A New Method for Integrating 3D Spatial Information about Vertically Stratified Ownership Properties into the Property Map Base

Abbas RAJABIFARD, Behnam ATAZADEH, Mohsen KALANTARI and Ian WILLIAMSON, Australia

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SUMMARY

In many jurisdictions, a property map base is typically considered as an underlying basis to support and facilitate making spatial decisions over the development process of buildings and infrastructure facilities. The property map base provides the most accurate and reliable methods for recording, managing and representing legal boundaries of ownership properties. Existing property map bases mainly rely on 2D-based representation schemes to show the legal extent of land parcels and, consequently, failing to communicate spatial arrangements of vertically stratified properties. These include various types of private, communal and public properties such as apartments, office buildings, shopping centres, subway stations, utility systems, and subterranean passages, which are prevalent in urban built areas. In this article, an approach to integrating 3D spatial information about vertically stratified ownership properties into current 2D-based property maps will be presented. The proposed approach mainly comprises creating 3D digital models of ownership properties, validating these models before integration into the current property map base, and analysing 3D property boundaries. The proposed approach will help implement 3D property ownership map bases which not only can be used to manage legal arrangements in complex urban environments but also have the potential to be leveraged for broader urban applications.

Integrating 3D spatial information about vertically stratified ownership properties into the property map base

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1. INTRODUCTION

Over the last years, the unprecedented urbanization has fostered the rapid development of multi-storey buildings and infrastructure facilities, resulting in spatial and functional complexities in cities. The traditional and fragmented approaches for managing and planning cities are becoming less effective and the concept of smart cities is rising to manage cities in an integrated, digital, collaborative and interoperable data environments (Casey et al., 2016). Smart management of cities reduces costs considerably, and increases productivity, sustainability and well-being of urban communities (Escamilla Solano, Plaza Casado, & Flores Ureba, 2017). 3D digital models have been developed widely to manage and communicate both physical and cognitive notions of cities (Chaturvedi & Kolbe, 2016). Ownership of properties is a cognitive notion of urban areas, which specifies the legal entitlements for doing activities within an urban community at individual, group and public levels. Currently, property map bases utilize 2D-based spatial representations to communicate the legal extent of land parcels. The spatial dimensions of properties located above and below the earth's surface are not represented in property map bases of most jurisdictions around the globe (Tsiliakou, Labropoulos, & Dimopoulou, 2013). These include various types of private, communal and public properties in multi-storey buildings, shopping centres, subway stations, utility systems, and subterranean passages, which are prevalent in urban built areas. For example, only the name of multi-storey properties located inside the land parcel is provided in the current property map base of Victorian State of Australia (see Figure 1).

Figure 1, An example of a land parcel for a multi-storey building development highlighted in orange within the Victorian property map base

This inadequacy of current property map bases results in serious consequences in the management of urban areas with high-density developments. These consequences are:

- The knowledge gap about 3D properties in the map base typically requires organizations to conduct extra surveying activities in complex ownership situations.
- The spatial information about vertically located properties is often stored in proprietary and non-interoperable data environments, which leads to costs associated with duplication of 3D spatial information. For instance, in Victoria the cost of data duplication is predicted over $1.8 million per annum (CRC for Spatial Information, 2008).
- It affects the reputation of authorities responsible for maintaining the property map base and providing critical spatial information services to the community.
- Over the development and establishment of new built assets, unpredictable impairments can be done to other assets, particularly those assets located below the Earth's surface.
- The current 2D property map base would not effectively support decision making in managing and planning other aspects of urban settings such as launching National Broadband Network for multi-level developments (NBN Company, 2016).

In this research, the underpinning postulation is that effective decisions in planning and managing our urban environment could be made if 3D spatial arrangements and boundaries of above and underground properties and infrastructure are managed in the property map base systems. Therefore, the overall aim is to explicate innovative approaches for managing 3D spatial data resulted from subdividing vertically located properties in order to enhance the current 2D property map base. This will facilitate the delivery of a 3D property map base for urban land administration, responding to core business objectives for many governments around the world. Technical challenges and solutions for incorporating spatial information about 3D property rights, restrictions and responsibilities (RRRs) into the property map base will be investigated.

2. RELATED WORK

In this section, the relevant literature will be reviewed in three parts. In the first part, major challenges in developing 3D property map base will be highlighted. The second part is dedicated to 3D spatial data models which underpin the logical basis of storing 3D spatial information in the property map base. The final part reviews related preliminary implementations of 3D property map base in various countries around the globe.

2.1 Challenges in Development of a 3D Property Map Base

To implement and use 3D property map bases, two categories of technical challenges should be considered: Challenges in validating spatial integrity of 3D properties, and challenges in analyzing and querying boundaries of 3D properties.

2.1.1 Spatial Integrity Challenges

Spatial integrity refers to the rigorous procedures for checking and rectifying possible errors in the 3D property map base using a predefined set of validation rules (Thompson & Van Oosterom, 2011). Validation rules are typically considered on two levels, namely individual 3D property object and a set of 3D property objects (Zhao, Guo, Li, & Ying, 2012). Therefore, the first challenge is to ensure that the geometry of a single 3D property object is defined by a valid volume. Currently, multi-surface and solid modelling approaches are commonly used for defining the geometry of 3D spatial objects. However, these approaches should be validated against the rules used for ensuring spatial integrity of a single 3D property object. Another spatial integrity issue is legal interests associated with a set of 3D property objects. For instance, a common property is defined by composing various cognitive spaces and physical objects. Developing appropriate validation rules is necessary to ensure that the whole spatial structure of a set of 3D property object is logically valid.

2.1.2 Challenges of 3D boundary query and analysis

Boundaries of 3D properties are often cannot be easily perceptible due to the existence of complex structural and architectural elements inside complex urban developments. Therefore, there are challenges in finding and analysing these boundaries (Billen & Zlatanova, 2003). The first challenge is to define an appropriate query language to identify the spatial relationships between 3D property boundaries and their corresponding physical elements (Atazadeh et al., 2017). Another challenge is analysing boundaries to determine various private, communal and public rights within urban built developments. Analysing 3D property boundaries requires a different methodology to that used for other 3D spatial objects. This stems from the way 3D boundaries are defined by the legislation. In addition, relationship of boundaries with physical objects makes querying and analysing the boundaries more complicated.

2.2 Spatial Data Models for 3D Property Map Base

There are a number of spatial data models developed for modelling physical and legal complexities of vertically located properties in urban built environments. Among these models, three international standards have been mainly considered as capable of delivering a successful implementation of 3D property map base systems. These include Land Administration Domain Model (LADM), CityGML and Industry Foundation Classes (IFC) standards.

2.2.1 LADM

This standard provides a conceptual schema for describing purely legal representation of ownership properties (ISO19152, 2012). The concept of spatial units provides a broad definition of both 2D-based land parcels and legal spaces. Relevant to 3D ownership properties, there are two specific types of spatial units, namely building units and utility networks. Building units define legal spaces inside buildings, while utility networks provide legal spaces surrounding utility elements. Legal boundaries are defined by two LADM entities, namely "LA_BoundaryFaceString", and "LA_BoundaryFace", which are respectively used for modelling boundary lines and boundary faces. In these entities, there is no semantic information or semantic relationship with physical objects when a legal boundary references a physical element (Aien, Kalantari, Rajabifard, Williamson, & Wallace, 2013). Another point is unclear definition of solid objects in LADM to support valid volumetric legal objects (Pouliot, Vasseur, & Boubehrezh, 2013).

2.2.2 CityGML

CityGML is a spatio-semantic 3D model of the urban built environment in terms of its physical elements and cognitive functional spaces (Kolbe, Gröger, & Plümer, 2005). The standard mainly assigns semantic entities to boundary surfaces of physical elements to distinguish different types of physical boundaries such as internal and external boundaries of walls, internal and external boundaries of ceilings, and virtual boundaries (Groger, Kolbe, Nagel, & Hafele, 2012). Solid models of boundary representation (B-rep) are supported in CityGML. Various extensions of CityGML have been proposed to manage ownership of 3D properties (Çağdaş, 2013; Dsilva, 2009; Rönsdorff, Wilson, & Stoter, 2014). These extensions mainly developed at conceptual level and are yet to be realized in case studies.

2.2.3 IFC

This standard provides a thorough set of semantic and spatial concepts to model every component inside complex building developments (ISO16739, 2013). An investigation by Atazadeh et al. (2017) showed that IFC standard can be used for modelling both geometric and semantic aspects of a wide range of legal boundaries defined inside buildings. Cadastral extension of IFC standard was also proposed to model complex ownership arrangements in multi-storey developments (Atazadeh et al., 2017).

2.3 Review of Preliminary Implementations of 3D Property Map Base

Over the last decade, several investigations have been conducted to develop the foundation of 3D property map base. These investigations mainly fall under the topic of a full 3D cadastre, studying various aspects of recording, managing and visualizing 3D spatial information, and integrating it with 2D spatial information which is existent in current ownership map bases.
One of the preliminary and implementable 3D cadastral models, which lay the foundation of 3D ownership property map bases, was proposed by Stoter and Van Oosterom (2005). Their proposed model was predicated on two distinct but complementary types of land parcels to partition the property map base, namely 2.5D surface land parcels based on digital elevation models and volumetric land parcels (or vertically stratified properties). The strength of this model was the capability to define the linkage between 3D volumetric properties and the 2D property map base used in current practices. In this study, the refined constraint TINs (Triangular Irregular Networks) are found to be the best potential approach to modelling the geometry of 2.5D land parcels. Polyhedron data types were observed as an appropriate geometric representation entities for modelling 3D volumetric parcels (Stoter & Van Oosterom, 2005). Although this investigation provided a good starting point for development of 3D property map bases, there are some limitations of its proposed model. These limitations mainly include inadequate support for modelling semantic relationships between legal objects. For example, it was unclear how different land parcels associated with a unique legal interest can be semantically linked to each other.

A more recent study was done by Guo et al. (2013) who developed a property ownership map base comprising both 2D-based land parcels and 3D legal spaces. In this investigation, Shenzhen city in China was selected as a case study area to prove the viability of the proposed solution. It was found that existing 2D property map base can be upgraded into a 3D ownership map base without disruptive effect on the existing system configuration. Therefore, a main advantage of this solution was to minimize conflicts in upgrading the ownership map base in future. Nevertheless, the study identified organizational changes as a major barrier in implementing a 3D ownership property map base since 2D-based practices are highly entrenched in land planning and design departments.

Another remarkable investigation was a transition model from 2D-based cadastral model to a 3D real property cadastre in the context of Slovenian land administration system (Drobež, Fras, Ferlan, & Lisec, 2017). Currently, land administration system of Slovenia comprises two distinct 2D-based spatial databases, namely the land cadastre and the building cadastre. The proposed transition approach consisted of two stages. In the first stage, additional 3D data was incorporated into each database. For the land cadastre database, topographic data and 3D terrain model were incorporated. For the building cadastre, the additional data comprised floor plans and cross sections in vector format, and floor heights. In the second stage, databases of the land cadastre and the building cadastre were integrated to represent spatial extent of ownership properties in a 3D digital data environment. This research used several case studies including a set of single-family detached houses with their road and utility networks, a multi-storey building development, a tunnel and a viaduct. These case studies showcased the feasibility of the proposed model for upgrading current 2D-based ownership map to a 3D one in Slovenia.

The common shortcoming for all the spatial data models and implementations proposed for the property map base is that they can model spatial extent of vertically stratified properties but the approach into the validity check of 3D spatial objects constructed by these models have not yet been substantially examined. In addition, these investigations did not utilize 3D spatial queries for analysing and retrieving legal boundaries of 3D properties inside complex developments. The main difference between this research and previous investigations is that we propose an approach to incorporating 3D spatial information about vertically stratified properties into the current 2D property ownership map base and use it for 3D boundary query and analysis. In other words, our approach is more holistic and considers the stages of creating, validating, querying and analysis of 3D spatial information for 3D property ownership map bases.

3. PROPOSED APPROACH FOR DEVELOPMENT OF 3D PROPERTY MAP BASE

The proposed approach comprises three main steps: 1) Constructing 3D digital ownership models; 2) Validating spatial integrity of 3D ownership models; 3) Performing spatial queries and analyses in the property map bases. Each step is explained in detail in the following subsections.

3.1 Creating 3D Digital Models of Ownership Properties

In this step, 3D data authoring methods is used to define boundaries and spatial extent of various types of 3D property objects. The common and user friendly approaches for constructing a shape of 3D property objects include Constructive Solid Geometry (CSG) and sweeping solids. CSG solid modelling approach defines the geometric shape of 3D spatial objects by applying Boolean operators to the standard primitive objects (Rossignac & Requicha, 1999). These primitive objects usually include simple shapes such as cuboids, cylinders, pyramids, spheres, cones, and so on. Mainly used Boolean operators in CSG are union ($\cup$), intersection ($\cap$), difference ($-$) and geometric transformations such as translation, rotation, and scaling. CSG solid models can be expressed as ordered binary trees, in which the primitive objects are represented as leaf nodes, results of Boolean operators are defined within the internal nodes, and the final CSG model is represented as the root node of the tree. Figure 2a shows an example of CSG solid model defined by applying Boolean operators on primitive 3D spatial objects. The fundamental idea behind swept solid models is to represent them by a 2D profile and a predefined curve (Agoston, 2005, p. 174). The 2D profile could be a primitive object such as a rectangle, circle or polygon. The volumetric extent of swept solid models is formed by either rotating or translating the 2D profile alongside the trajectory of the predefined curve (see Figure 2b). Some building elements, such as walls, columns or beams, can be defined by through applying translational swept solid models.

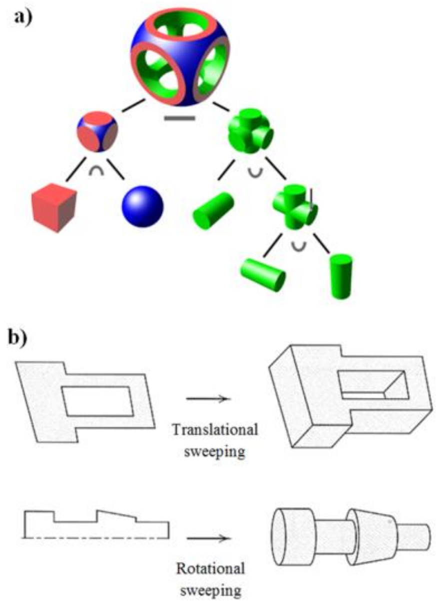

Figure 2, a) Example of a CSG solid model, adapted from (Wikipedia, 2014) b) Examples of swept solid models, adapted from (Anand, 1996)

3.2 Validating 3D Digital Models of Ownership Properties

In order to validate 3D property objects, one solution is to adopt the boundary representation (B-rep) and develop axioms for engineering validation rules accordingly. Therefore, the geometry of 3D property objects, which could be in CSG or sweeping solid, should be converted into B-rep-based solid models. Figure 3 shows the fundamental entities in defining a valid volumetric property objects. B-rep-based solid models are merely defined based on a set of connected boundary surfaces. These boundary surfaces or faces are formed by a graph of edges and vertices (Allen, 1984). The final representation of a B-rep solid model is shown by at least one shell. One shell, the outer, shall completely contain all the other shells and no other shell may contain a shell. The Eular-Poincaré formula defines the following quantitative relationship among number of faces (F), edges (E), vertices (V), faces' inner loops (L), shells (S), and genus of shells (G) in B-rep solid models (Mantyla & Sulonen, 1982):

$$F-E+V-L = 2(S-G) \quad (1)$$

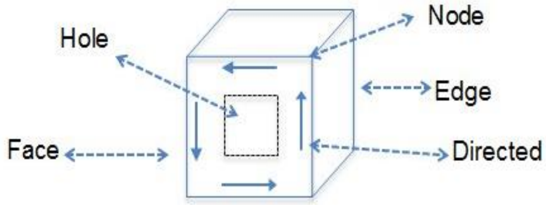

Figure 3, Fundamental entities of a B-rep-based solid model

In addition to the equation (1), Thompson and Van Oosterom (2011) proposed that additional geometrical axioms specific to 3D property objects must be applied. These axioms are (Thompson & Van Oosterom, 2011):

– The distance between two vertices should be less than e.
– Each vertices must have at least three incident faces
– The incident faces of a node must not have intersection with each other. They can intersect each other at an edge.
– There must be at least e distance between two non-intersecting edges.
– Every directed-edge of a face in the shell must belong to a fold. A fold is a pair of faces meeting at anti-equal directed edges with no other faces between them.
– The directed-edges defining a hole in a face must be part of the other faces
– Bounded faces must be planar within the tolerance of e'.
– A node should have e distance with a face except it is a constituent node of the face.
– No directed-edge may intersect a face except at a node of that edge

These validation rules can be used for ensuring the spatial integrity of the 3D digital models. Once the 3D digital models of ownership properties have passed all the validation rules, these models can be integrated into the current property map base.

3.3 Spatial Query and Analysis of 3D Property Boundaries

After integration of the 3D digital ownership models into the property map base, the query and analysis capabilities should also be enhanced to retrieve and analyse 3D spatial data. Spatial relationships play a fundamental role in performing spatial analyses and queries. However, 3D digital data environments do not explicitly specify all of the possible spatial relationships between spatial objects. For instance, the “above” or “below” adjacency relationships between a slab object and a wall object are not defined. Additionally, in complex urban built environments, 3D digital models utilize a large number of spatial entities to store information about physically existent elements as well as invisible or cognitive spatial elements. Retrieving the required subset of information from such complex and abundant data environment for a specific purpose is a very difficult task. To address these challenges, 3D spatial query languages have been introduced to automate extraction of essential spatial information from 3D digital information models (Borrmann & Rank, 2009a, 2009b; Borrmann, Schraufstetter, & Rank, 2009). These languages typically adopt three types of spatial operators to perform queries and analyses: proximity, directional and topological. The spatial extent of ownership rights, restrictions and responsibilities (RRR) in buildings can be defined as invisible and volumetric legal spaces. The boundaries of these legal spaces are often determined via defining spatial relationships between these spaces and physical elements. This means that these boundaries are defined via geometric connection of legal spaces to physical elements in three ways: 1- The boundary touches the interior face of the building element 2- The boundary touches the exterior face of the building elements 3- The boundary passes through the median of the building element.

Such definition of 3D legal spaces implies that topological operators can be applied to the geometry of invisible spaces as well as building elements, which in turn automatically deduces type of boundary and its corresponding building element. The 9-Intersection model, proposed by Egenhofer and Herring (1990), is the renowned topological formalism in spatial information science. For each spatial object (A), this model subdivides topological space with any dimension, in this case R3, into three regions: 1- Interior of spatial object (Ao) 2- Boundary of spatial object (jA) 3- Exterior of spatial object (Ae). According to this decomposition, the following 3 × 3 matrix is constituted to determine topological relationships between two spatial objects (A, B):

(2)
$$I = \begin{bmatrix} A^o \cap B^o & A^o \cap \partial B & A^o \cap B^e \\ \partial A \cap B^o & \partial A \cap \partial B & \partial A \cap B^e \\ A^e \cap B^o & A^e \cap \partial B & A^e \cap B^e \end{bmatrix}$$

The values of this matrix can be empty () or non-empty ($\neg\emptyset$). If we assume that both A and B are 3D solids, then the possible topological relationships between two solids are: Disjoint, Contains, Inside, Equals, Touches, Covers, Covered by, and Overlaps. All of these relationships and their corresponding intersection matrix are represented in Figure 4.

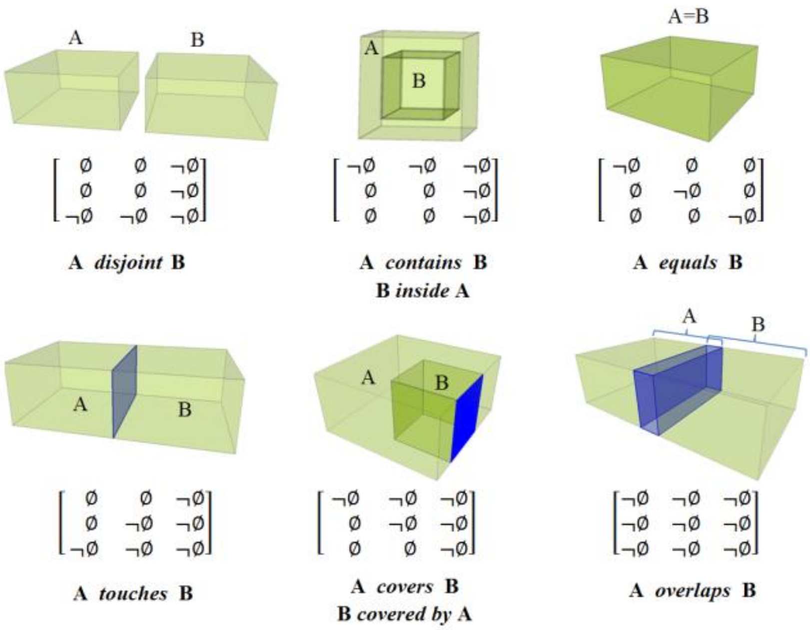

Figure 4, Common topological relationships between two 3D spatial objects

Among these relationships, Touches, Overlaps and Covers are relevant topological configurations for analysing legal boundaries in the property map base. Let A is a legal space and B is a building element. We have:

A Touches B → Interior Boundary (see Figure 5a)
A Overlaps B → Median Boundary (see Figure 5b)
A Covers B → Exterior Boundary (see Figure 5c)

Spatial analysis of 3D legal boundaries will support a range of common queries about vertically located properties. This includes queries such as:

- Where are the 3D legal boundaries associated with this property?
- What are the legal rights associated with an apartment unit?
- What is the association of an infrastructure with its surrounding legal spaces?

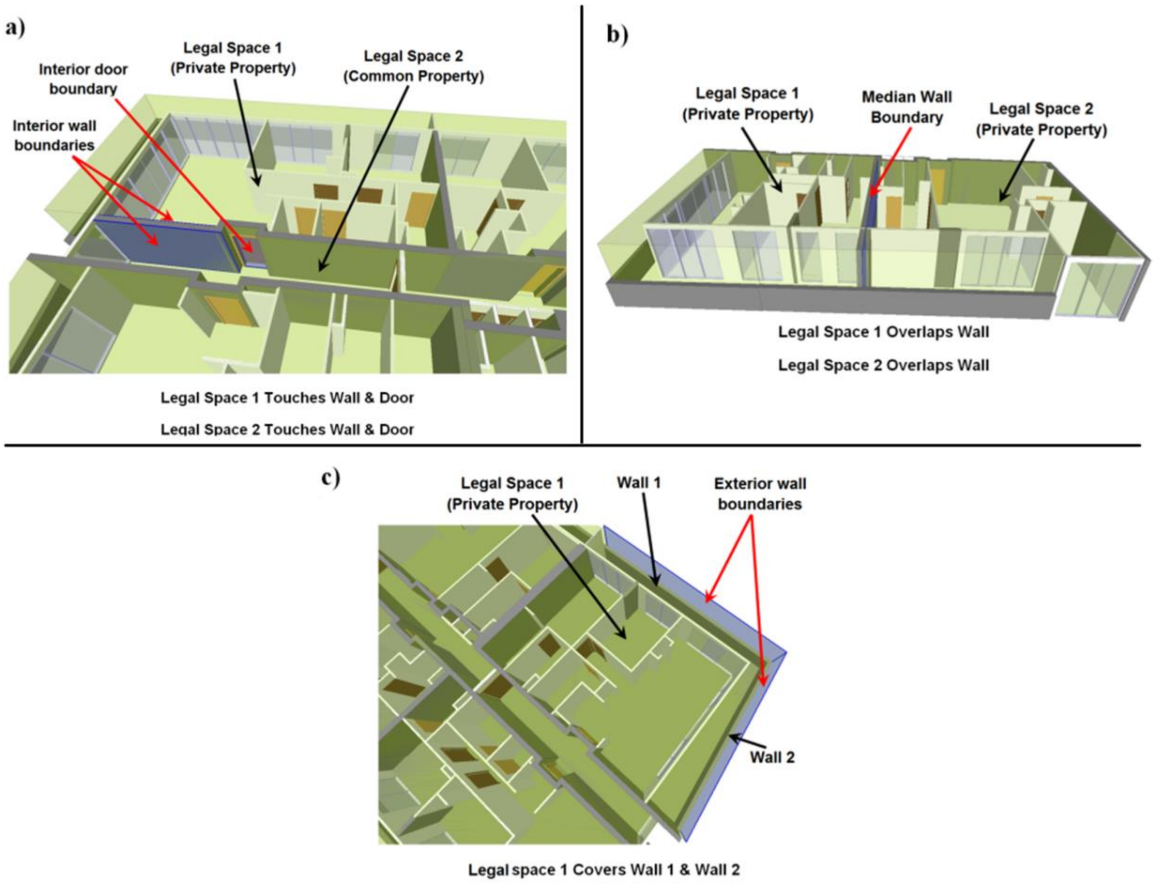

Figure 5, Analysis of legal boundaries in the 3D property map base

4. DISCUSSION

In previous section, the main steps towards realizing a 3D property map base was presented. The development and implementation of a 3D property map base will bring new implications in managing RRRs in complex urban built environments. The potential implications of the proposed approach are discussed below.

The 3D property map base will change current practices associated with recording and managing ownership of stratified properties. Stakeholders need to interact and communicate in a 3D digital environment. For instance, instead of 2D subdivision plans, 3D digital models will be exchanged among land surveyors, city councils and land registry organizations. 3D property map base will provide the ability to insert and extract 3D digital data over the land and building development process. Current uses of 2D property map base can be improved if it is upgraded into a 3D one. Spatial location of property units above and below the ground can be easily determined in 3D property map base, which would subsequently improve delivery of spatial services relying on the property map base. 3D property map base will support volumetric representations of legal and physical spaces. In addition, computations and analyses associated with volumetric property objects will be realized in 3D property map bases. These new capabilities will support the responsible authorities in making better decisions when a new multi-storey development is constructed since 3D property map base can represent how this development will affect other underground and aboveground properties within its neighbourhood.

Another implication is the emergence of new use cases for property map bases. This would provide the ability to leverage the property map base for new urban applications such as estimating the density of occupancy in 3D space. 3D property map base allows 3D analysis based on population and employment forecasting to enable capacity modelling of existing and proposed services. This 3D digital environment allows us to produce interactive and narrative products which facilitate better community participation in the decision-making process.

The above factors imply that development of a 3D property map base would potentially uncover the camouflaged value of legal information in complex urban built environments and increase the functionality of the current property map base in better governance of an urban built environment. However, there are underpinning organizational barriers in realization of 3D property map base in the current legislative settings of jurisdictions. These obstacles stem from the fact that the procedures for recording and managing legal information in 3D digital environment would be different to the current analogue data environment which is predicated on subdivision acts and regulations. For instance, the new 3D digital validation rules must be rigorously reviewed and approved by the legislative bodies.

5. CONCLUSIONS

Spatial arrangements of ownership properties located underground and aboveground in dense urban built environments cannot be adequately recorded and represented in the current 2D property map bases. Integration of 3D digital models into the current property map base could provide a potential solution to alleviate spatial problems in communicating and managing vertically stratified properties. However, this integration entails two major technical challenges, namely ensuring spatial integrity of ownership properties and analysing legal boundaries in 3D digital data environments. In this article, a theoretical approach for integrating 3D spatial information about vertically stratified ownership properties into the current 2D property map base was proposed. The potential implications of the 3D property map base in better management of urban built environments have been also highlighted. The coherent 3D digital representation of the property map base would provide valuable intelligence in making spatial decisions associated with legal ownership of underground and above ground properties.

6. ACKNOWLEDGEMENT

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BIOGRAPHICAL NOTES

Abbas Rajabifard is Professor at the University of Melbourne and head of the Department of Infrastructure Engineering and Director of both the Centre for SDIs and Land Administration and the recently established Centre for Disaster Management and Public Safety. He is immediate Past-President of Global SDI (GSDI) Association and is an Executive Board member of this Association. Abbas was Vice Chair, Spatially Enabled Government Working Group of the UN Global Geospatial Information Management for Asia and the Pacific. He has also consulted widely on land and spatial data policy and management and SDI.

Behnam Atazadeh is a post-doctoral research fellow in the Centre for Spatial Data Infrastructures and Land Administration, Department of Infrastructure Engineering. He has extensive experience in using 3D building information models and other 3D digital technologies for cadastral surveying in urban areas. As part of his research, Behnam has published several articles in reputable scientific journals and conferences in the domain of spatial and urban informatics.

Mohsen Kalantari is a Senior Lecturer in Geomatics Engineering and Associate Director at the Centre for SDIs and Land Administration (CSDILA) in the Department of Infrastructure Engineering at The University of Melbourne. He teaches Land Administration Systems (LAS) and Building Information Modelling and his area of research involves the use of 3D digital and spatial technologies in LAS and SDI. He has also worked as a technical manager at the Department of Sustainability and Environment (DSE), Victoria, Australia.

Ian Williamson is Emeritus Professor at the University of Melbourne**.** His teaching and research is concerned with cadastral, land and geographic information systems, land administration and spatial data infrastructures, in both developed and developing countries. He has published extensively on these topics. He has undertaken research or consultancies world-wide including for AusAID, the United Nations and the World Bank. He is a Member of the Order of Australia (AM), a Fellow of the Academy of Technological Sciences and Engineering Australia (FTSE), a Fellow of the Institution of Surveyors Australia Inc., a Fellow of the Institution of Engineers Australia, a Fellow of the Royal Institution of Chartered Surveyors, an Honorary Fellow of the Mapping Sciences Institute, Australia and an Honorary Member of the International Federation of Surveyors (FIG).

CONTACTS

Abbas Rajabifard
Department of Infrastructure Engineering, University of Melbourne
VIC 3010 AUSTRALIA
E-mail: abbas.r@unimelb.edu.au
Website: www.ie.unimelb.edu.au/
Behnam Atazadeh
Department of Infrastructure Engineering, University of Melbourne
VIC 3010 AUSTRALIA
Email: batazadeh@student.unimelb.edu.au
Web site: http://www.csdila.unimelb.edu.au/people/behnam-atazadeh.html

Mohsen Kalantari
Department of Infrastructure Engineering, University of Melbourne
VIC 3010 AUSTRALIA
Email: mohsen.kalantari@unimelb.edu.au
Web site: http://www.csdila.unimelb.edu.au/people/saeid-kalantari-soltanieh.html

Ian Williamson
Department of Infrastructure Engineering, University of Melbourne
VIC 3010 AUSTRALIA
Email: ianpw@unimelb.edu.au
Web site: http://www.csdila.unimelb.edu.au/people/ian-williamson.html