

Comparing Three Types of BIM-based Models for Managing 3D Ownership Interests in Multi-level Buildings

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Key words: BIM, 3D Ownership Interests, Multi-level Buildings, Physical Model, Legal Model

SUMMARY

There are various 3D spatial data models to support digital management of legal and physical aspects of buildings. These data models adopt three possible approaches to represent and manage spatial dimension of 3D ownership interests, namely pure legal, pure physical and integrated methods. Building Information Modelling (BIM) is a method for managing physical elements. However, its open standard can be enriched with legal information to manage spatial extent of 3D ownership interests defined inside buildings. Our recent research has proven that the open data model of BIM can be used in all the three approaches for managing 3D ownership interests. Currently, no single investigation has yet explored the performance of these approaches in BIM environment. The aim of this research is to evaluate the performance of three types of BIM-based building models in terms of communication, storage and management of 3D ownership interests defined inside multi-level buildings. The selected jurisdiction for this study is Victoria, Australia. Strata lots and common properties are the main types of 3D ownership interests in this jurisdiction. We examined how spatial extent of these ownership interests is defined in current cadastral practices. We then selected a relatively complex multi-level building comprising various private and communal 3D ownership spaces, and we developed three types of BIM-based models, namely legal, physical, and integrated ones, for the selected building. The adopted metrics for comparing the models include number of objects, geometry batches, visualization speed in terms of frame rate, query speed, and communication of structural boundaries. The outcomes indicate mixed results.

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1. INTRODUCTION

Various 3D spatial data models have hitherto been developed to provide a foundation for managing legal and physical dimensions of buildings. Some data models provide spatial entities for managing legal spaces. For instance, Land Administration Domain Model (LADM) uses the concept of spatial units to define the spatial extent of ownership interests (Lemmen, van Oosterom and Bennett, 2015). On the other hand, there are also data models, which define data elements for managing physical objects inside buildings. An example of such physical data model is CityGML, which defines various types of physical boundaries within its building module (Groger, Kolbe, Nagel and Hafele, 2012).

Ownership interests defined inside multi-level buildings are vertically overlapped and interweaved into each other. In the context of 3D models, effective representation and management of spatial complexity inherent in stratified ownership interests are very challenging for current land administration systems. There are a few possible approaches for managing spatial extent of 3D ownership interests delineated inside buildings. One approach is the use of only legal spaces to show and represent 3D cadastral objects (e.g. using LADM). Another way is to delineate boundaries of 3D ownership interests by only using physically existent building elements such as walls, doors, windows and slabs (e.g. using CityGML). One possible approach could also be using both legal and physical objects in an integrated data environment to manage spatial dimension of 3D ownership interests.

Over recent years, Building Information Modelling (BIM) paradigm has emerged in the construction industry to improve coordination and information communication in the construction industry (Eastman, Teicholz, Sacks and Liston, 2011). This paradigm utilizes a 3D digital data space for managing semantic and spatial information associated with building elements over the lifecycle of a construction project (NBIMS, 2012). Currently, BIM provides a rich data repository of information about physical aspects of buildings. BIM models not only include bona-fide (tangible) spatial objects, such as walls, doors, windows, and slabs but also they can contain fiat (intangible) volumetric spaces. Additionally, some spatial relationships between fiat and bona-fide spatial objects are defined within BIM models (Borrmann and Rank, 2009). The open data model for BIM is the Industry Foundation Classes (IFC) standard, and it has been developed for promoting interoperability over the building development process (ISO16739, 2013). IFC standard provides a hierarchical spatial structure to store building information. This means that the building project can be decomposed into manageable subsets such as site, building, stories, spaces and building elements inside stories (Liebich, 2009).

Although BIM is a method for modelling physical elements, in our recent research we have enriched its open standard with legal information to manage spatial extent of 3D ownership

interests defined inside buildings (Atazadeh, Kalantari, Rajabifard, Ho and Champion, 2016). Our recent research has proven that the data model of BIM can be used in all the three approaches for managing 3D ownership interests (Atazadeh, Kalantari, Rajabifard, Ho and Ngo, 2016). Currently, no single investigation has yet explored the performance of these approaches in BIM environment. Therefore, the aim of this research is to evaluate the performance of three types of BIM-based building models, which are developed based on the above-mentioned approaches, in terms of communication, storage and management of 3D ownership interests defined inside multi-level buildings.

In next section, relevant 3D spatial data models in both BIM and geospatial domain are reviewed. Subsequently, the research methodology is presented in Section 3, which is followed by identification of main 3D ownership interests in Section 4. Section 5 describes the implementation of BIM models for a multi-level building. Results of comparison will be provided and discussed in Section 6. Final section is dedicated to conclusions and recommendations for potential future research.

2. RELATED WORK

In this section, we will review various legal, physical and integrated 3D spatial data models in terms of modelling 3D ownership interests defined within multi-level buildings.

2.1 Pure physical modelling

Pure physical models are not particularly designed for the purpose of mapping ownership arrangements and boundaries within multi-level buildings. However, they can be harnessed or extended for representing and managing cadastral information. These models usually manage spatial and semantic information associated with physically existent objects in various levels of details. Among physical models, IFC and CityGML provide a comprehensive set of entities, some of which could be potentially used for mapping ownership interests within indoor environments. Below, we will review the relevant parts of each of these physical models, which can be utilized in 3D cadastral domain.

2.1.1 IFC

IFC is an internationally recognized open standard used for enhancing interoperability in BIM domain (Liebich, 2013). The basis of this standard is underpinned by EXPRESS language (Schenck and Wilson, 1994). IFC includes a large number of entities used for exchanging building information over the whole lifespan of buildings. Various properties of building objects such as their geometry, semantics, spatial relations, materials, fabrication and so on can be modelled inside IFC standard. In addition, IFC includes entities for modelling construction processes such as actors and their activities and tasks (BuildingSMART, 2013a). Here, we only explain those IFC concepts used for modelling spatial structure and physical parts of buildings (BuildingSMART, 2013b). Typically, spatial data of a building project is structured in IFC models in a hierarchical way. Five key entities are used to arrange spatial structure of buildings, namely “IfcProject”, “IfcSite”, “IfcBuilding”, “IfcBuildingStorey”, and “IfcSpace”. “IfcProject” is the topmost container of building spatial data. Each IFC project can include one or more “IfcSite” instances, which refer to topographic land surfaces or

parcels on which buildings are constructed. Each site can contain one or more “IfcBuilding” instances used for modelling buildings. “IfcBuildingStorey” specifies information about levels of buildings. “IfcSpace” defines intangible and volumetric functional spaces, which can potentially be used to manage ownership interests inside buildings. For modelling physical parts of buildings, “IfcBuildingElement” entity is specialized into various subclass entities such as IfcWall, IfcDoor, IfcSlab and so on. If ownership interests are modelled by “IfcSpace”, subclasses of “IfcBuildingElement” can be considered as cadastral boundaries since they are connected to “IfcSpace” via “IfcRelSpaceBoundary” relationship.

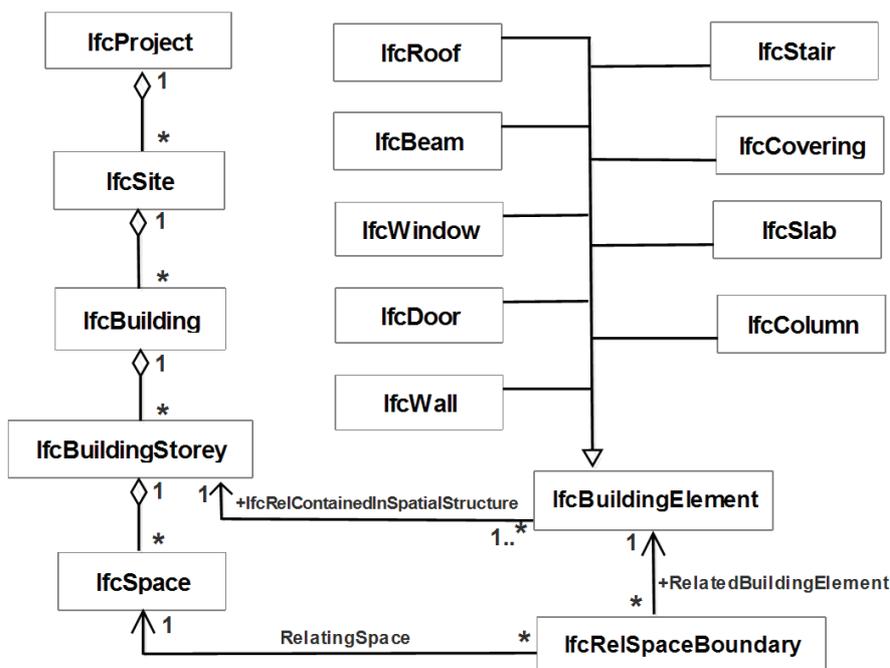


Figure 1. Spatial data structure of IFC standard

2.1.2 CityGML

In the domain of geographic information systems (GIS), CityGML standard is widely known for interoperable exchange of 3D geospatial data about urban built environment (Gröger and Plümer, 2012). This standard models topological, geometrical, semantical, and appearance properties associated with urban objects. The most important part of CityGML is dedicated to physical modelling of buildings (see Figure 2). The appropriate semantic entity for modelling ownership interests could be “_Room” class since this entity describes any functional volumetric space within buildings. In addition, CityGML supports various types of physical boundaries to define the spatial extent of ownership interests in both vertical and horizontal directions. As indicated in Figure 2, the abstract “_BoundarySurface” class has subclasses for modelling wall, ceiling, floor and roof boundaries. In addition, there is “ClosureSurface” subclass which can be used for modelling boundaries without physical manifestation such as those ones defined in balcony and terraced areas.

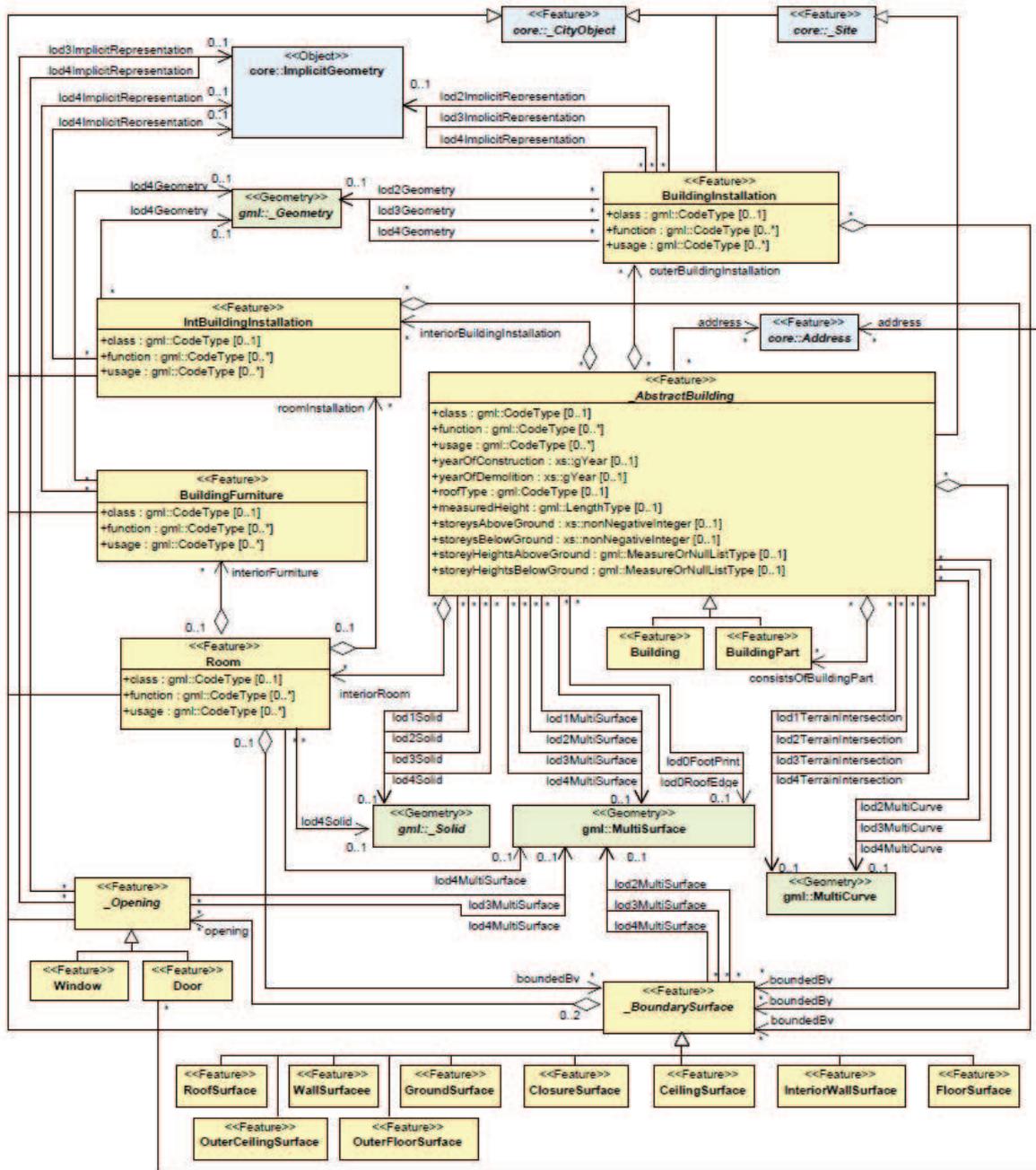


Figure 2. Building model of CityGML, adapted from (Groger et al, 2012, p. 63)

2.2 Pure legal modelling

Pure legal models are mainly designed according to the legal regulations of each jurisdiction. Most legal models support 2D representation of ownership interests. Among legal models, Land Administration Domain Model (LADM) is one of a few legal models being able to support 3D legal objects. This model has been recently proposed as a conceptual international standard for managing cadastral information (ISO19152, 2012). In this standard, spatial unit entity (“LA_SpatialUnit”) provides various spatial representations of ownership interests defined inside any jurisdiction (see Figure 3). These representations include textual

descriptions, sketch maps, points, unstructured set of lines, areal and volumetric 3D objects. Additionally, concept of basic administrative unit (“LA_BasicAdministrativeUnit”) is also defined to arrange and group a set of spatial units associated with the same ownership interest. For instance, spatial units of an apartment unit, its carpark and storage areas can be assembled in one basic administrative unit which represents an individually owned property within a multi-level building. The boundaries of each spatial unit are defined through association relationship with boundary faces which are modelled by instantiating “LA_BoundaryFace” entity.

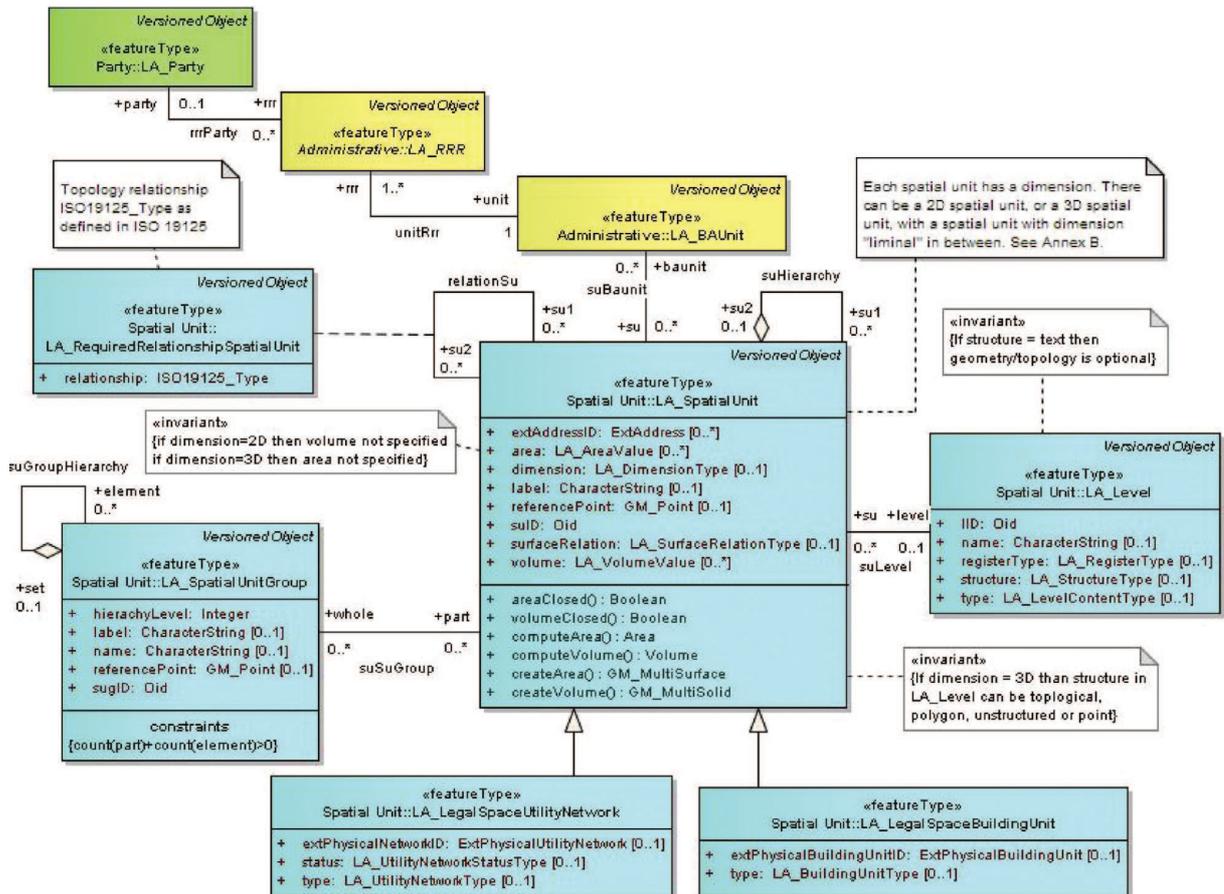


Figure 3. Package of spatial unit in LADM, adapted from (Lemmen et al, 2015, p. 541)

2.3 Integrated approaches

Recently, a few 3D spatial data models are proposed to integrate both legal and physical dimensions of multi-level buildings. The main reason for developing integrated data structures is that some jurisdictions, such as those of Australia, define arrangements of ownership interests within multi-level buildings using both physical structures and legal spaces. For instance, common properties in Victoria typically consist of not only cognitive legal spaces, such as corridors, but also building elements such as walls and slabs between two individually owned legal spaces. Physical data models, such as IFC or CityGML, usually provide their own extension mechanism for incorporating legal objects, whereas legal data models, such as LADM, can be connected to physical objects through external linkages.

Within geospatial domain, CityGML standard is extended with legal objects and ownership attributes by leveraging its Application Domain Extension (ADE) capability. Dsilva (2009) proposed a preliminary ADE of CityGML for cadastral purposes, in which a new legal object called “_KadasterApartment” is particularly defined for modelling ownership interests associated with apartment units. Subsequently, Cagdash (2013) developed a more detailed ADE comprising a number of legal objects such as cadastral parcels, individually owned condominium units, joint facilities and annexes. Finally, Li et al (2016) developed a comprehensive LADM-based ADE comprising legal objects defined in the Chinese jurisdiction. This integrated model is capable of managing relationships between legal objects and physical elements and can represent ownership structure of various private and commonly owned condominium units defined in multi-level buildings. Another investigation, which is distinct from the previous ones in geospatial domain, is 3D cadastral data model (3DCDM) developed by (Aien, 2013). The implementation of this integrated data model was realized via defining an application schema of Geography Markup Language (GML). 3DCDM is able to support various legal and physical elements associated with urban objects including multi-leveling buildings, tunnels, utility networks and so on.

In land administration domain, Soon et al (2014) explored the interconnection between LADM and CityGML standard through the use of a semantics-based fusion framework. They proposed that “LA_LegalSpaceBuildingUnit” in LADM can be linked to “_AbstractBuilding” and its subclasses “Building” and “BuildingPart” in CityGML. Another study by Zlatanova et al (2016) found the synergies between LADM and IndoorGML. They suggested that “LA_SpatialUnit” entity in LADM can be externally associated with “CellSpace” entity in IndoorGML.

In BIM domain, we extended IFC standard to manage ownership interests over the lifecycle of buildings. The first version of cadastral extension of IFC standard defined “IfcLegalPropertyObject” entity as a subclass of “IfcSpace” (Atazadeh, Kalantari, Rajabifard, Ho and Ngo, 2016). “IfcLegalPropertyObject” represents all types of private and common property ownership spaces. In the second version of our extension, we extended the concept of spatial zones (IfcSpatialZone) to manage arrangements of ownership interests in terms of both cognitive spaces and physically existent elements (Atazadeh, Kalantari, Rajabifard, Ho, and Champion, 2016). For instance, a common property spatial zone can be composed of communal spaces, such as lobbies and corridors, and building elements such as walls, columns and ceilings.

3. METHODOLOGY

Three major stages constitute the research methodology.

- The first stage is to identify how 3D ownership interests are defined inside multi-level buildings. The selected jurisdiction for this study is Victoria, Australia. Strata lots and common properties are the main types of 3D ownership interests in this jurisdiction. We examine how spatial extent of these ownership interests is defined in current cadastral practices (cf. Section 4).

- In the second stage, we select a relatively complex multi-level building comprising various private and communal 3D cadastral spaces, and we develop three types of BIM-based models, namely legal, physical and integrated models, for that building (see Figure 1). After constructing the BIM models, we export them in open IFC data format (cf. Section 5).
- Finally, we compare models by using some metrics. The adopted metrics include number of objects, geometry batches, visualization speed in terms of frame rate, query speed, and communication of structural boundaries (cf. Section 6).

4. 3D OWNERSHIP INTERESTS IN VICTORIA

The ePlan handbook developed by Land Victoria (2016) organization describes any type of ownership interests defined across the Victorian jurisdiction. Ownership interests with 2D or 3D spatial extent are classified into two main categories, namely primary and secondary ones. Primary ownership interests are base level parcels that constitute the continuous cadastral fabric. They include all types of lots, common properties, roads, reserves, and crown parcels. Secondary ownership interests provide benefits and/or pose restrictions on primary ownership interests. These include easements, restrictions, depth limitations and airspaces. Among primary ownership interests, strata lots and common properties are the most prevalent ones, which have 3D spatial extent, defined inside multi-level building developments (Atazadeh, Kalantari, Rajabifard, Champion, and Ho, 2016). Therefore, the main focus of this investigation is on those ownership interests.

Strata lots usually consist of at least one main volumetric space, which is typically an apartment unit and associated with an individual ownership right. Additionally, it can include accessory volumetric spaces such as storage areas and carparks. Figure 4 represents a typical example of strata lots.

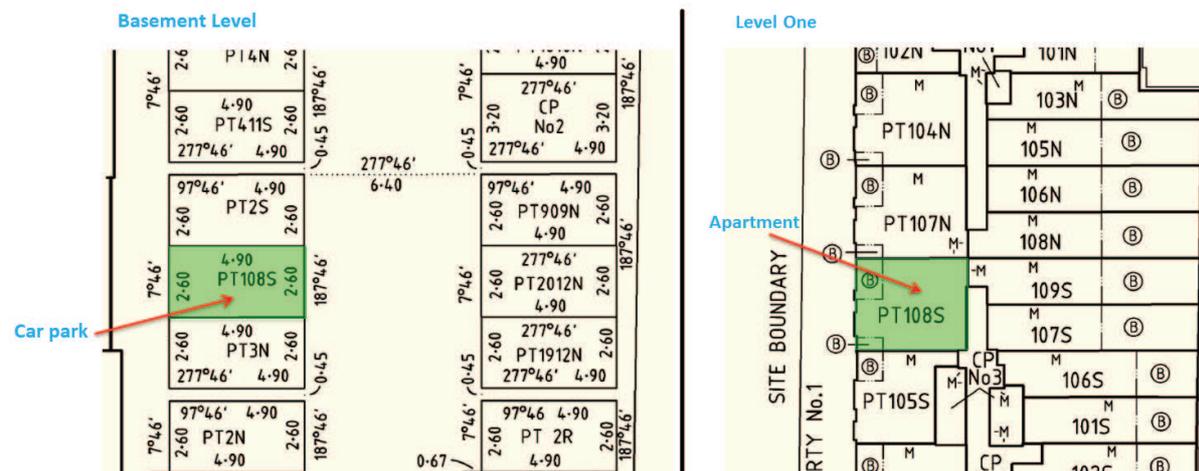


Figure 4. Parts of a strata lot

The arrangements of common properties are more complicated than strata lots. This type of ownership interest is usually composed of various indoor and outdoor spaces as well as

physically structures. Current surveying practices in Victoria only delineate the spatial extent of spaces on subdivision plans and there is no clear representation of physical structures. However, it is implicitly stated that which physical structures belong to the ownership of common property area. For instance, for common property No. 1, which is highlighted in Figure 5, it is notated that “All walls defining boundaries, floor and ceiling slabs, columns, internal service ducts, conduits, pipe shafts, and electricity consumer mains cables within the building and courtyards are deemed to be part of common property No.1”

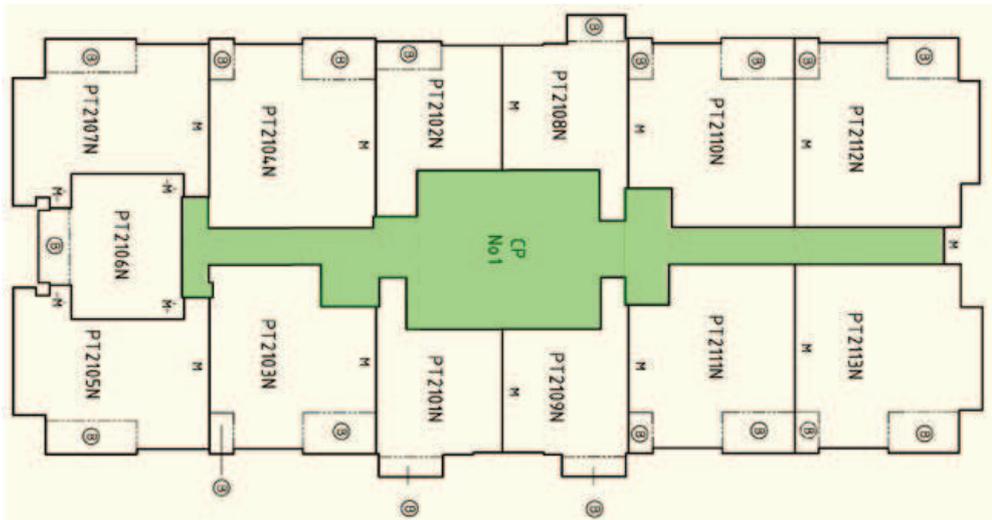


Figure 5. Common property delineated in floor plan diagram

Precise delineation of each part of 3D ownership interests are determined by various types of ownership boundaries. We developed a comprehensive taxonomy of ownership boundaries in our recent investigation, which is predicated on widely known dichotomy between general and fixed boundaries (Atazadeh, Kalantari, Rajabifard and Ho, 2016). Among those boundaries, structural (interior, median and exterior) boundaries are very prevalent in multi-level buildings in Victoria. Therefore, accurate understanding of them is very important for associated interest holders. As an example, it can be seen in Figures 4 and 5 that median boundaries are notated using “M” letter.

5. IMPLEMENTATION OF BIM MODELS

The implementation consists of constructing three types of BIM models for a multi-level building located in Melbourne, Australia. The BIM authoring software used in this study is Autodesk Revit 2016. First, we created a pure legal BIM model of the building using its subdivision plans. Legal spaces for both strata lots and common properties are defined within the model (see Figure 6a). Afterwards, we used architectural plans to construct the pure physical model of the building. Various architectural components of the building such as its walls, ceilings, floors, doors and windows are authored (see Figure 6b). Finally, we created an integrated BIM model comprising both legal spaces and physical elements. Since Revit software has its own proprietary and closed data format for storing BIM models, we converted

the BIM models into open IFC format which can be opened in any BIM environment. We used Solibri Model Viewer for visualization of IFC files. In addition, we used xBIM API to perform various queries on IFC files. The specifications of workstation used for querying and visualizing BIM models include an Intel Core i7 340 GHz CPU, 4GB of RAM, AMD Radeon HD 6350 GPU running Windows 7 x64.

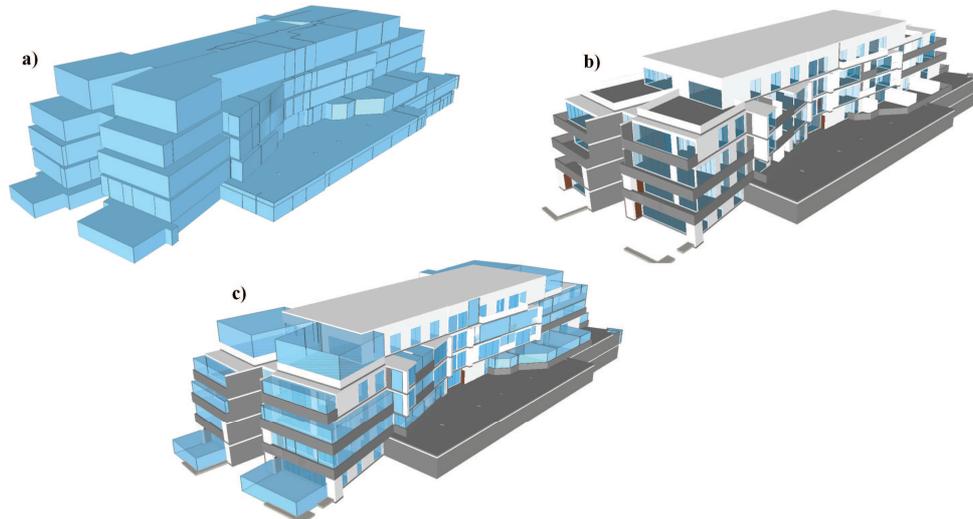


Figure 6. BIM-based building models, a) Pure legal model b) Pure physical model c) Integrated model

6. RESULTS

In this section, we report preliminary results obtained from each model using the adopted metrics.

- Number of objects and geometry batches: Table 1 compares the models in terms of number of objects and number of geometry batches. These metrics are used for measuring the size of BIM models. 'Number of objects' metric refers to all spatial objects, whether physically existent or cognitive spaces, constituting the BIM model. A geometry batch refers to number of parts constituting each spatial object. For instance, windows are composed of two batches, one for the frame and the other for the glass, while walls typically include one batch. It can be seen that legal BIM model has the minimum size, whereas the largest size belongs to the integrated model.

Table 1. Metrics used for measuring the size of each BIM model

BIM Model	Number of objects	Number of geometry batches
Legal model	146	146
Physical model	962	1131
Integrated model	1108	1277

- Frame rate: Frame rate or frame per second (FPS) represents the visualization and rendering speed of applications. In 3D environments, a threshold of 15 Hz is essential for smooth interaction with 3D models. For many applications, the recommended FPS is usually around 30 Hz. We measured the minimum, maximum and average FPS values for

each BIM model (see Figure 7). The FPS values of the physical model are found more than those of the legal model, although the number of objects for physical model is more than the legal model. This can be explained by the fact that volume of the 3D space occupied by building elements is less than volume of the legal spaces. Therefore, interacting with the physical model was smoother than the legal model. The integrated model was the least interactive model with FPS values between 15 and 17 Hz.

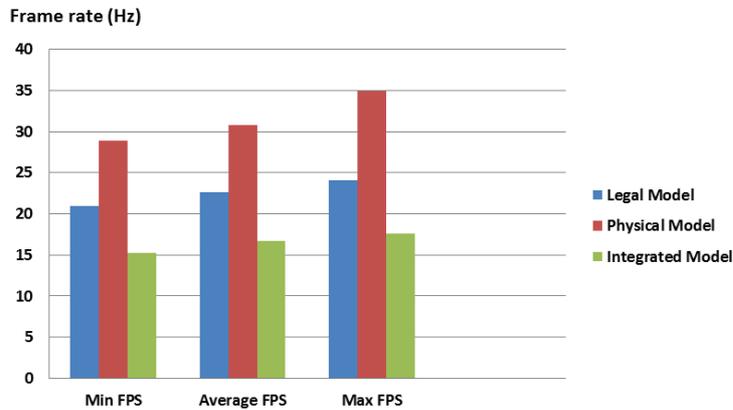


Figure 7. Minimum, maximum and average FPS for each model

- Query speed: For both strata lots and common property of the building, semantic queries were executed (see Figure 8). Queries in the legal model were executed faster than the physical model. This is because the number of objects in the legal model was fewer than in the physical model. Unsurprisingly, querying of ownership interests took the longest time interval in the integrated model since it has the largest number of objects. Another result is that querying time for the common property of the building is more than strata lots in all models. The reason is that common property is composed of a large number of parts in comparison with strata lots.

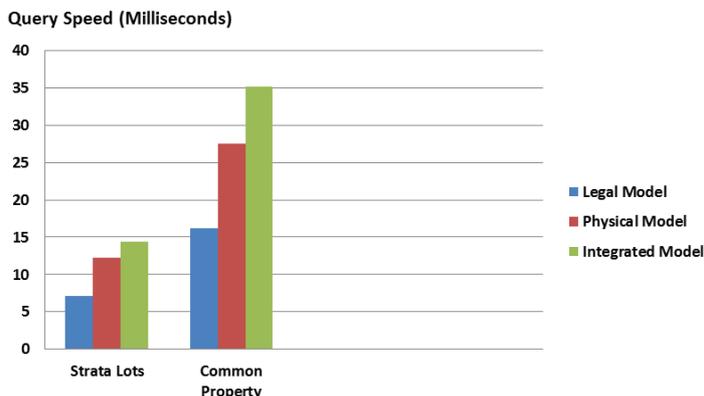


Figure 8. Measured time for executing semantic queries in BIM models

- Communication of structural boundaries: Figure 9 represents how structural boundaries can be visually represented in each BIM model. In legal model, it is difficult to intuitively disambiguate the location and type of boundary. In physical model, internal and external boundaries can be visually distinguished from each other; however, this model is not

capable of visualizing median boundaries. The integrated legal and physical model is able to visually communicate all types of structural boundaries. Table 2 summarizes the visual communication of structural boundaries in BIM models.

Table 2. Visual communication of structural boundaries in each model

BIM model	Interior Boundaries	Median Boundaries	Exterior Boundaries
Legal model	Incommunicable	Incommunicable	Incommunicable
Physical model	Communicable	Incommunicable	Communicable
Integrated model	Communicable	Communicable	Communicable

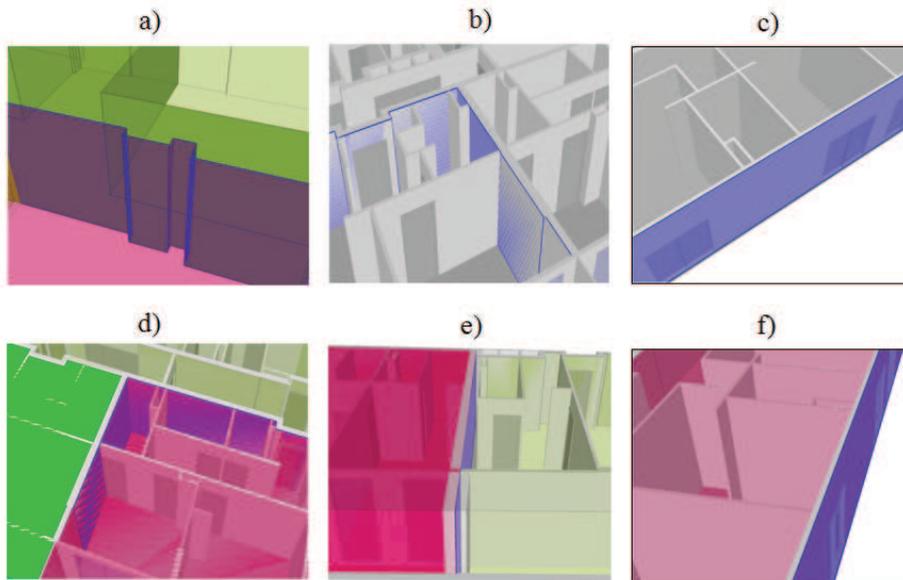


Figure 9. Visualization of structural boundaries in BIM models: a) Visually ambiguous boundary type in legal model b) Internal boundary in physical model c) External boundary in physical model d) Internal boundary in integrated model e) Median boundary in integrated model f) External boundary in integrated model

Overall, the above metrics indicate that manipulating, navigating and querying pure legal or physical models of multi-level buildings are easier than integrated ones. However, integrated models provide better communication of 3D ownership interests in multi-level buildings. In addition, integrated models would help to perform various spatial queries, analyses and computations associated with 3D ownership interests. For instance, topological relationships between ownership spaces and building elements would help to determine the location of structural boundaries if semantic relationships between them are not defined in the stage of constructing BIM model. Another example could be applying visibility analysis on ownership spaces, which would potentially help to determine value of private properties in multi-level buildings.

7. CONCLUSIONS

In this paper, pure legal, pure physical and integrated BIM-based approaches are suggested as possible solutions to manage 3D ownership interests in multi-level buildings. To evaluate the performance of these approaches, we developed a BIM model for each method. By using a few number of metrics, we showed that how each model can store, manage and communicate spatial extent of strata lots and common properties in multi-level buildings. One major finding is that pure models can perform better in terms of visualizing and querying, whereas integrated models would provide more intuitive and visual communication of 3D ownership interests.

BIM environment and, especially IFC standard, is currently being extended to model other urban objects such as roads, bridges or tunnels. Therefore, using the adopted approaches to model and visualize ownership interests associated with other urban infrastructure can be considered as a possible future research direction. Another important aspect of BIM environment is to provide a multi-dimensional (nD) modelling of buildings, which is management of any information over the whole lifecycle of buildings. Therefore, another future research can be investigating the viability of BIM environment for managing lifecycle of cadastral information (nD modelling) in multi-level buildings.

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BIOGRAPHICAL NOTES

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