for planning the underground space in a comprehensive manner (Guler, 2023; Kuchler et al., 2024). There is an increasing trend for digitalizing the building permit procedures that are essential mechanisms for ensuring the sustainable development and resilience of urban areas (Fauth et al., 2024; Guler and Yomralioglu, 2022; Noardo et al., 2022). This digitalization significantly benefits from the 3D digital data models of various datasets such as zoning plans (e.g., CityJSON) and designed buildings (e.g., IFC) (Emamgholian et al., 2024). Since the presented cases in this paper encompass the possible compliance checking of the designed underground facilities with respect to existing cadastral restrictions, they can be exploited as additional support for the implementation of digital building permitting that covers the underground space developments. It should be highlighted that the integration between CityJSON and IFC standards can be highly useful to obtain solid 3D models that represent the underground cadastral RRRs in the context of digital building permitting because these models can be utilized to enable automatic compliance checking. It is crucial to note that the current studies regarding digitalization mainly concentrate on aboveground and the examination regarding the subsurface is lacking.

As mentioned in the related research section (Section 2.2), there is a large number of previous works that focus on the development of CityGML ADE for the 3D modelling of cadastral RRRs. Regarding this, different studies mention that there is a limitation in supporting software and tools that enable to visualizing, storing, and amending the CityGML files that are created based on the developed CityGML ADE (Biljecki et al., 2018; Saeidian et al., 2023b, 2024). This issue might impede the implementation of 3D underground land administration. Therefore, the present paper provides considerable evidence for the practicability of the CityJSON data model by benefitting from its extension mechanism that eases the exploitation of the created CityJSON files based on the developed extensions. It is essential to note that the created CityJSON file in this study can also be used readily within different software such as QGIS[10] alongside an open web tool namely *ninja*. The feasibility of the created CityJSON file within a spatial database that is established through open tools is also

[10] https://www.qgis.org/en/site/

demonstrated by means of several case studies. This issue does separate the present paper from existing works notably.

Given that previous works frequently concentrate on the 3D delineation of legal spaces instead of legal boundaries (Döner et al., 2011; Ramlakhan et al., 2023), this study provides significant basis on how to create interoperable geoinformation covering these boundaries for subsurface. In addition to existing works (Guler, 2024; Nega and Coors, 2022; Saeidian et al., 2024), it is also demonstrated that the surfaces representing the legal boundaries can be modelled such that they encompass the different attributes regarding ownership such as private ownership for a specific unit or common ownership (see Figure 11). This information can be used to hinder legal disputes transparently.

FME software is the only proprietary tool within the proposed approach in the present paper. This software is used with a free license that is provided for research purposes. This can be mentioned as one of the limitations of this study. Another limitation lies in that an exemplary CityJSON file could be created by including the underground municipal pipes such as drainage pipelines and pile foundations of the buildings or other existing underground structures in a more comprehensive manner.

8. Conclusions

The present paper provides the 3D delineation of both legal spaces and boundaries in the subsurface in an integrated manner. Reliable interpretations regarding the underground cadastral RRRs and their physical counterparts can be achieved completely. They can prevent the legal disputes and facilitate the developments in subsurface. The proposed CityJSON extension not only enables the 3D modelling of ownership below the surface it also allows for 3D representation of aboveground cadastral RRRs. For example, this extension can be beneficial for modelling legal spaces and boundaries belonging to condominium units within the building that exist both aboveground and underground. 3D property ownership information including surface and subsurface can be efficiently integrated into 3D city models and therefore the decisions can be supported through the comprehensive spatial data source that is provided. This data can be exploited by different stakeholders such as urban planners, city administrations, and land registry and cadastre agencies for implementing different applications that utilize 3D standardized geoinformation in terms of geometry and semantics to be able to ensure the resilience of the urban areas. The digital twins/geodatabase covering the subsurface can be established by using the 3D geoinformation that is created based on the developed extension. This extension can also be enhanced in a way to cover the different counterparts of the land administration in the context of ensuring sustainability of underground urban space. For instance, they can be benefitted as an important source for valuation of underground space, which is a current topic and requires solid input data (Mavrikos and Kaliampakos, 2021; Qiao et al., 2022; Wu et al., 2024). The insights of the present paper that are provided through use cases where created geoinformation respecting to the extension is utilized have important implications for improving 3D spatial planning including subsurface. The further outcome is that they can be practical for digitalization of building permitting in the sense of automated compliance checking through standardized geoinformation of the subsurface.

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Supplementary Files

The data related to this study is available at https://github.com/geospatialstudies/land-administration

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