Utilizing the BIM-based standard for supporting 3D digital representation of legal spaces in major infrastructure projects

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Key words: BIM; IFC; land administration; major infrastructure; 3D data model; legal space

SUMMARY

Major infrastructure projects, such as tunnels, roads, and railways, present critical challenges for land administration due to multi-level spatial complexity, stratified ownership rights, and complex spatial relationships. Traditional 2D methods cannot adequately capture these complexities, and existing 3D models remain focused on buildings, lacking the capability to represent the physical and legal dimensions of infrastructure projects. A BIM-based approach offers an enhanced 3D representation of legal spaces, interoperability, lifecycle data integration, and the ability to unify physical and legal data. This paper aims to utilize the Industry Foundation Classes (IFC), which is the open BIM standard, to support the 3D digital representation of legal spaces in major infrastructure projects, addressing 3D land administration challenges in these projects. With a focus on the limitations of current 2D methods and addressing the research gap in land administration for infrastructure projects, this research provides a pathway towards improved 3D data management in land administration for infrastructure projects using BIM-based approaches.

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1. INTRODUCTION

Infrastructure projects, including roads, railways, and tunnels, have grown increasingly with spatial and legal complexities due to the rapid expansion and the need for efficient services. These major infrastructure assets often span multiple levels and spatially intersect with other developments, which is challenging for traditional land administration systems (Davies et al., 2014). The first significant challenge for these major assets is the complexities in defining legal boundaries and rights, restrictions, and responsibilities (RRRs), which are essential for effective land and property management (Ramlakhan et al., 2023). In addition, traditional land administration practices primarily rely on 2D survey plans and cadastral maps to represent legal spaces and boundaries. However, these 2D representations are limited in capturing the multi-dimensional nature of current and future infrastructure projects (Atazadeh, Kalantari, Rajabifard, Ho, et al., 2016). For instance, projecting complex, stratified structures onto 2D plans often results in misinterpretation and misunderstanding (Paasch & Paulsson, 2023), particularly when legal spaces are located in the vertical dimension (see Figure 2 and Figure 2). Furthermore, 2D methods are insufficient for handling spatial conflicts, overlaps, or depth limitations of land parcels within such projects (Aien et al., 2013; T. Li et al., 2024).

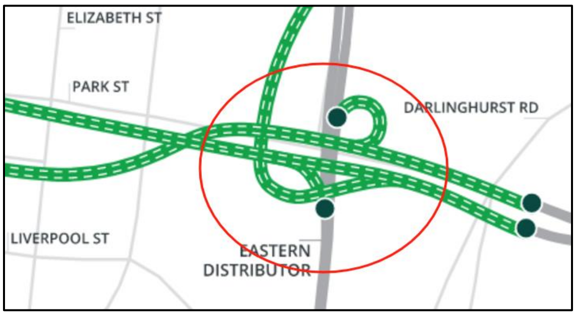


Figure 1: An example of overlapping top view of Cross City Tunnel in Sydney, adopted from (Road Interchanges, 2013)

Figure 2: An example of the junction of the Tunnel, Airport Link and Inner-City Bypass in Brisbane, adopted from (ROADS AUSTRALIA, 2015)

The limitations of 2D methods have led to increased interest in developing advanced 3D data models that can digitally represent both physical and legal data (Guler, 2024). Data model is one of the critical and fundamental stage of data lifecycle management in major infrastructure projects (Kalogianni et al., 2020). Building Information Modelling (BIM) has been widely adopted for managing the 3D physical dimensions of buildings, and studies have shown that BIM-based approaches are beneficial for managing 3D legal data in urban land administration (Ramlakhan et al., 2023). The Industry Foundation Classes (IFC) standard, an open and interoperable BIM data model, facilitates the exchange and integration of building data across various platforms. However, existing 3D data models have largely focused on 3D land administration for buildings rather than infrastructure and current 3D models do not provide sufficient information to represent the legal complexities for these projects (T. Li et al., 2024).

To address these limitations, this research aims to explore how the IFC standard can be harnessed to support the 3D digital representation of legal spaces in major infrastructure projects. This research contributes to providing a pathway towards integrated 3D data management in land administration for infrastructure projects using BIM-based approaches. Additionally, the proposed approach for 3D digital representation of legal spaces and boundaries would provide guidelines for future adoption of BIM by surveyors, land registries and other key stakeholders involved in the infrastructure projects. This would potentially contribute to the roadmap towards to 3D Cadastre (Paasch & Paulsson, 2023).

The structure of this paper is as follows: Section 2 reviews the challenges of existing 3D data models in representing legal spaces for infrastructure projects and examines the potential of IFC for 3D digital representation. Section 3 outlines the research methodology. Section 4 categorizes the 3D land administration data requirements into legal and physical dimensions. Section 5 highlights the key IFC entities relevant to 3D land administration. Section 6 presents a prototype BIM model and 3D visualization of legal spaces for an infrastructure project. Finally, Section 7 offers a discussion, conclusions, and future research directions.

2. LITERATURE REVIEW

Modelling 3D elements for major infrastructure projects differs significantly from modelling multi-story urban development's due to the complexity and variety of RRRs (Andritsou et al., 2023; Huang et al., 2022; S. Li et al., 2021). The development of a BIM-based 3D data model for land administration requires a comprehensive understanding of the existing research aspects. This literature review addresses two critical areas: 1) Current challenges in 3D data models, and 2) The role of BIM in advancing 3D data management for land administration in infrastructure projects.

2.1. Challenges in modelling legal spaces for infrastructure projects

Effective 3D data modelling for legal spaces in major infrastructure projects relies on managing the spatial data lifecycle, including acquisition, validation, modelling, storage, visualization, querying, and analysis (Kalogianni et al., 2020). Among the 3D legal data models, LADM Edition II has been developed to extend its adoption (Kara et al., 2024). Additionally, 3D data models like CityGML and IFC are designed to handle physical data effectively. Integrated models such as CityGML-LADM, IndoorGML-LADM, and IFC-LADM enable the combined representation of both legal and physical data. This section reviews the limitations of existing models in the 3D representation of legal spaces for infrastructure projects.

2.1.1. Legal data models

Legal data models, such as ePlan and LADM, are foundational tools for representing RRRs information of lands. (Atazadeh et al., 2018). However, these legal data models present limitations in modelling legal spaces required for major infrastructure projects. Firstly, ePlan's primary reliance on 2D representations creates challenges in accurately capturing 3D ownership boundaries for multi-layered infrastructure, such as tunnels or underground railways (Shojaei et al., 2016). For instance, in Australian projects, ePlan's 2D framework has proven inadequate for handling underground developments, resulting in spatial ambiguities where legal boundaries intersect in layered environments (Olfat et al., 2016). The LADM was initially designed to support 3D representation of legal objects through entities, such as LA_BoundaryFace and GM_Surface (Ho & Hong, 2023). The former entity defines the boundaries of legal spaces, including curved surfaces, while later entity provides geometric representation capabilities for complex 3D shapes. These entities enable precise modelling of legal boundaries in scenarios such as underground spaces or overlapping ownership structures. However, despite these capabilities, the recent updates in Edition II encounter limitations in addressing the integration of physical and legal data for multi-jurisdictional and infrastructure contexts (Kara et al., 2024). In Sweden, attempts to use LADM for underground infrastructure reveal a lack of capacity to differentiate overlapping rights effectively, particularly when multiple RRRs are assigned to different project layers (Madsen & Paasch, 2023).

2.1.2. Physical data models

Physical data models like CityGML and LandInfra are designed to represent urban environments and infrastructure elements but face limitations in modelling legal spaces in 3D for infrastructure projects (Den Duijn et al., 2018; Jeong & Shin, 2021). CityGML was initially designed for 3D physical data modelling in city scale. CityGML encounters challenges in terms of efficiently representing complex geometries for major infrastructure projects (Saeidian et al., 2023). For instance, curved or branched underground tunnel structures require extensive simplification, as evidenced in South Korean metro tunnel projects, which cannot be fully captured within CityGML without sacrificing essential geometric fidelity. This simplification leads to loss of crucial details needed for engineering and legal verification (Jeong & Shin, 2021). In addition, CityGML shows limitations in integrating legal data. For example, in Hong Kong's transit systems, CityGML's inability to natively integrate legal attributes results in ambiguity over legal boundaries within shared infrastructure, hindering the effective management of ownership rights and usage restrictions (Ho & Hong, 2023). Similarly, LandInfra, while targeted at civil engineering infrastructure, lacks robust support for representing detailed 3D geometries and complex spatial relationships needed for infrastructure projects with overlapping legal spaces. For example, in Korea, LandInfra mainly focuses on the planning, construction, operation and maintenance of highways, while the management of complex infrastructure such as tunnels for representing vertical ownership boundaries needs further explorations (Kumar et al., 2019).

2.1.3. Integrated data models

Efforts have been made to integrate legal and physical data models, such as CityGML and LADM, to facilitate the representation of physical and legal information simultaneously (Atazadeh, 2017). For instance, extensions of CityGML have been proposed to incorporate legal information from LADM by adding legal attributes to CityGML classes or creating new classes to represent legal entities (Saeidian et al., 2023). Additionally, integration of IndoorGML and LADM was investigated, particularly for legal aspects of indoor space, by linking access rights to indoor spatial data for enhanced usability in indoor environments (Alattas et al., 2017). However, the focus on indoor spaces of LADM-IndoorGML integration limit its applicability to infrastructure projects, which often span both indoor and outdoor environments with overlapping legal boundaries (Kim et al., 2021). Aligning different data models and their semantic integration is a significant challenge, and existing tools and software may not support the integrated model effectively, hindering practical applications in 3D land administration (Buuveibaatar et al., 2022; Pavlidou, 2022; Surmeneli et al., 2020).

2.2. BIM and 3D land administration data management for infrastructure projects

2.2.1. BIM and 3D land administration

The opportunities of BIM-based data models not only provide a 3D digital sharing environment that enables all stakeholders to collaborate in real-time on the same platform, improving information transparency and communication efficiency. Countries around the world have different degrees of application of BIM in land administration.

Sweden has made significant progress in adopting BIM and 3D cadastres for infrastructure projects, with a focus on sustainable urban development and efficient land use. In Sweden, authorities have extended LADM-based models to handle complex infrastructure projects like rail systems, highways, and utility networks (Madsen & Paasch, 2023). Singapore has invested heavily in 3D data modelling as part of its Smart Nation initiative, where BIM plays a central role in managing complex ownership and legal rights in vertical urban developments (Yan et al., 2019). For instance, Singapore's approach allows for detailed representation of high-rise building ownership, shared common spaces, and underground utilities, facilitating clear delineation of legal boundaries. Challenges in Singapore include ensuring compatibility across different data models and software platforms, as well as addressing privacy concerns related to the detailed 3D representation of privately owned spaces (Rajabifard et al., 2019; Ong et al., 2022). China's approach to BIM and 3D land administration is largely driven by national government mandates to manage rapid urbanization and infrastructure projects (Zhang et al., 2017). However, current practices emphasize the physical aspects of infrastructure, with less focus on detailed legal dimensions (Zhou et al., 2020; Li et al., 2021). Chinese researchers are actively exploring ways to extend existing BIM frameworks to better represent ownership and usage rights, especially for projects that span multiple administrative regions (S. Li et al., 2021).

2.2.2. Relevant IFC literature for infrastructure projects lifecycle management

IFC standards contain a complete set of entities for managing spatial and semantic information of building elements and can effectively model the spatial relationships between these elements (Atazadeh, Kalantari, Rajabifard, Champion, et al., 2016). Figure 3 shows that IFC standards have been adopted for infrastructure projects to represent these different types of elements. During the planning phase, IFC facilitates project visualization and simulation, enabling stakeholders to better understand the overall layout and design. The use of IFC ensures interoperability, improving design quality and reducing errors. The latest IFC has been explored to provide the 3D representation of main attributes for infrastructure projects (see Figure 4).

In the construction phase, integrating BIM with 4D (time) and 5D (cost) models enables dynamic schedule and budget management (Bradley et al., 2016). This integration enhances efficiency, supports real-time monitoring, and allows project managers to optimize resources and minimize waste (Lee et al., 2017). Additionally, IFC standards facilitate the dynamic documentation of changes throughout a project's lifecycle, such as adjustments to legal spaces due to shifts in legal boundaries. Infrastructure projects often result in changes to legal boundaries from land parcel subdivisions or consolidations (Paasch & Paulsson, 2021). By integrating legal and physical data, IFC provides a robust mechanism for accurately managing these changes within a 3D land administration context (Lee et al., 2017).

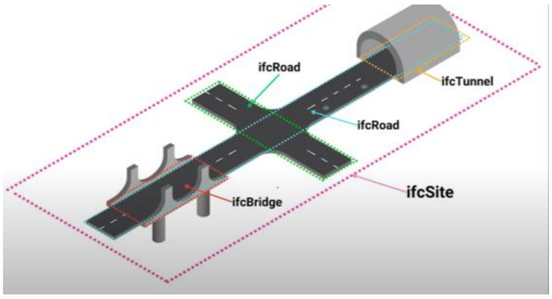


Figure 3: An example of IFC spatial breakdown structure for infrastructures, adopted from (Trimble Civil Construction, 2023)

Figure 4: An example of the latest IFC 4.3 attributes for roads, adopted from (Pszczolka, 2022)

3. RESEARCH METHODOLOGY

This study adopts a structured methodology in three main steps to adopt the IFC standard for 3D digital representation of legal spaces within major infrastructure projects:

- **3D land administration data requirements (Section 4):** The identification of 3D land administration data requirements for infrastructure projects was guided by insights from the literature review, which highlighted critical gaps in existing data models and standards. These requirements are categorized into 3D physical data, 3D legal data, and specific classifications such as crown land in Victoria, Australia.
- **IFC entities for modelling legal spaces (Section 5):** The relevant entities in the IFC standard for modelling legal spaces in infrastructure projects are examined and investigated. This step involves analysing the existing IFC schema to determine how it accommodates the identified data requirements to select entities that can represent legal spaces for infrastructure projects.
- **Create and visualize a prototype IFC model (Section 6):** A prototype IFC model based on a selected area of a tunnel project in Victoria, Australia is created. The visualization of this prototype is based on the findings from the previous steps, demonstrating the practical application of the IFC standard in modelling legal spaces within infrastructure projects.

4. 3D LAND ADMINISTRATION DATA REQUIREMENTS

Developing an advanced 3D data modelling approach for major infrastructure projects starts with identifying specific data requirements (Saeidian et al., 2021). This section focuses on the data requirements, categorizing essential 3D data elements that underpin the implementation of 3D land administration for infrastructure projects in Melbourne, Victoria, Australia. The requirements applied in this section are primarily derived from a combination of literature in the land administration domain including official government websites, reports, guidelines, and published research papers in the context of major infrastructure projects.

4.1. 3D physical data requirements

For major infrastructure projects, physical data requirements, in Table 1 below, are categorized into built environment data and natural environment data.

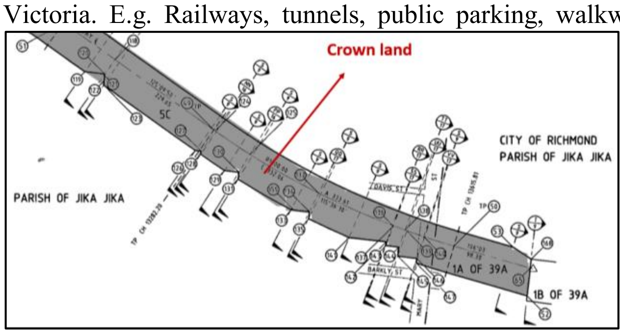
Table 1: 3D physical data requirements for infrastructures

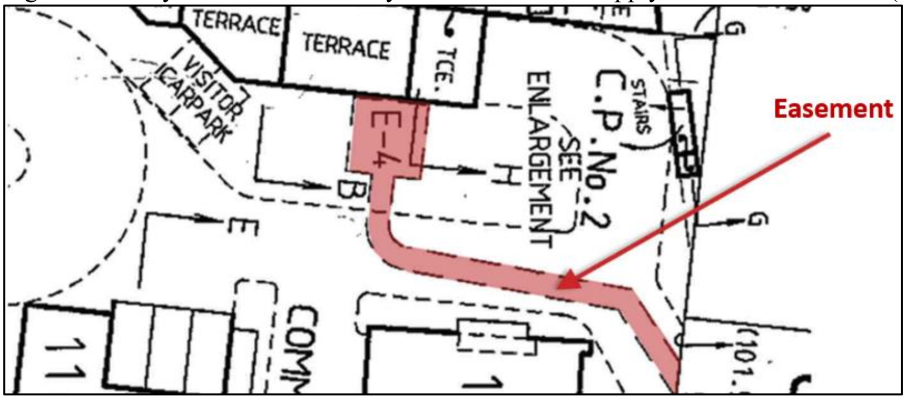
Physical data	Explanation and examples
Built environment data	For transport infrastructure like tunnels, bridges, roads, and railways, this includes dimensions (e.g., length, width, height), materials, and capacity. Utility networks, including electricity, water, gas, and telecommunication systems, require information on cable and pipeline positions, material types, and network layout.
Natural environment data	For transport infrastructure, this includes soil composition, groundwater levels, and climate patterns such as temperature and humidity, which impact structural stability. Utility networks require environmental considerations, such as underground conditions, water quality monitoring, and the impact on local ecosystems.

4.2. 3D legal data requirements

Table 2 outlines the key data requirements for managing 3D legal spaces in the context of infrastructure projects. These requirements address the legal complexities of infrastructure projects, with distinctions made between primary parcels, which represent the core ownership and land boundaries, and secondary interests, which cover legal rights such as easements, airspace, and depth limitations.

Table 2: 3D legal data requirements for infrastructures

3D Legal spaces	Explanation and examples
Primary parcels	
Lot and Stage Lot	This interest is owned by an individual or private owner and defined by land lot and volumetric lot (apartment unit and accessory part). E.g. Buildings, storage, basements, shopping malls, private parking, etc.
Common Property	This interest is for the benefit and use of some/all lots and is defined by unlimited (for the benefit of all owners) and limited (must be used by a specific group of owners) common property. (See **Fejl! Henvisningskilde ikke fundet.**)
Reserve	This interest is owned by city councils for public use and includes those land parcels owned by the city council. Reserves are represented as land parcels in subdivision plans. E.g. Parks or similar amenities
Road	This interest is owned by the government, and the category of road types is summarized in the Victorian ePlan Handbook (State Government of Victoria 2016a). E.g. Carriageway, pavement, verge, curb, etc.
Crown Land – Crown Allotment/Portion	This interest was owned by the government and defined the allotment of crown land in Victoria. E.g. Railways, tunnels, public parking, walkways, train stations, etc. (See )

Secondary interests	
Easement	This interest refers to a legal right that allows an individual, company, or public authority to use a portion of another person's land for a specific purpose, without occupying it. E.g. Pathways and walkways for the supply of utilities. (See )
Depth Limitation	This interest defines the vertical extent of a parcel, particularly concerning underground spaces external to a building. E.g. Restrictions on the depth of water, electricity, gas, sewerage pipelines, tunnels, excavation depth for bridge foundations, etc.
Airspace	This interest has a spatial extent defined above the ground and external to the building. E.g. Height restrictions for buildings, bridges, construction equipment, telecommunications towers, etc.
Restriction	This interest refers to applying specific limitations on the use of certain spaces within a land parcel or lot, which are prohibited or regulated. E.g. Building height restrictions, vegetation restrictions, environmental protection areas, etc.
Crown Land Service	This interest refers to overseeing the allocation, use, management, development, and conservation of Crown land. E.g. Granting permits, leases, or licenses

5. IFC PERTINENT ENTITIES FOR 3D LAND ADMINISTRATION

In the realm of 3D RRR data management, the pertinent entities within the IFC standard are classified into two main categories (Atazadeh, 2017). This section will summarize and categorize the main IFC entities for 3D land administration to support infrastructure legal spaces modelling. The first category comprises spatial elements, with the IfcSpatialElement acting as the superclass for these components. These elements facilitate the modelling of various spatial structures within an IFC project, which can be organized either hierarchically or non-hierarchically (buildingSMART International, 2023). Non-hierarchical decompositions are represented by IfcSpatialZone, allowing for flexible grouping of spatial features without a strict hierarchy. For hierarchical spatial structures, two primary abstract entities are defined namely IfcSpatialStructureElement and IfcExternalSpatialStructureElement. The second category involves physical elements, with IfcElement as the abstract superclass for entities representing physically existing objects, such as IfcBuildingElement, IfcDistributionElement and IfcGeographicElement. The Table 3 below summarizes some of the key IFC entities and relevant legal data in infrastructure legal spaces representation.

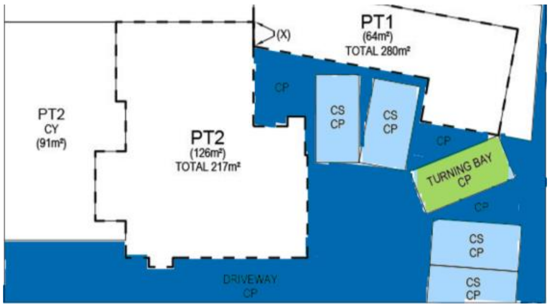


Figure 5: An example of different types of common property in a 2D plan

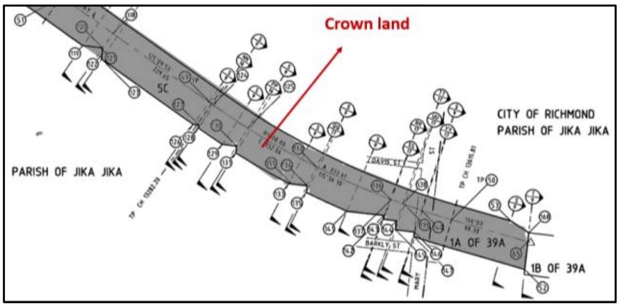


Figure 6: An example of a crown plan (tunnel) in a 2D plan

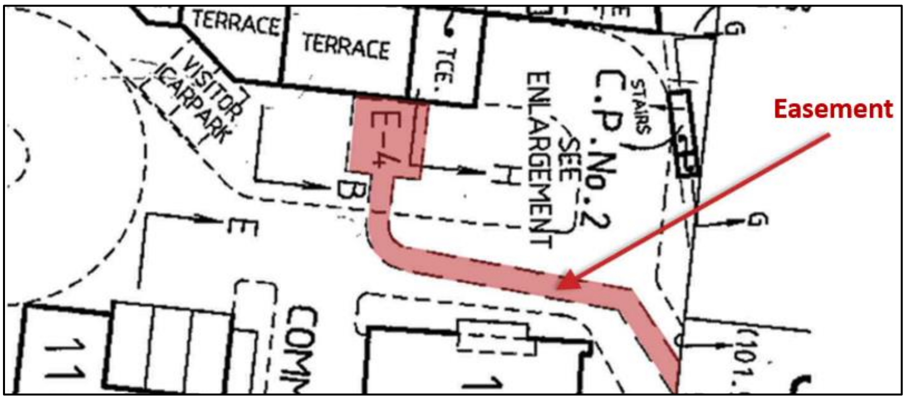


Figure 7: An example of easement in 2D subdivision plan

Table 3: Key IFC entities and relevant legal data for infrastructures

IFC entities	Description of relevant legal data
IfcSpace	It can be utilized to define the boundaries of legal spaces such as land parcels or rights of way. This entity can represent a legal boundary, such as the footprint of a crown allotment or an easement.
IfcPropertySet	Allows for the attachment of legal attributes to IFC entities and can store legal data, including LandUse, LegalRights, OwnershipType, and ParcelID
IfcZone	Multiple spaces need to be grouped. A set of adjacent land parcels or connected infrastructure components represent a larger legal entity.
IfcRelSpaceBoundary	Defines the relationship between a legal space (represented by IfcSpace) and the physical boundaries of the infrastructure. This entity can model both internal and external relationships.
IfcRelAssignsToGroup	Links a group of legal spaces (modelled as IfcSpace or IfcZone) to a common legal entity. For example, a series of easements for utility tunnels could be grouped and assigned under a single contract or legal agreement.

6. PROTOTYPE 3D MODEL FOR AN INFRASTRUCTURE PROJECT

This section presents the creation of 3D models for a selected area in Victoria, which demonstrates the feasibility of using BIM-based models for 3D land administration. The chosen area provides a diverse range of infrastructure components, along with complex land parcels and spatial elements 3D representation overall and separate view.

6.1. Infrastructure assets in the selected area

The selected area (see Figure 8), part of the Burnley Tunnel project in Melbourne, was chosen due to its high spatial complexity, involving multiple overlapping land parcels and infrastructure. The tunnel's route intersects both public and private land, making it a suitable test case for evaluating the capability of IFC for supporting 3D digital representation of different legal spaces. This area also includes other legal spaces such as depth limitations and easements, which are critical to demonstrate the feasibility of BIM in representing legal spaces.

Figure 8: Selected area with a part of the tunnel project and some assets: a) Default view; b) Satellite view

6.2. Creation and visualization of 3D models

Firstly, the physical model of the infrastructure elements was created using Autodesk InfraWorks. This model included the tunnel structure, nearby buildings, and associated land parcels, derived from open data sources (Figure 9a and Figure 9b). Secondly, the legal model was developed using Autodesk Revit to represent ownership boundaries, depth restrictions, and easements. 2D legal data were converted into 3D spaces. Finally, both the 3D physical and legal models were integrated together for visualization using Solibri (Figure 10), which shows the capabilities of IFC to support 3D modelling and representation of 3D land and property data. Figure 11 provides 3D representation of specific physical and legal data. A typical example of legal spaces, crown allotment in Figure 12, is presented in the selected area as legal spaces of tunnel in underground environment.

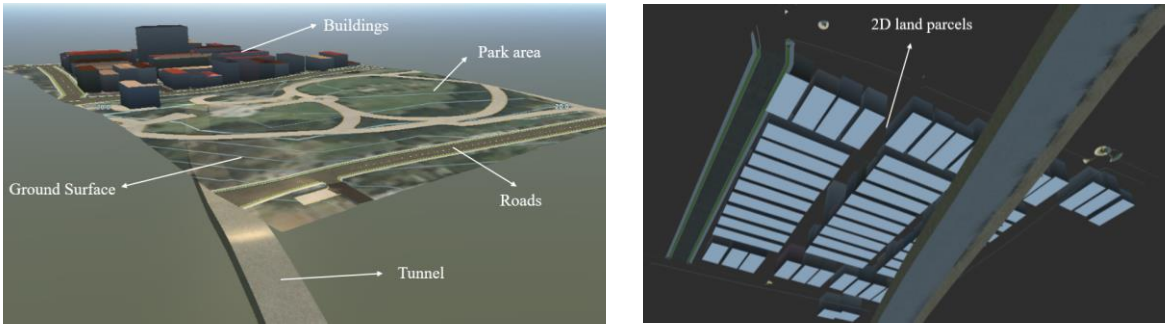


Figure 9: The 3D physical model of the selected area: a) Overall view; b) Bottom view

7. DISCUSSION AND CONCLUSION

This study advances the extension of IFC standards to address the current land administration challenges posed by major infrastructure projects. While previous work has focused on IFC for land administration in multi-storey buildings, this research fills a critical gap by exploring how IFC can be adapted to represent legal spaces in such infrastructure developments.

Infrastructure projects often span multiple land parcels, cross public and private properties, and extend both above and below ground, making the representation of legal spaces particularly challenging. Unlike buildings, which are typically confined to a single parcel of land, infrastructure projects require a more robust model to account for the overlapping RRRs that exist across different land and property ownership and multiple jurisdictions. This study demonstrates that IFC, with its flexible schema, is well-suited to accommodate the complexities inherent in such projects. By creating a prototype BIM model for a section of the Burnley Tunnel project in Victoria, Australia, this research showcases the capability of IFC to digitally represent not only the physical reality of infrastructure but also the associated legal data such as legal spaces, depth limitations, easements, and legal boundaries.

Despite its potential, the IFC standard has limitations compared to other 3D data models for major infrastructure projects. While IFC excels in interoperability and lifecycle data integration, its capabilities in data visualization, validation, and querying are still developing, particularly for complex legal spaces. Future research will involve extensive consultation with industry professionals and stakeholders to refine and validate legal and survey data requirements, enhancing the framework's applicability and effectiveness in real-world infrastructure projects. 3D data models, such as CityGML, provide more tailored visualization frameworks (Saeidian et al., 2023), though they lack IFC's depth in integrating legal and physical data. In addition, current CityGML land administration extensions mainly focus on the underground environment; however, infrastructure projects span both underground and aboveground environments. LandInfra is designed for civil engineering applications and does not specifically address modelling multi-layered and overlapping legal boundaries in infrastructure projects, limiting its utility for 3D land administration in these projects (Kumar et al., 2019). Similarly, while LADM provides robust support for representing legal spaces in implementation (ISO 19152-6, 2019), it still faces challenges in addressing the physical aspects of infrastructure, such as detailed geometric or spatial relationships (Kara et al., 2024). This study is based on the requirements identified in the context of Victoria, providing a justification for its applicability to infrastructure projects. Our proposed approach highlights the potential for connecting LADM and IFC standards, offering a generic methodology for managing land and property data in complex infrastructure.

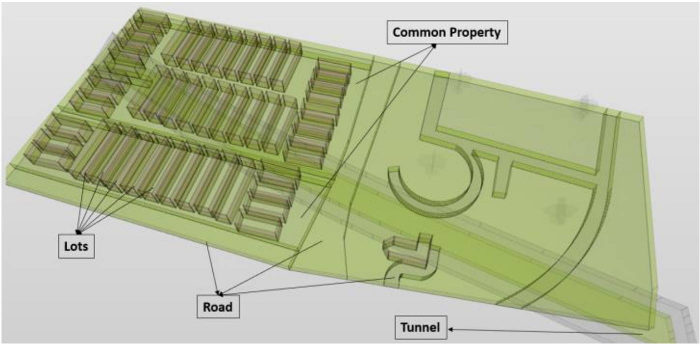


Figure 10: The 3D model of spaces: IFC visualization in Solibri

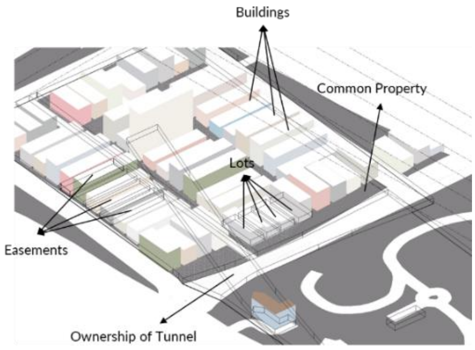


Figure 11: Specific legal and physical data of 3D integrated model

While this study successfully utilized IFC standard for modelling legal spaces, it did not fully explore the most recent developments in the IFC4.3 schema, which includes specific extensions for infrastructure projects. IFC4.3 introduces new features that are specifically tailored to infrastructure environments, such as better support for road, rail, and bridge projects (Borrmann et al., 2024). In our future research, we will investigate the capabilities of IFC4.3 to ensure that its full potential is harnessed, particularly for the representation of complex legal data in major infrastructure projects.

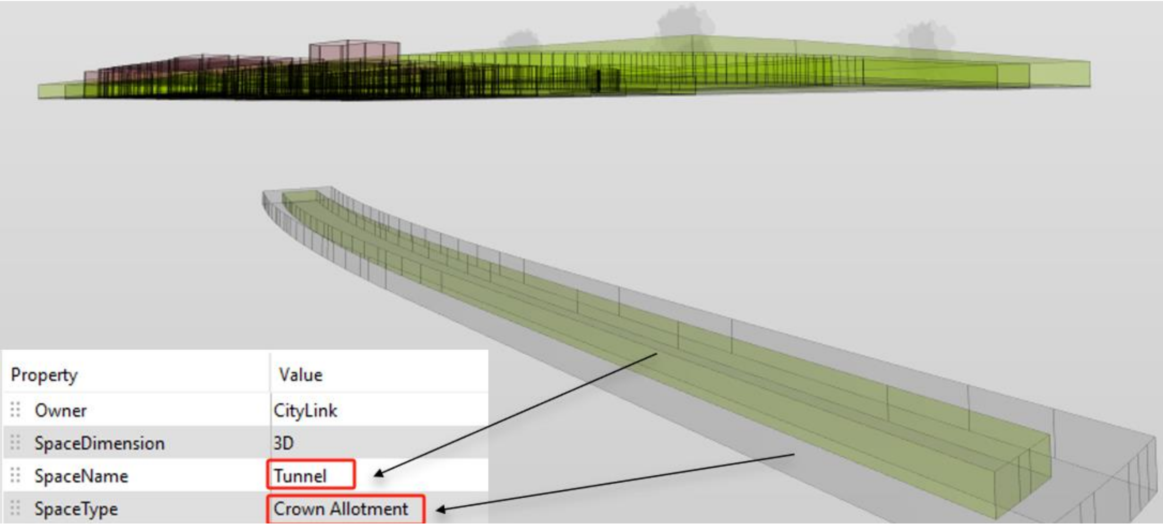


Figure 12: Tunnel and its underground external space of the selected site

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